Citizen science:

Knowledge, networks and the boundaries of participation

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Abstract

The water-related challenges facing humanity are complex and urgent. Although solutions are not always clear, involving the public in localised knowledge production and policy development is widely recognised as a critical part of this larger effort. Such public engagement is increasingly achieved through "citizen science"—a practice that involves non-professionals in scientific research and monitoring. Academic literature has recognised that, while citizen science is both important and necessary to strengthen environmental policy, its acceptance and successful implementation is a difficult governance challenge. Researchers agree that overcoming this challenge depends on the ability of volunteers, coordinators, scientists and decision-makers to work together to convert the potential of citizen science into practice. However, little is known about the collaborative relationships or the broader social contexts that shape and define the practice. To address these shortfalls, this thesis advances a conceptual framework for the relational analysis of citizen science that illustrates social networks and the boundaries between expert and community-based knowledge as critical sites of investigation. Through its multi-phase and mixed-methods research design, the findings of this thesis shed light on the contributions of citizen science to key waterway governance objectives, including the social, political and cultural factors that influence its acceptance and uptake in governance contexts. By unpacking the relational dimensions of citizen science, this thesis provides both theoretical and practice-based insights into how actors within and outside citizen science programs work together to achieve collective aims to engender stronger connections between science, society and policy. This thesis will benefit practitioners, policymakers and participatory advocates interested in achieving practical social change in efforts to understand and manage natural resources.

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…

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Statement of authorship and originality

Except where explicit reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgement in the main text and the list of references of the thesis. No editorial assistance has been received in the production of the thesis without due acknowledgement. Except where duly referred to, the thesis does not include material with copyright provisions or requiring copyright approval.

Signed:	Signed:
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Candidate	*Principal Supervisor*

It seems to me to be urgent for the planet and for all its creatures that we discover ways of living in more collaborative relation with each other and the wider ecology. I see…participatory approaches to inquiry and the worldview they foster as part of this quest.

Peter Reason (1994, p.325)

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Article II
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Article III
Bonney, P., A. Murphy, B. Hansen, and C. Baldwin. 2020. Exploring the citizen science-policy interface: a social network perspective. *Submitted to Society and Natural Resources*

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Statement of contribution

The original research presented in this thesis was conceived in consultation with the supervisory team (Angela Murphy, Birgita Hansen and Claudia Baldwin). I developed the data collection instruments, collected and analysed the data and wrote each paper, with suggestions for improvements provided by co-authors.

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1 Introduction

Across Pennsylvania and New York, a broad network of volunteers and community organisations work together in hundreds of catchments to monitor the impacts of hydraulic "fracking" in the Marcellus shale (Jalbert et al. 2014). Using the tools of science, these groups collect surface water quality data to advocate for policy change and fill knowledge gaps in areas where no other monitoring exists. In several locations across the world, from Hong Kong to Brazil, citizens collaborate with scientists from Freshwater Watch to create a database of water quality information at a global scale (Thornhill et al. 2019). Data from Freshwater Watch have advanced scientific understanding on the drivers of poor water quality in urban streams, the dynamics of phytoplankton blooms and sources of litter in lake ecosystems. And, in New Zealand, Te Awaroa ("the long river") seeks to transform relationships between people and waterways through community-led and place-based research (Salmond et al. 2014). The project integrates local, indigenous and scientific knowledge and aims to restore the ora ("health") of 1,000 rivers by 2050.

These examples illustrate different forms of "citizen science"—a rapidly expanding practice that involves non-professionals in generating and applying scientific knowledge (Bonney et al. 2009). While these examples are all situated in freshwater contexts, they highlight citizen science as a diverse practice that is open to many definitions and possible outcomes (Eitzel et al. 2017). The shared characteristics among these approaches is a desire to broaden conceptions about who can contribute to science, the power of participation in understanding waterway problems and the desire to transform relations between people,

place and science. In this thesis, I am interested in how and why involving members of the public in scientific inquiry creates productive, meaningful and lasting connections between the public and the sustainable management of water resources. In examining this issue, I take "relations" or the "spaces" in between people and phenomena as the starting point for empirical inquiry and focus these efforts in the context of waterway governance. This relational approach is central to this thesis and builds on several decades of sociological research that demonstrates why relationships matter, how they shape who we are and how we act in the world. Before expanding on these issues in the following chapter, the remainder of this introduction briefly maps the practice and potential of citizen science and identifies general challenges regarding its relationship with environmental governance. I then propose that a relational perspective is a promising approach not only to study these challenges, but also to reconceptualise citizen science practice.

1.1 The rise of citizen science

From the outset, it is important to note that citizen science is not new. Following the professionalisation of science in the early 20th century, members of the public without qualifications have engaged in scientific inquiry to study the natural world (Miller-Rushing et al. 2012, Vetter 2011). A commonly cited example is the National Audubon Society's annual Christmas Bird Count, which, since 1900, has involved the public in recording and submitting bird observations across the United States (Lebaron 2009). In freshwater contexts, more localised and community-driven water monitoring activities also have a long history, with the first surveys conducted by the Izaak Walton League of America in 1926 (Firehock and West 1995). Today, however, citizen science is far greater in scale, depth of engagement and accessibility than these projects of the past (Haklay 2015). Many factors are responsible for these developments, including rising public environmental concern, a realisation that volunteers can provide skills and knowledge of benefit in a decreasing funding environment and an increased availability of technology to support data collection and management.

Across the world, citizen science projects now number in the thousands and are practised in diverse ways (Eitzel et al. 2017): as a *capacity building* approach that empowers

communities to advocate for issues of local interest or concern (e.g. Jalbert et al. 2014); as *tool* to acquire data at large spatial and temporal scales to benefit research and government monitoring (e.g. Thornhill et al. 2019); and, as a *movement* to democratise scientific inquiry and place greater emphasis on the values, cultures, and knowledge of the public (e.g. Salmond et al. 2014). While these varied approaches have many different labels[1], "citizen science" is the increasingly accepted umbrella term. Citizen science is steadily becoming a more professional practice as evidenced by the establishment of organisations to support practitioners and researchers, such as the Citizen Science Association (CSA; founded in 2013) in the United States, the European Citizen Science Association (ECSA; founded in 2014), and the Australian Citizen Science Association (ACSA; founded in 2016). These organisations have been considered milestones in the professional development of the practice as they facilitate local and global collaborative efforts (Storksdieck et al. 2016).

Within the last decade, citizen science has gained increasing credibility and policy support within government agencies. In the United States, for instance, the Obama administration took a number of actions to increase the visibility of citizen science and encouraged its acceptance and use across various government departments, including through the *COMPETES Act* (2013) and the *American Innovation and Competitiveness Act* (2017). Additionally, the United States Environmental Protection Agency (USEPA) is actively supporting crowdsourcing and citizen science as a core tenet of environmental protection (USEPA 2016). In Europe, the European Commission has embedded citizen science within its research and innovation program *Horizon 2020* and other open data initiatives (Commission 2017). And, in Australia, the Office of the Chief Scientist released an Occasional Paper entitled *Building Australia Through Citizen Science* (2016), which aimed to highlight how citizen science is 'strengthening Australia's research capacity, solving real

[1] The issue of citizen science terminology has recently become a focal point in contemporary research (Eitzel et al. 2017, Auerbach et al. 2019, Heigl et al. 2019). Rather than engage in this debate, in this thesis I employ 'citizen science' as a catchall term to describe the many variants of public participation in scientific research or monitoring, such as civic science (Bäckstrand 2003), community science (Carr 2004), participatory monitoring (Villaseñor et al. 2016b), community based monitoring (Conrad and Hilchey 2011), crowdsourced data collection (Howe 2012) and public participation in scientific research (Shirk et al. 2012).

world problems and enhancing awareness of science' (Pecl et al. 2015). For advocates of citizen science, this institutional support is encouraging as it validates existing efforts and lays the foundation for the future development of the practice.

1.2 Citizen science and environmental governance

The relationship between citizen science and environmental governance took shape in the early 1990s. Around this time, international discourse on sustainable development, such as the 1992 Rio Declaration on Environment and Development and Agenda 21, instigated a transformation in government policy to include public participation as a central feature of environmental decision-making (Principle 10). Supporting participation in community-based research and monitoring was considered one way to raise awareness of environmental problems, improve stewardship behaviour and satisfy these emerging ideological commitments. During the past three decades, these programs have operated primarily as community engagement exercises and stimulus for local action. Within this context, science can be a powerful ally to communities because it provides a set of structured methods and tools for communities to build confidence in conservation action, inform advocacy and influence decision-making without diverging from epistemological conventions (Taylor and de Loë 2012). Encouraging the public to "adopt the language of science" is especially critical since many environmental problems are largely invisible and only revealed through science and technology (Beck 1992, Eden 1996).

In recent years, the potential for citizen science to enhance key environmental governance objectives has become a topic of serious consideration (Hyder et al. 2015, McGreavy et al. 2016, Newman et al. 2017, McKinley et al. 2017a, Hecker et al. 2018a). Of particular interest to researchers is the potential for citizen science data to inform policy and on-ground management actions. However, emerging research suggests that such contributions remain quite limited (Hecker et al. 2018a). The slow uptake of citizen science in environmental decision-making has been attributed, at least partly, to enduring hesitations by scientists and decision-makers to accept citizen science data as a credible, salient and legitimate source of environmental information (Kosmala et al. 2016). Outside of

the scientific dimensions of citizen science, the practice can produce a range of benefits in environmental governance, including improved stewardship, enabling opportunities for civic engagement, inclusion of local knowledge in decision-making, social and institutional learning and stronger societal connections (Bela et al. 2016, Storey et al. 2016, Danielsen et al. 2019, Jordan et al. 2019).

For researchers interested in the relationship between citizen science and policy, the complex reality and possible benefits of the practice means there are many points for conceptual and theoretical departure (Jordan et al. 2015). However, to date, researchers have tended towards a particularly narrow set of scientific, technical and programmatic explanations to understand and manage this relationship (Mahr et al. 2018). Although this literature has been enormously useful in advancing the field both theoretically and practically, a cohesive account of *how* individuals in citizen science programs interact with each other to promote productive engagement in different contexts is currently lacking (Pettibone et al. 2018). More far-reaching understandings and alternative conceptual foundations that capture the complexity and rapidly evolving nature of citizen science practice are needed. For this reason, this thesis adopts a relational research perspective, which views creation and realisation of citizen science as situated within a broader social context and shaped by the interplay between social *structure*, relational *meaning* and the enactment of *boundaries*.

1.3 Studying citizen science through a relational perspective

Citizen science is a 'profoundly social activity' (Irwin 2015 p. 2). The role and importance of social relationships is clearly evident across each phase of the research process and broader project development. In particular, a project's capacity to recruit and coordinate volunteers, collaborate with others, collect and share data and influence people in positions of power will depend on the nature and quality of these connections (Berkes 2004). Moreover, as actors enter into citizen science, they do so with different, and even conflicting, roles, values, motivations for involvement and capacities to exert influence (Vann-Sander et al. 2016). Ultimately, the capacity for citizen science to foster sustainable environmental governance

depends on how citizens, coordinators, scientists, decision-makers and other stakeholders convert its potential into practice. Thus, for the practice to succeed in promoting innovation in environmental governance, attention to the social aspects of citizen participation in science is an important research endeavour.

Studying citizen science through a relational perspective means overtly recognising that the practice is a product not only of its scientific practices, but also of its embeddedness in a broader social, political and institutional context (Jasanoff 2003, Chilvers and Kearnes 2020). The research perspective adopted in this thesis shifts attention to how social structure, including how actors navigate and place meaning on their own relationships, enable and constrain the processes and outcomes of citizen science (Bodin and Prell 2011). Furthermore, in relation to decision-making contexts, a relational perspective views the boundaries between research, policy and practice not as fixed and stable—as is often assumed to be the case (Wehrens 2014). Rather, empirically grounded insights from Science and Technology Studies (STS) reveal boundaries as socially constructed, which are defended, blurred and dismantled through a process known as "boundary work" (Gieryn 1983). In this view, boundaries are not just barriers to overcome, but also spaces for negotiation in which actors can meaningfully interact to co-create knowledge that is actionable in decision-making (Miller and Wyborn 2018, Mach et al. 2020).

For citizen science, a relational perspective is a promising approach to examine the complex, dynamic and interdependent nature of participatory knowledge practices (Fritz and Binder 2018), including how they might support more effective, equitable, responsive and robust environmental governance systems (Bennett and Satterfield 2018). More broadly, a relational perspective means overtly recognising 'research, politics, researchers, and publics are intertwined in a constant struggle of justifications, explanations, and decisions in an uncertain and complex world' (van Kerkhoff and Lebel 2006 p. 473). Such a perspective provides a pathway for rethinking citizen science as a core feature of the science-society-policy interface and not just an "add-on" to the margins (Irwin 2015).

1.4 Thesis aims and overview

This thesis seeks to understand how actors in citizen science work together to achieve collective aims in the context of sustainable waterway governance. As a starting point for empirical inquiry, an exploratory study reviews the extent, characteristics, influence and partnership structures of freshwater and estuarine citizen science programs in Australian natural resource management. The findings of this review provided the basis for selection of two (anonymised) case studies in Australia. The case studies were then examined through two relational concepts: (i) social network analysis and (ii) boundary work. These separate studies enabled the assessment of three relational dimensions: social *structure*, relational *meaning* and the enactment of *boundaries*. The application of this perspective, and its accompanying methodologies, provided a means to understand how the interplay between these dimensions enabled and constrained the capacity of citizen science to enhance waterway governance. The research findings led to an opportunity to reconceptualise citizen science practice as occupying a "hybrid space" between research, policy and practice. Overall, this thesis highlights the importance of building the necessary relationships and political support to promote the acceptance and uptake of citizen science in environmental governance, including the practices and strategies that make this possible.

1.5 Research questions and contributions

The overarching research question for this thesis is: *How does citizen science create productive, meaningful and lasting connections between science, society and policy for the sustainable management of water resources?* In order to answer this question, a series of sub-questions were developed and studied through four separate articles that are provided within this thesis (Table 1). Note that the second research sub-question is addressed in two articles providing a conceptual/methodological (**Article II**) and empirical perspective (**Article III**).

Table 1. Research sub-questions addressed in the four articles that contribute to this thesis

Article	Question
Article I	In what ways do freshwater citizen science projects in Australia contribute to the management of freshwater environments, and which factors enable or limit these contributions?
Article II & III	What role do social networks play in shaping citizen science practice and knowledge outcomes, and how can the conceptual and methodological tools of social network analysis be applied to advance this understanding?
Article IV	How do boundary work practices that create, maintain or break down boundaries between citizen science and expert communities shape the outcomes of citizen science knowledge and practice?

The main contribution in this thesis is demonstrating how 'relational thinking' serves to advance understanding on the social dimensions of citizen science and open up possibilities for practical social change within governance contexts. More specifically, this thesis makes the following contributions to theory and practice, by:

1. Documenting the impacts of freshwater citizen science on waterway decision-making, and the barriers to creating productive linkages between communities and governments;
2. Providing methodological guidance on the role of social networks in citizen science and describing how social structure influences program outcomes and collaborative potential;
3. Illuminating and describing various practices, strategies and tactics employed by actors participating in, or interacting with, citizen science programs to enable or limit collaboration between these actors and improve uptake of actionable knowledge;
4. Presenting a reconceptualisation of citizen science as occupying a "hybrid space" between science, society and policy, which enables a more productive, dynamic and relational view of citizen science knowledge and practice.

1.6 Structure of thesis

This doctoral thesis is written as a thesis by publication with four articles published, under review or written for submission to international peer-reviewed journals. After this introduction, *Chapter 2* traces the evolution of freshwater citizen science within the context of shifting water governance regimes, explores research trends and emerging challenges in citizen science, and seeks to develop a research framework to study the relational dimensions of citizen science. *Chapter 3* describes the multi-phase mixed methods research design and methodological approach for this thesis. *Chapter 4* summarises the aims, main findings and linkages between the four articles written as part of this thesis, before presenting the full articles in *Chapters 5-8*. *Chapter 9* is a discussion that brings together the insights gained in the four articles. Organised into three parts, this chapter reflects on historical developments and future trajectories of citizen science in Australian natural resource management. It then addresses the core promise made in this thesis that 'relational thinking' provides important insights to advance citizen science, both theoretically and practically. Finally, the discussion consolidates these conceptual and theoretical contributions to rethink citizen science programs as hybrid spaces. The final chapter, *Chapter 10*, concludes this thesis by summarising the theoretical and practical implications, reflects on limitations of research design and methodology, presents several opportunities for future research. The thesis ends with some final comments about future trajectories of freshwater citizen science, both globally and in Australia.

2 Citizen science for sustainable water futures: towards a relational framework

2.1 Introduction

The aim of this chapter is to (i) document the historical development of citizen science in freshwater environments; (ii) highlight emergent opportunities and challenges for enhancing waterway governance; and (iii) propose a novel conceptual perspective that extends citizen science inquiry through a relational perspective. The review begins with an overview of freshwater ecosystems and describes the evolution of approaches to water monitoring and knowledge production, before discussing citizen science as an increasingly active participatory knowledge practice. I then discuss the role of citizen science in enabling effective, equitable, responsive and robust waterway governance based on a framework developed by Bennett and Satterfield (2018). In presenting the opportunities and challenges associated with linking citizen science with waterway governance, I propose a novel analytical framework for studying citizen science. Specifically, I argue that a focus on three relational dimensions—*structure*, *meaning* and *boundaries*—can address important and under-researched dimensions of citizen science that affect its uptake, acceptance and outcomes. The chapter concludes with a synthesis of review findings and proposes three research questions that constitute the basis of this thesis.

2.2 Freshwater ecosystems: monitoring threats and managing change

Fresh water is perhaps the most essential natural resource, providing countless benefits to society and playing a crucial role in the maintenance of ecosystem services and biodiversity (Bhaduri et al. 2016). Yet, as human demand and mismanagement of freshwater resources increased throughout the 20th century (Gleick 2018), so too have threats to water security and freshwater biodiversity (Dudgeon et al. 2006, Vörösmarty et al. 2010, Hoekstra and Mekonnen 2012). Major threats include overexploitation, water pollution, flow regulation, habitat degradation and problems caused by exotic species (Reid et al. 2019). Additionally, anthropogenic climate change is exacerbating and complicating these multiple stressors such that freshwater environments are some of the most threatened ecosystems in the world.

Many emerging water quality problems are invisible and hard to detect (Damania et al. 2019). Understanding the nature and severity of freshwater problems thus requires the implementation of scientific monitoring programs to systematically measure and evaluate the status and trends in water resource condition. Scientific monitoring programs provide much of the information necessary to identify environmental problems, manage risks, assess conservation effectiveness, inform and evaluate policy, and meet legislative and statutory agreements (Sutherland et al. 2004). They also provide the public a way to understand the condition of local environments through information access, reporting and dissemination (Reed et al. 2006). Monitoring is thus an essential activity for sustaining social-ecological systems by improving knowledge of environmental change and assuring the sustainable development of water resources.

The capacity for monitoring programs to identify freshwater problems and inform subsequent management is impacted by several challenges. One longstanding issue relates to the quality of its design and overall effectiveness, especially with respect to its capacity to influence decision-making processes (Cullen 1990). Other challenges include high expense, discontinuity leading to gaps in datasets, technical and logistical issues, and the perceived irrelevance of monitoring to policymaker needs (Danielsen et al. 2005). Furthermore, Danielsen et al. (2005) argue that environmental monitoring has often neglected to take into consideration the needs and objectives of local communities. This is problematic because

local communities, particularly those in socially disadvantaged areas, are more likely to be affected by degraded environments (Frickel and Bess Vincent 2011). Considered together, these challenges can reduce the capacity of governments to track and forecast changes in waterway health, which ultimately hinders protection of freshwater resources and supporting community needs, values and concerns.

Addressing monitoring challenges, particularly in the face of growing human and financial resource constraints (Mackechnie et al. 2011), has led researchers and policymakers to seek alternatives to existing approaches. Advances in technology can overcome some of these constraints and have made monitoring more feasible and reliable (August 2015). These advancements include remote sensing (Sagarin and Pauchard 2010), molecular techniques for taxonomic identification (Carew et al. 2013) and continued developments in digital spatial technologies (Rodell et al. 2018). Furthermore, data are also becoming more accessible as governments adopt open data policies (Chun et al. 2010), which promote novel research opportunities and save time and financial resources (Hampton et al. 2013).

Still, managing the growing water crisis requires more than just the implementation of government monitoring programs and the adoption of new technologies. It also requires strategies and practices which support "good governance" (Lockwood et al. 2010, Pahl-Wostl et al. 2013). In this thesis, the term governance used in reference to natural resource management relates to social and institutional structures and the processes that influence that management (Bodin and Crona 2009). In recent decades, environmental governance researchers sought to examine the possibilities of participatory knowledge production as a way to build both more efficient and more legitimate governance systems (Kirchhoff et al. 2013, Turnhout et al. 2020). Participatory knowledge production is a process that aims to integrate different ways of knowing by bringing different groups of people together who jointly develop knowledge to enable effective and legitimate solutions to environmental problems (Turnhout et al. 2020). Such approaches include boundary organisations, participatory technology assessment, civic ecology, science-policy dialogues, and citizen science, among others. These new models of knowledge production are expected to result in

inclusive and non-hierarchical science-policy processes, increases in decision-making legitimacy and quality, and a balancing of power relations.

2.3 The (re)emergence of freshwater citizen science

As a participatory knowledge practice, citizen science has recently attracted broad government support and a parallel rise in academic research attention. Despite this recent interest, citizen science has a long history (Vetter 2011), particularly in freshwater environments. For example, Hopkins and Freckleton (2002) detail the prominent role of amateur naturalists in taxonomic research of aquatic insects and other fauna over the past century. Njue et al. (2019) describe an early citizen science project in hydrology involving the use of "drift bottles" in the 1960s and 1970s to study the patterns of water currents in the Caribbean Sea. Firehock and West (1995) document a history of community-based water monitoring in the United States, with waterway monitoring conducted in 1926 by the Izaak Walton League of America (IWLA). In 1969, the IWLA launched Save Our Streams (SOS), an influential program, which still operates to this day, and that trains volunteers to monitor environmental conditions in their local waterways (IWLA 2020).

Perhaps the most significant development in the history of freshwater citizen science was the sharp rise in similar community-based water monitoring programs in the early 1990s. Data from the United States indicate that, by 1992, 32 states had community-based water quality monitoring projects, rising from 14 in 1988 (Pfeffer and Wagenet 2007). Around the same time, similar efforts were launched in other parts of the developed world, including Australia and Canada (Kingham 2002, Conrad 2007). These developments were, in part, spurred on by international discourse about policy on sustainable development and the importance of participatory environmental governance, particularly following the publication of the Brundtland Report *Our Common Future* (Michelsen et al. 2016). During the same period, community-based water monitoring programs caught the interest of government agencies in the United States, whose own water monitoring programs were being challenged due to ineffective monitoring strategies and little substantive return on investments (Ward 1996). From a practical standpoint, supporting volunteer efforts through

collaborative monitoring was viewed as a possible strategy to improve water quality management while upholding emerging ideological commitments to collaborate with the public as active agents in decision-making. From a theoretical perspective, the emergence of community science and monitoring was considered a critical mechanism to improve on the 'deficit-based model' of public understanding of science (Irwin 1995), since it offered the public deeper and more nuanced engagement with science and the natural world (Carr 2004).

In the last decade, citizen science has grown rapidly and is a more mature, accessible and diverse practice (Silvertown 2009). Researchers, policymakers and practitioners increasingly employ the term 'citizen science' to capture the many variants of public participation in scientific research and monitoring, such as such as civic science (Bäckstrand 2003), community science (Carr 2004), participatory monitoring (Villaseñor et al. 2016b), community based monitoring (Conrad and Hilchey 2011), crowdsourced data collection (Howe 2012) and public participation in scientific research (Shirk et al. 2012). The many variants of citizen science have recently become a focal point in contemporary research (Eitzel et al. 2017, Auerbach et al. 2019, Heigl et al. 2019). However, it is outside the scope of this thesis to engage in this debate and, instead, I use 'citizen science' as a catchall term to describe the processes and outcomes of public participation in scientific research or monitoring.

Several commentators have suggested a number of changes in society that are responsible for what has been described as the 're-emergence' or 'new dawn' of citizen science (Silvertown 2009, Haklay 2015). Researchers have noted an upsurge of public interest in the protection of valued natural areas, including perceptions that governments were inadequately monitoring water environments to address local information needs (Conrad and Hilchey 2011). Silvertown (2009) highlighted the critical role of new technologies, which have greatly increased the capacity and motivation of the public to contribute environmental information. Silvertown (2009) further suggested that rising support for citizen science is driven by a need for institutions to encourage public engagement as a necessary condition for securing research funding. STS scholars take a

more political and economic perspective and have suggested citizen science projects advocating individual responsibility and localised problem solving are growing due to the processes of neoliberalisation of environmental governance (Kinchy 2016). In this view, governments utilise a network of volunteers to monitor environments, which mitigates against declines in their own programs and funding constraints (Lave 2012). While legitimate concerns have been be raised about the relationship between citizen science and neoliberalism, some scholars have suggested that these tendencies may be "generative." That is, they may give rise to new research areas, collaborative potential and opportunities for the public to have a "seat at the table" (Ottinger 2017, Vohland et al. 2019).

2.3.1 Characterising contemporary practice

Over the course of its development, citizen science researchers have sought to identify major types of activity and develop useful frameworks for advancing the field, both theoretically and practically. Citizen science projects have been categorised based on levels of participant engagement (Wilderman 2007, Bonney et al. 2009, Shirk et al. 2012, Haklay 2013), governance structures (Lawrence 2006, Conrad and Hilchey 2011), unique resource characteristics (Chase and Levin 2016), program goals and degrees of virtuality (Wiggins and Crowston 2011) and, more recently, differences in epistemic practices (Strasser et al. 2018). The most influential and widely applied framework was developed by Bonney et al. (2009), dividing citizen science projects into three categories (contributory, collaborative and co-created) based on the level of volunteer involvement in the research process. In the contributory model, scientific data is collected by volunteers with project design, analysis and interpretation conducted by professional scientists. The collaborative model involves deeper levels of engagement, with projects designed by scientists and the public contributing data as well as refining project design, analysing data and disseminating findings. Co-created projects are jointly developed by scientists and members of the public to address a specific issue usually of local community concern, with a commitment to promote high levels community control in the research process. Most citizen science projects today tend to fall into the contributory model (Pocock et al. 2017), but many freshwater

citizen science projects are collaborative in nature as they often involve volunteers in data collection as well as analysis and dissemination of findings (Roy et al. 2012).

Although characterising citizen science by "degrees of participation" has been useful in describing and comparing different approaches, there are some emerging criticisms. In particular, some researchers argue these typologies miss key dimensions of participation, such as the agency of actors involved in citizen science, the fluid and evolving nature of relationships that shape and define projects and why similar projects might succeed in one context but fail in another (Kimura and Kinchy 2019, Phillips et al. 2019). In short, commonly used typologies might oversimplify citizen science. For example, Lawrence (2006) found that not only was it difficult to clearly define which type of citizen science a program fell within, but also that empirical insights on the benefits of a particular type of citizen science did not align with its expected outcomes. Lawrence (2006 p. 293) suggested that this issue presented a critical need to reconsider citizen science 'in a more dynamic way, showing how people, environmental values, data and governance are woven together.' In response to these issues, I avoid problems associated with *a priori* characterisations of citizen science to instead acknowledge the "messiness" and diversity of citizen science practice (Kimura and Kinchy 2019 p. 10).

2.3.2 Research trends

The combination of scientific discovery, public engagement and education makes citizen science a unique interdisciplinary endeavour (Jordan et al. 2015). Yet, citizen science research has mainly been advanced by scientists or researchers embedded in a positivist tradition (Mahr et al. 2018). As a result, a predominant focus in literature is on the benefits of citizen science for scientific research and monitoring and associated scientific and technical issues. Tracing this strand of research shows a growing number of studies that use citizen science data in their analyses (Follett and Strezov 2015, Theobald et al. 2015, Burgess et al. 2016). In freshwater contexts there is not yet a dedicated review of scientific advances. However, a special issue in the journal Freshwater Science included several studies that used citizen science data to understand a range of freshwater issues (Thornhill et al. 2019)

Other major research foci include aspects of volunteer participation, such as participant motivations and learning opportunities, and recommendations for best practice. An increasing body of literature is concerned with participant motivations, converging to agree on the importance of integrating this knowledge about participants into the planning and implementation of citizen science projects (Rotman et al. 2012, Alender 2016, Geoghegan et al. 2016, West and Pateman 2016, Larson et al. 2020). A brief summary of this research shows volunteers are recognised to hold multiple motivations at once and that these can change over time. Research also shows that, in citizen science, such motivations consistently stem from strong environmental values, a general enjoyment of nature or concern about the environment, a desire to contribute scientific knowledge and social reasons. Other citizen science research is focused on the individual benefits acquired through participation, such as content knowledge gain, scientific literacy, and changes in environmental attitudes, behaviours and nature connections (Jordan et al. 2011, Bonney et al. 2016, Haywood et al. 2016, Chase and Levine 2018). Practitioners and scholars have also written extensively about various practical issues and best practice recommendations (Hecker et al. 2018b, Robinson et al. 2019), including overcoming challenges of volunteer management, acquiring resources and funding, project design and data quality assurance strategies.

A less explored, but increasingly emphasised, strand of citizen science research is its wider-societal outcomes (Shirk et al. 2012), which include opportunities for improving waterway governance. Shirk et al. (2012) suggested such impacts relate to the access and use of citizen science knowledge in conservation decision-making, improved relationships between communities and government agencies and increases in the likelihood of public engagement and advocacy in environmental matters. To date, this research is less explored than other research foci, but is a critical priority as citizen science becomes increasingly embedded in government strategies and policies.

2.4 How can citizen science benefit waterway governance?

To understand how citizen science can benefit waterway governance, I draw on Bennett and Satterfield's (2018) practical framework for the design, evaluation and analysis of

environmental governance, which the authors developed through a comprehensive review of academic literature. The framework comprises four generalisable yet distinct environmental governance objectives: (1) to be *effective*, (2) to be *equitable*, (3) to be *responsive*, and (4) to be *robust*. The aim of this section is not to provide a detailed review of these environmental governance objectives. Rather, the framework is employed as a heuristic device to describe the opportunities and challenges of citizen science for achieving these key objectives in the context of waterway governance (Table 2).

Table 2. Opportunities and challenges of citizen science for enhanced waterway governance

Governance objective	Opportunities	Challenges
Effective	• Improved waterway condition • Impacts on policy and management decisions • Public conservation actions	• Developing a clear vision and appropriate dividing tasks, roles and responsibilities • Skill development, capacity-building • Effective feedback and accountability mechanisms
Equitable	• Increased civic engagement • Inclusion of local and cultural knowledge in policymaking • Representation of marginalised communities	• Balancing different values, cultures, knowledges and needs • Improving public access and representativeness in decision-making and agenda setting • Acceptance of local and cultural knowledge in decision-making
Responsive	• Social and institutional learning • Experimentation and new ways of working • Triggering management actions	• Creating productive spaces for dialogue and learning • Developing flexibility and capacities for innovation
Robust	• Stronger or new forms of horizontal and vertical connections e.g. trust and social capital • Spatial and temporal augmentation of water monitoring networks • Information diffusion through wider community	• Understanding connectivity between actors and network functioning • Capacity of programs to embed and sustain citizen science in governance systems • Promoting favourable institutional conditions and cultures

2.4.1 Citizen science for 'effective' waterway governance

Effective waterway governance refers to the ability of governance systems to maintain the function and integrity of social and environmental systems (Bennett and Satterfield 2018). Citizen science supports this objective by increasing the knowledge base available to inform management and policy decisions (Laird et al. 2012, Huddart et al. 2016, McKinley et al. 2017a, Carlson and Cohen 2018), building community capacity for local conservation actions (Storey et al. 2016), and, ultimately, improving waterway condition (Conrad and Hilchey 2011). However, studies showing citizen science projects making direct links to improvements to environmental quality are rare and considered difficult to measure given the long timescales required for environmental improvement (Floress et al. 2011). Instead, researchers have sought to examine "intermediary outcomes" (Carr et al. 2012), such as impacts on policy and management actions, which are considered as a precursor to environmental improvement. Only a handful of examples describe instances where volunteer data has informed decision-making such as through policy change (Laird et al. 2012), evaluating stream restoration activities (Huddart et al. 2016), detecting pollution impacts and failures to comply with water quality standards (McKinley et al. 2017a). Even less research has examined how citizen science enables communities to leverage their own data for advocacy and community action. Examples of community-directed data use, while limited, highlight the important role of science in bolstering and justifying public environmental concerns.

In recognising that uptake of citizen science in decision-making has been slow, researchers have turned to examining the various barriers that hinder successful linkages. Research has mostly focused attention on the associated scientific, technical or programmatic challenges. For example, Chapman and Hodges (Chapman and Hodges 2016 p. 257) contend that the contribution of citizen science to decision-making depends on projects being 'well conceived, designed and implemented' and producing data of 'suitable quality and quantity.' Similarly, Hyder et al. (2015 p. 115) place emphasis on data quality challenges in policy-relevant marine citizen science, particularly as it relates to the 'accuracy and precision, spatial and temporal resolution, robustness, documentation, and access' of

citizen science data. While this literature is useful, since it highlights the importance of accurate data and appropriate project design, framing the barriers to knowledge outcomes in this way has been criticised for neglecting the broader social and political context known to shape knowledge production and use (Kimura and Kinchy 2019). Furthermore, environmental governance literature suggests that linking knowledge with action is dependent on developing a clear vision, supportive institutional cultures, social and technical skill development and effective feedback and accountability mechanisms.

2.4.2 Citizen science for 'equitable' waterway governance

Equitable waterway governance means that decision-making processes are fair, inclusive, transparent and representative (Bennett and Satterfield 2018). Citizen science is often lauded for its inclusiveness since it enables citizens' voices, values and knowledge to be integrated into management and policy decisions (Kythreotis et al. 2019). An emerging topic of research interest is the extent to which projects foster improved civic engagement of participants. This includes the ability of volunteers and local community groups to be active producers of knowledge and drivers of change beyond their role as data collectors. However, uneven power relations and top-down framing of citizen science projects can prescribe the scope of participation, thereby constraining this potential (Turnhout et al. 2010, 2020). For example, Ellis and Waterton's (2004) study on volunteer naturalists in the United Kingdom found project organisers and collaborators established relationships with volunteers that limited their interactions to knowledge exchange, which ultimately framed-out these volunteers from decision-making processes.

To further enable equitable environmental governance, citizen science provides a mechanism for local and cultural knowledge to be embedded in the processes of decision-making, which is an important principle of sustainable environmental development (Murdoch and Clark 1994). This knowledge may be relatively simple, such as choosing scientifically relevant and safe sites for water monitoring, or more complex, such as indigenous knowledge that complements or even challenges western systems of knowledge production (Wynne 1991, Danielsen et al. 2019). Recent evidence suggests governments are

attempting to better integrate traditional and local knowledge into their governance systems (Leonard et al. 2013). However, more work is needed to highlight how citizen science programs facilitate this process, including creating opportunities for greater representation and participation of marginalised communities (Danielsen et al. 2019).

2.4.3 Citizen science for 'responsive' waterway governance

Responsive waterway governance refers to being adaptable to changing environmental and social conditions and to different contexts (Bennett and Satterfield 2018). Citizen science can strengthen this objective by triggering actions on local environmental issues (McKinley et al. 2017a) and promoting social learning. In particular, social learning refers to learning that occurs through social influence and connections with others, that is, through observation, imitation and dialogue (Schusler et al. 2003). This type of learning contrasts with individual (or factual learning) and relates to groups reflecting and acting on the assumptions that underlie their actions. This process may lead to changes in attitudes, beliefs and social norms, which promote new ways of working and adaptive waterway governance (Pahl-Wostl et al. 2007, Reed et al. 2010). Bela et al. (2016) revealed that studies on learning have mostly focused on factual learning among volunteers, which neglects the processes of learning that can happen between volunteers, scientists and institutions. To enable social learning processes, the development of productive spaces for dialogue, experimentation, flexibility and innovation has been highlighted as an important strategy (Toomey 2017).

2.4.4 Citizen science for 'robust' waterway governance

Finally, *robust* waterway governance refers to the overall functioning of institutions, and their capacity to maintain their performance over time in spite of external disturbances (Bennett and Satterfield 2018). Citizen science can improve the robustness of governance systems by augmenting government research and monitoring networks (Hadj-Hammou et al. 2017) and by strengthening societal relationships. In relation to this second point, citizen science has, so far, been successful in generating platforms for social interaction among

diverse actors (Göbel et al. 2016, Tiago 2017, Skarlatidou et al. 2019). For example, Göbel et al. (2016) conducted a qualitative stakeholder analysis of 16 citizen science projects and identified six stakeholder groups who regularly engage in project development and knowledge generation: (1) Civil society organisations, informal groups and community members; (2) Academic and research organisations; (3) Government agencies and departments; (4) Participants, i.e. citizen scientists; (5) Formal learning institutions such as schools; and, (6) Businesses or industry. While this research provides a useful starting point to understand the different roles, motivations and influence of actors within and outside the citizen science community, the ways in which these actors are connected in networks and sets of relationships is largely unknown.

The ability of citizen science to contribute to enhancing the robustness of waterway governance will depend on the ability of programs to embed and maintain its processes within an organisation or governance system. This could be achieved through formal policy mechanisms, or through perceptions of program legitimacy by stakeholders (Lockwood et al. 2010). Irwin (2015) suggested that without favourable institutional conditions it will be difficult for citizen science to be a central feature of environmental and science-based decision-making. In this respect, the responsibility for reassessing and restructuring relations through citizen science lies as much with institutions as it does with individual projects.

2.4.5 The role of social science

For citizen science to enable more effective, equitable, responsive and robust waterway governance, research must grapple with both the social complexity of environmental decision-making, as well as the dynamic and relational nature of citizen science practice. Previous research has often favoured scientific-technical explanations on these issues, which neglects the broader social, political and institutional factors that shape the creation and realisation of citizen science knowledge. A critical step forward relates to the application of social science research to bring to light this complexity. As Mahr et al. (2018 p. 103) suggested, the social sciences and humanities 'would benefit the citizen science community,

for example, by bringing more knowledge about the sociology of citizen involvement or addressing some of the tensions and dilemmas involved in citizen science work.'

Indeed, it is now commonplace to assert that environmental governance and conservation needs social science (Bennett et al. 2016). However, researchers have also noted several issues that constrain efforts to integrate human *and* biophysical explanations in natural resource management, including a dogmatic preference by decision-makers for positivist, quantitative data; a lack of understanding of social science epistemology and methods; a consistent lack of embeddedness of social research methods in program design; implementation and reporting; and a general ambivalence towards the discipline of social science (Roughley and Salt 2005, Gill 2006, Bennett et al. 2016). These challenges are further complicated by the potential for social science to highlight issues that environmental agencies may find uncomfortable, or even disrupting (Roughley and Salt 2005, Gill 2006).

The social sciences have many benefits for understanding contemporary natural resource management issues. Box 1 list ten such benefits based on a comprehensive review by Bennett et al. (2016 p. 93). It is possible to extend Bennett's argument to suggest that the contemporary challenges of citizen science will benefit from greater attention to its human and social dimensions to progress the field both theoretically and practically. This includes attention to agenda setting, the subjective experiences of volunteers, coordinators and decision-makers, and, importantly, how these actors are connected to each other and the decision-making process (Toogood 2013). I consider a relational perspective to capture these critical yet complex social issues for advancing citizen science theory and practice. Box 1 list ten such benefits based on a comprehensive review by Bennett et al. (2016 p. 93).

Box 1. The value and contributions of the conservation social sciences. (From Bennett et al. 2016)
1. Documenting and increasing understanding of the diversity of ways in which conservation occurs in different contexts (descriptive value) 2. Facilitating learning about and knowledge of conservation challenges, practices and processes as well as successes or failures (descriptive or diagnostic value) 3. Aiding in proactive consideration of and reactive rethinking about why and how conservation does or should occur (diagnostic, disruptive or reflexive value) 4. Interrogating the underlying assumptions, concepts and models of conservation (disruptive or reflexive value) 5. Allowing for imagination, innovation and creation of novel or desirable concepts, practices or models for conservation (generative or innovative value) 6. Improving conservation management practices and governance processes, including understanding how to better engage different stakeholders (instrumental value: to better processes) 7. Enabling planning and design of conservation initiatives that match different social, economic, cultural and governance contexts and that are socially acceptable (generative, innovative or instrumental value: to better conservation design and models) 8. Helping to justify and normalize conservation actions (instrumental value: to conservation action) 9. Increasing the likelihood of more ecologically effective conservation planning and management in different social, economic and political contexts (instrumental value: to ecological outcomes) 10. Facilitating more socially equitable and just conservation processes and outcomes (instrumental value: to social outcomes)

2.5 A relational perspective for citizen science research and practice

Broadly speaking, a relational perspective is concerned with examining the "spaces in between" people and phenomena of interest (Emirbayer 1997), rather than these entities in isolation. As such, it differs in fundamental ways to conventional (functionalist and rationalist) social science studies (Wasserman and Faust 1994). The latter typically employ an attribute-based approach which groups actors based on a set of common characteristics to understand which attributes disproportionately determine particular outcomes. However, this approach tends to neglect the broader sets of relationships in which such individuals are embedded and how these relations produce emergent and often unexpected outcomes.

In recent years, relational theories, concepts and methodologies have been applied to contemporary environmental challenges, including public participation (Chilvers and Kearnes 2015, Fritz and Binder 2018), environmental governance (Bodin and Prell 2011),

social movements (Diani and McAdam 2003), human-nature relations (Lejano 2019) and public policy (Lejano 2020). Since citizen science shapes, and is shaped by, these diverse research areas, a relational perspective to citizen science practice provides a realistic and productive avenue of research.

I use a relational perspective to consider how citizen science outcomes emerge from the working and reworking of relationships between actors participating in or interacting with citizen science programs. Specifically, I consider:

i. citizen science to be embedded in a wider social context, including the perspectives of actors participating in *and* interacting with citizen science programs;

ii. social networks that underpin citizen science are created by different patterns of relations, having important consequences; and,

iii. the boundaries between research, policy and practice, are not static and separate but fluid and evolving through social practice.

I argue that such a perspective is a promising approach to advance understanding of key citizen science issues by capturing the increasingly complex nature of citizen science practice. The view does not replace, but rather supplements existing analyses.

A relational perspective is a conceptual framework that combines various relational theories and accompanying methodologies. As such, there is not a unified theoretical framework, but rather the joining of perspectives and concepts from different research fields to form an interdisciplinary 'patchwork of knowledge about social relations' (Eacott 2018 p. 32). In this thesis, a relational perspective is informed by (1) relational sociology (Emirbayer and Goodwin 1994, Emirbayer 1997, Mische 2011), (2) social network theory and analysis (Wellman 1988, Wasserman and Faust 1994), and (3) boundary work (Gieryn 1983, Star and Griesemer 1989, Lamont and Molnár 2002).

Relational sociology is a growing school of thought that investigates social phenomena by studying social relations (Powell and Dépelteau 2013). Various versions of relational sociology have been proposed (Emirbayer 1997, Donati 2010, Crossley 2011, Mische 2011),

but all relational theorists converge to reject the idea that social facts can be understood without reference to social connections. For example, Emirbayer (1997 p. 287) argues that the ultimate starting point in sociological analysis should be on social relations and not on the 'discrete, pre-given units such as the individual or society.' A key concept in relational sociology is that actors (individuals, organisations or other social actors) are formed through their relationships with others, and it is only in the context of those relations that they achieve notions of independence, autonomy and individuality.

While relational sociology is a theoretically grounded view of social life, social network analysis provides a methodological approach to systematically explore relational ties. In this way, social networks—defined as structures of relationships linking social actors—are both measurement constructs as well as social reality (White 2008). Social networks shape the lives of individuals, from their attitudes and behaviour, to their access to resources and information (Pescosolido 2006). As such, a focus on social networks allows researchers to ask questions about the connectivity between actors in a particular network (e.g. between volunteers, scientists, decision-makers), and how these connections influence actors and their actions (Bodin et al. 2011). As social network analysis is a complex topic, Chapter 6 in this thesis provides a detailed study of the core principles and potential benefits of this approach for citizen science research.

In research on the sociology of science, boundary work focuses on the objects, organisations and practices that shape the boundaries between science, policy and practice. The concept was originally conceived to understand the demarcation of "science" from "non-science", whereby scientists defend their territory and use their individual and discipline power to exclude those assessed as not being part of their privileged space (Gieryn 1983). More recently, an instrumental view of boundary work has sought to understand how boundaries can be aligned and intentionally coordinated to improve the uptake of scientific knowledge (Clark et al. 2011)

This strand of research has examined how differing perspectives, knowledge brokers, boundary organisations and boundary objects influence the flow and understanding of knowledge across science, policy and practice. While both the normative and instrumental

views of boundary work have been developed in relative isolation from relational sociology and social network analysis, the concept serves to reinforce important insights on relational processes between science, policy and practice (Wyborn 2015). In particular, boundary work provides a perspective on boundaries not as rigid and stable, but "made real" through dynamic social processes and interactions (Tuinstra et al. 2006).

2.5.1 Implications for citizen science practice

Taking a relational perspective has at least three implications for the improving the capacity of citizen science to create positive relationships within waterway governance. First, as the approach situates citizen science within a broader social context, it focuses attention on the importance of balancing various scientific, institutional, local and practical considerations (van Kerkhoff and Lebel 2006). Second, as it illuminates that not all citizen science networks are created equal, a relational perspective highlights that different network characteristics and patterns of relations enable *and* constrain the creation and realisation of knowledge (Bodin et al. 2011). Third, since a relational perspective emphasises the "gaps" between research, policy and practice as being co-constructed through social and political processes—or boundary work—it reveals important insights into the processes of inclusion and exclusion of citizen-based knowledge (Epstein 1995, Ottinger 2010, Kimura 2019). Boundary work has additional benefits in enabling the management of different interests, values and forms of knowledge between actors so that they are balanced in a mutually satisfying way (Clark et al. 2011). Overall, understanding how the social aspects of citizen science create productive connections between citizen science and governance opens up opportunities for reconfiguring relationships or bringing them into new alignments to encouraging more productive interaction, exchange of knowledge and trust (Lejano 2020).

2.5.2 A framework for relational analysis

Having described theory and concepts of a relational perspective and its implications for citizen science research and practice, I now propose a framework for relational analysis. This

framework has three elements: (1) the *structure* of relations between actors and their connections within a larger social network; (2) the *meaning* of relationships, including how actors navigate and experience relationships with others in a broader social context; and, (3) the *boundaries* between citizen science and waterway governance, which are enacted through boundary work. I now describe these elements in turn, with particular emphasis on suitable methodological pathways.

Structure refers to the patterns of relations and network characteristics of a citizen science social network. A social network perspective offers researchers an alternative lens through which to study citizen science – one that centres investigations on the structure, meaning and consequences of social relationships. In particular, its application provides a way to: (i) understand the degree of connectivity between actors in citizen science programs; (ii) identify relevant stakeholders; and (iii) understand the implications of different network patterns and characteristics, such as network density and network centralisation (Prell et al. 2009). In recent years, the conceptual and methodological tools of social network analysis have greatly improved understanding on key issues in environmental governance, such as how collaboration unfolds and how information is shared and applied (Groce et al. 2019). Thus, the social network perspective seems to be a useful framework to apply to the study of the social side of citizen science as well. This argument is further strengthened by the numerous studies that have shown that the existence of informal social networks among and between various stakeholders and groups is critical in successful cases of bottom-up community-based natural resource management (Folke 2003, Lauber et al. 2008, Wossen et al. 2013). However, a purely structural focus has been criticised for missing other important features of social networks, such as the content, quality and meaning of relationships (Hollstein 2010).

Meaning refers to how actors navigate and experience relationships with others within a particular context. The concept can be theorised at the subjective level to explain individual motivations when they seek particular relationships and abandoning others,

thereby actively creating their social network, or at the intersubjective level, which highlights how meaning is established and negotiated through the processes of communication (Fuhse and Mützel 2011). Citizen science is increasingly characterised by a diversity of actors who interact in broad social networks. These actors hold different roles, motivations for involvement and capacities to exert influence. With respect to network research, qualitative methods are most appropriate to characterise actor subjectivities and network perceptions. Fuhse and Mützel (2011) argue that through qualitative research both subjective and intersubjective dimensions of meaning add important additional insights neglected in purely quantitative network approaches. Moreover, qualitative methods, such as in-depth interviews and participant observation, can be combined with quantitative techniques to enable a holistic understanding of social networks (Hollstein 2014). In such cases, quantitative methods allow descriptions of the structural characteristics from an 'outsider' perspective, qualitative methods, such as in-depth interviews and participant observation, enable greater understanding of the meanings and outcomes of these relationships from an 'insider' perspective (Bolíbar 2016, Yousefi Nooraie et al. 2018). Additionally, triangulating quantitative and qualitative methods in data collection and analysis improves the validity of the structural analysis and their explanatory power.

Boundaries refer to physical, social and conceptual distinctions that limit the inclusions and exclusion of citizen science knowledge and practice. These boundaries shift and move through the dynamic social processes known as boundary work, which influence, and be influenced by, the structure of social relations (Lamont and Molnar 2002, Pachucki et al. 2007). In highlighting the socially constructed nature of boundaries, Wehrens (2014 p. 547) argues that research on knowledge-action relationships should focus 'not only how the boundaries can be bridged, but how – and at what moments – these boundaries are maintained, redrawn or re-established – and for what purposes.' This points to a need for analytical perspectives that draw out different forms of boundary work, such as how boundaries are constructed, defended, aligned and blurred (Langley et al. 2019).

Appropriate methods are those that capture the practices and subjectivities of different actors across the social worlds of science, policy and practice. In addition, researchers have developed the concept of boundary objects and boundary spanners to describe the artefacts, such as maps, databases, modelling and reports, and the individuals that enhance the capacity to span boundaries and shape an understanding of mutually recognised problems (Star and Griesemer 1989). A focus on these related boundary concepts serves to generate additional insights into how citizen science knowledge and practice is embedded in the processes of waterway decision-making.

Structure, meaning and boundaries can be viewed as having a common foundation in relational thinking. The concepts thus orient the current thesis and are considered to have substantial analytical power and potential for theoretical development in understanding the creation and realisation of citizen science. To summarise, this framework can be applied to better understand how citizen science serves an intermediary role between community and the management of water resources by: (i) systematically examining the structure of relationships within and outside citizen science projects (ii) studying the subjectivities of actors, including their perspectives on possible factors (i.e. social, political, institutional) that enable or limit their capacity to develop new, or strengthen existing connections; (iii) examining how boundaries are constructed and/or coordinated by actors through the practices, processes and objects of boundary work (Figure 1).

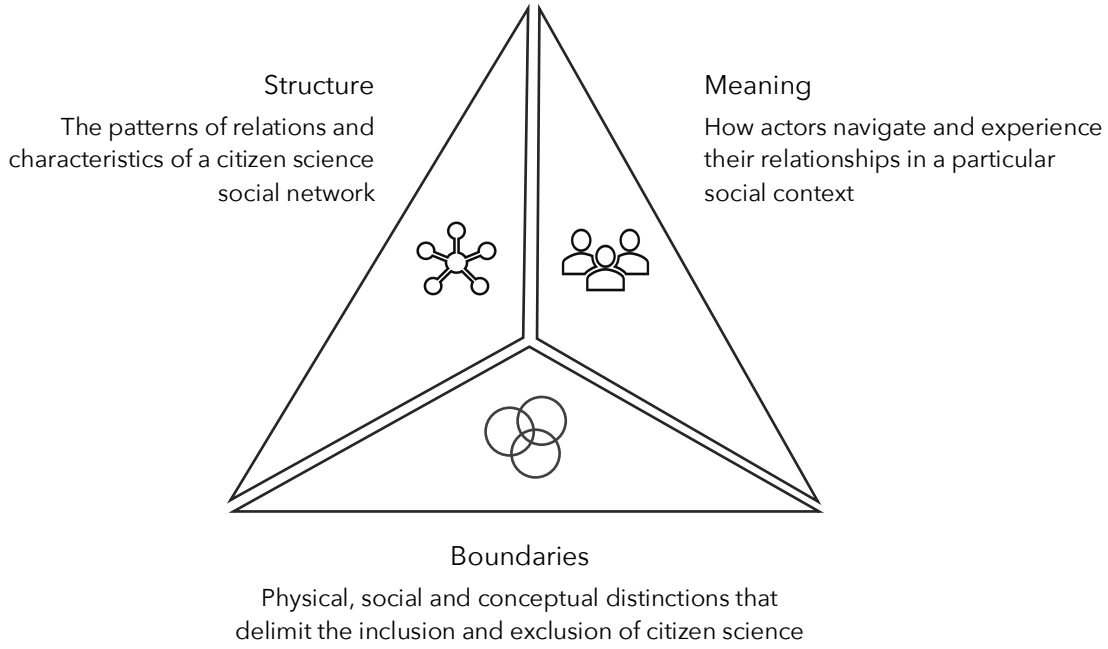

Figure 1. Structure, meaning and boundaries as key dimensions orienting the relational approach in this thesis

Before addressing the specific methodological approach taken in this thesis, the following section synthesises the findings of this review and proposes three research questions.

2.6 Synthesis and future directions

The water-related challenges facing humanity are complex and urgent. Although citizen science is not a panacea, many programs exhibit the fundamental characteristics that, if fostered, have the potential to enable the required transformations towards sustainable waterway governance. In realising this potential, this review of freshwater citizen science research points to the following insights and areas for future research.

First, citizen science offers both government agencies and communities a structured and broadly accepted method to monitor and manage waterway problems. For government agencies, investing in citizen science programs provides a way to overcome limitations in their own monitoring programs by filling knowledge gaps and speeding up the detection of

environmental change by having "many eyes on the ground." For communities, citizen science can be a powerful ally to justify their environmental concerns and disseminate water condition information throughout the rest of the community. However, the ways in which citizen science data informs water resource decision-making, or are applied by community members themselves, are poorly understood. Thus, there is a need to examine this important outcome of citizen science programs including attending to what factors constrain effective "action." In doing so, studies will benefit from conducting research across multiple cases rather than single programs to assess both positive and negative (or null) outcomes (Stepenuck and Green 2015). The following research question serves to examine these issues:

> **Research question 1:** In what ways do freshwater citizen science projects in Australia contribute to the management of freshwater environments, and which factors enable or limit these contributions?

Second, citizen science is often positioned as an effective means to renew and strengthen the relationship between science and society and has, so far, been largely successful in creating new platforms for interaction among diverse people and organisations. To gain further insight into the nature of these new connections, systematic explorations into how these relationships influence projects and the challenges associated with building effective partnerships between citizens, research and policymaking is an important but underexplored research area. Moreover, methodological guidance is lacking. Adoption of this research approach builds on a growing body of environmental governance research, which takes a social network perspective and 'structurally-explicit' approach to examining key governance issues through social network analysis. The following research question is posed:

> **Research question 2:** What role do social networks play in shaping citizen science practice and knowledge outcomes, and how can the conceptual and methodological tools of social network analysis be applied to advance this understanding?

Finally, previous research has viewed the contributions of citizen science across the boundaries of science, society and policy to be a function of a program's characteristics,

design features or levels of volunteer participation. However, this research tends to conceive these social worlds as static categories, whose boundaries are crossed as internal processes are improved or different outcomes are achieved. An alternative perspective from STS scholarship considers boundaries as dynamic and evolving through social practice, thereby shaping social relations. In recent years, researchers have adopted boundary concepts to demonstrate how boundaries can be practically aligned and coordinated through boundary work. For citizen science, the concept of boundary work is useful since it emphasises social and contextual factors affecting the processes of knowledge inclusion and exclusion. It can also lead to the development of strategies employed by citizen science programs to coordinate activities across the boundaries of science, society and policy, including the different contexts in which these strategies are most effective. The following research question approaches these issues:

> **Research question 3:** How do boundary work practices that create, maintain or break down boundaries between citizen science and expert communities shape the outcomes of citizen science knowledge and practice?

2.7 Conclusion

Freshwater citizen science has a long history but has entered a new era as interest and support for the practice reaches unprecedented levels. Current projects operate in diverse social and environmental contexts and advance multiple objectives to serve community and institutional needs, interests and concerns. This review highlighted that citizen science is well-placed to make significant contributions to the management of freshwater environments by creating new opportunities to inform policy decisions and advocacy; by creating fair and equitable decision-making processes; by promoting adaptable governance systems that promote learning and experimentation; and, by fostering new societal connections between diverse people and organisations. In this review, I have argued that the application of a relational perspective to address these issues is a promising way forward that focuses on the social dimensions that shape and define the practice. I now turn to describing the methodological approach taken in this thesis.

3 Methodology

3.1 Adopting a relational worldview

The methodology for this research study, as with all effective and coherent academic research, has emerged from a particular conceptual worldview. It was this worldview that has shaped and informed the choice of research design and data collection methods that defined this study (Holden and Lynch 2006). As the preceding chapter highlighted, researchers have most commonly understood and interpreted citizen science through a positivist, technological worldview. Part of the reason for this is that citizen science is strongly influenced by the theoretical foundations of conventional scientific practices, which strive for objectivity, standardised protocols (i.e. the scientific method) and separation of facts from social values (Mueller and Tippins 2012). However, within this paradigm, environmental problems as understood through neutral and value-free observation are detached from the historically contingent social contexts of inquiry.

Fundamental to citizen science is the search for generalisable knowledge that is at the same time relevant to locally specific contexts (Fischer 2000). In methodological terms, this type of collaborative scientific inquiry requires an approach that both works with, and moves away from, more traditional scientific approaches to making sense of knowledge generation. I consider positivism to be inappropriate to the study of citizen science due to the central role of subjectivity and meaning, the highly situated and interactive nature of

citizen science practice and the evolving and constructed nature of community-based knowledge. Moreover, the assumption that "better methods" will lead to "better outcomes" that is characteristic of a positivist worldview overlooks the influence of broader social, political and cultural contexts. These critiques, which are largely based on a constructivist understanding of social reality, provide reason to break away from a positivist conception of citizen science to instead adopt a worldview that appropriately attends to the emergent, relational and constructed nature of community participation in scientific inquiry (Chilvers and Kearnes 2015, Fritz and Binder 2018).

As such, this thesis was inspired by relational understanding of social phenomena and its tightly coupled methodologies and theoretical constructs, such as social network analysis and boundary concepts. As described in the preceding section, a relational view of social life considers the "relations" and the "spaces" occupied by people and phenomena as the ultimate starting point in sociological analysis (Emirbayer 1997). In recent decades, sociologists have described an emerging "relational sociology," which broadly rejects the idea that social facts can be understood without reference to social connections. A key concept in this theoretical paradigm is that social relations are not completely random but particular configurations in a network structure made up of actors and the social ties between them. Ultimately, how a person lives and acts in the world is, in large part, a reflection of their social relationships (Pescosolido 2006). These relations form social boundaries that reinforce social norms and thus create a collective identity. Applying relational concepts and theories to citizen science is similar to the co-productionist and performative account of Chilvers and Kearnes's (2015) work on the nature of public participation as co-produced, relational and emergent.

3.2 The research setting

Freshwater citizen science has been a long-lasting feature in Australian natural resource management and is largely associated with the community-based water monitoring program "Waterwatch." Waterwatch was launched nationally in 1993 and was delivered alongside several other 'Watch' and 'Care' programs focusing on various aspects of the

environment, including water quality, biodiversity, coasts, dunes, soils and riparian management. Promoting community participation through catchment management and monitoring programs was viewed as an important, albeit experimental, response to rising catchment degradation at the time.

In its early stages, Waterwatch was committed to encouraging the public engagement with the management of water resources through a combined process of on-ground learning and scientific inquiry. Underpinning this overarching goal were objectives to raise community awareness of waterway problems, improve the technical skills of volunteers to effectively monitor waterbodies and increase the availability of relevant water condition data for use by community members and government officials. As Waterwatch expanded across the country during the 1990s, it gained a sound reputation for its flexible approach that enabled programs to adapt to local environmental contexts and encourage place-based learning. By participating in Waterwatch, volunteers had substantial control over the processes and outcomes of their activities, which was expected to lead to more direct and effective action at a local level.

While the philosophy and overarching objectives of Waterwatch have been mostly consistent throughout its development, the practice has nevertheless evolved in several important ways. Most notably, there has been a consistent emphasis on improving the scientific rigour and focus of Waterwatch, including efforts to improve data standards and monitoring protocols, align monitoring activities with regional government objectives and improve data access and management through technological developments. This evolution has occurred against a backdrop of interest by scientists and land managers who have long viewed citizen science as a potential solution to fill knowledge gaps and speed up the detection of environmental change. However, a more implicit aim reflected a need to shift perspectives among the scientific community, since historically implementation of the approach had been met with scepticism and clear opposition by certain groups of researchers and elements of government (Finlayson and Mitchell 1999).

Within the last decade, strategic improvements to Waterwatch have become increasingly important as the practice was challenged to justify its value in a shifting

political and economic environment. For example, in 2008, changes to the delivery of federal environmental funding under the 'Caring for our Country' program had significant effects on the regional delivery of natural resource management (Robins and Kanowski 2011). Some community-based environmental programs, including Waterwatch, shifted from a national to a regional delivery model, which had a significant initial impact on program stability (Thomson 2007). Since this identified downturn, the characteristics and geographic extent of freshwater citizen science has not been assessed nor have the impacts of these general strategic improvements been reviewed.

3.3 Research design

To best explore the issues specific to the research setting, the current study has adopted a multi-phase mixed method research design involving a collection of single method and mixed method studies (Creswell and Plano Clark 2017). What links the studies together is the overall aim of the research, as described in Section 1.4.

The multiphase research design was both an intended aspect of this thesis but was also an evolving feature of the research journey. As such, the research design was both fixed and emergent (Creswell and Plano Clark 2017). This is not uncommon in mixed methods research as researchers adapt the implementation of their research in response to new findings or concerns about the trustworthiness of interpretation that may result from the use of a single method (Creswell and Piano Clark 2011). The use of both quantitative and qualitative methods was considered intuitive since either approach alone was inadequate to address the overall research aim. Furthermore, a multiphase design was appropriate since the overall research objective was not able to be completed as a single mixed methods study.

Some scholars have suggested that mixed methods research should have a primary "theoretical drive" (Morse and Niehaus 2009). This means that an investigation will either be driven by a qualitative/inductive or quantitative/deductive approach, with a contrasting and supplemental component. Other scholars have criticised this notion of a theoretical drive (e.g. Schoonenboom and Johnson 2017), suggesting that a single theoretical basis for an entire study discounts the possibility for addressing multiple research questions that

require multiple theoretical drives. As this thesis was focused on addressing multiple relational dimensions of citizen science practice, which required different methodological techniques, I adopt what Schoonenboom and Johnson (2017) call an "equal status" or "interactive mixed methods research." The equal status approach is consistent with pragmatist thought in which paradigms can be mixed and combined.

3.4 Research phases

This study is conducted in four phases, which I have termed (1) exploring; (2) contextualising; (3) synthesising; and, (4) theorising (Figure 2). The first phase, *exploring*, adopts a quantitative approach that sought to provide insight in the nature and of study cases for subsequent study. This phase both provided descriptive analysis of key characteristics, impacts and challenges faced by contemporary programs and enabled the targeted selection of study cases for subsequent study. The second phase, *contextualising*, was a comparative mixed methods case study of two longstanding Waterwatch programs. The case study approach involved the use of quantitative social network analysis and thematic analysis of interviews to answer the multiple research questions and test the relational framework explained and presented in Chapter 2. The third phase, *synthesising*, consolidated and discussed the implications of the survey research (Phase 1) and case study approach (Phase 2). The final phase, *theorising*, addressed the final aim in this thesis: to assess and present a reconceptualisation of citizen science that emphasises its relational dimensions and embeddedness in wider social context.

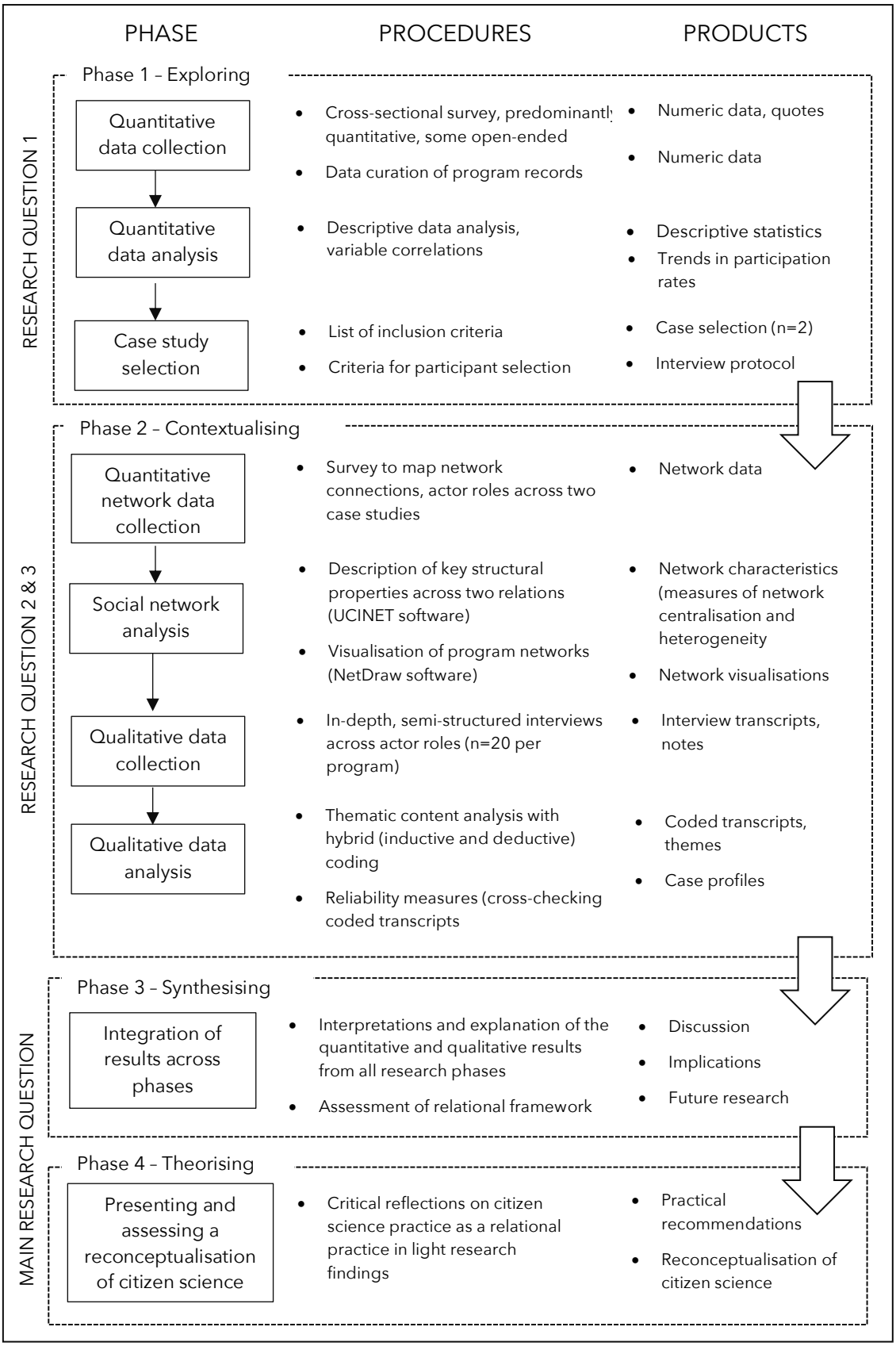

Figure 2. Research phases, procedures and products

3.4.1 Phase 1 – Exploring

Phase 1 is an exploratory study on freshwater citizen science in Australia. According to Terre Blanche et al. (2006) one of the aims of exploratory studies is to begin preliminary investigations into relatively unknown research areas. More specifically, Babbie (2008 p. 98) suggests that 'exploratory studies are most typically done for three purposes: (1) to satisfy the researcher's curiosity and desire for better understanding, (2) to test the feasibility of undertaking a more extensive study, and (3) to develop the methods to be employed in any subsequent study.' The paucity of research literature on freshwater citizen science programs in Australia lessened my confidence in conducting a more in-depth, explanatory research study from the outset. It also provided an approach to fill a critical gap in historical records regarding the extent, characteristics and influence of freshwater citizen science programs in Australia. For these reasons, a process of research exploration was considered a favourable approach to beginning this research. An additional practical goal of this phase was using the research findings for an informed and targeted selection of case studies for further inquiry (see Section 3.5.2). This exploratory research phase included the following methods:

1. A targeted questionnaire of program coordinators of freshwater and estuarine citizen science projects in Australia;
2. Secondary analysis of program data records over time (number of sites and monitoring records) from two freshwater citizen science programs to understand historical trends in participation rates; and,
3. Examination of program and policy documentation for contextual understanding and to verify coordinator reports.

3.4.1.1 Survey data collection and analysis

Yin (1994) proposed that surveys are useful in exploratory studies as they seek to establish the prevalence of a phenomenon and enable the development of further inquiry. Surveys are typically beneficial for reaching large populations and can cover wide geographic areas. Surveys are also relatively easy to conduct, flexible and can acquire a large amount of information on a given topic, if well-designed (Babbie 2008). Consequently, a survey was

used as a key tool for this phase of the research. The primary goal of the survey was to examine the national landscape of freshwater citizen science programs in Australia. While the primary focus of this thesis is on freshwater citizen science projects, estuarine citizen science projects were also included in the sample population but only if their primary data collection focus and activities did not extend into marine environments.

The survey gathered perspectives from program coordinators who were selected through a targeted, or purposive, sampling approach. A purposive sampling approach was appropriate as it was considered possible to sample the small population of freshwater and estuarine citizen science programs in Australia in their entirety. To select participants, emails were sent out to 61 programs across Australia, which were located through extensive online searches and through professional networks. Additionally, the study was promoted through other channels, including natural resource management email lists, newsletters and communications between program coordinators. These approaches to locating programs was considered to be most effective because, at the time of the study, a database of programs was not available.

The survey comprised 38 non-compulsory questions seeking coordinator responses on three categories: (1) general program characteristics, (2) program interactions and partnerships, and (3) program and volunteer contributions to catchment decision-making. Survey questions are presented in Chapter 5 and in Appendix A. Efforts were made to reduce survey burden by following a "need to know" rather "would be interesting to know" model (Jones et al. 2013). While surveys enable fast responses from participants and effective data compilation, they are susceptible to non-response. In cases where a coordinator or organisation did not answer the survey request, two rounds of follow-up requests were sent via email at two-week intervals after initial survey deployment.

The level of statistical treatment considered to be appropriate in a particular study will be informed by the research questions and the purpose of the study (de Vaus 2002). Therefore, as this was an exploratory study, analysis of survey data was limited to descriptive statistics and correlations of program characteristics, partnership structures and impacts of decision-making. In cases where surveys were incomplete (i.e. the participant did

not answer one or more questions), the survey was still included as part of the sample population when a majority of questions were answered. Where relevant, the number of responses for each question is noted in the results presentation (see Chapter 5).

3.4.1.2 Secondary data collection and analysis

Secondary data analysis is the process of analysing pre-existing data in an effort to answer a research question or objective. For this component of the study, the pre-existing data was program data records from two longstanding freshwater citizen science projects[2]. The primary goal was to understand trends in number of sites monitored and total data records as a proxy indicator for the historical rates of participation in each program. Both programs store citizen-generated data on online databases, which can be downloaded and analysed to understand trends in waterway condition. These data were collated and curated to only include sites and records from natural waterways and wetlands. Artificial waterways and waterbodies, such as bores, channels and stormwater drains were excluded from the analysis. From these curated data, the total number of monitoring records and sites monitored were tracked and calculated over time.

3.4.1.3 Supporting documentation

Documents, such as annual reports, policy documents, internal and external communication, newspaper article, online webpages and newsletters, were collected to provide valuable contextual information on freshwater citizen science in Australia. These documents were sourced through online searchers, requests from practitioners, government agencies and libraries. Documents were not systematically analysed applying structured content analysis techniques. This decision was shaped by the rationale behind the inclusion of documentary evidence. In this phase of the research, documentation was used as a

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[2] In Phase 1 study, permission was sought from each program to identify their program's name in research outputs. In the following phase, anonymity of participants and programs was assured given the in-depth and contextual nature of the study.

verifier for collected primary data. This is distinctly different to a structured documentary analytical process in which document content forms part of data triangulation. Instead, documents were examined in an unstructured way to verify or provide greater detail to the information supplied by survey respondents on specific issues relating to the use of citizen science data.

3.4.2 Phase 2 – Contextualising

Phase 2 involved a mixed method comparative case study involving two longstanding freshwater citizen science programs enabling a case within a real-world setting (Yin 2014). This approach was considered particularly useful for understanding how context influences the development of outcomes in citizen science since freshwater citizen science can be practised with different goals, objectives and levels of participant interaction. Adopting a comparative case study approach was viewed as a critical phase of this research to draw out and expand on the issues discovered in Phase 1, to answer research questions 2 and 3 and inform phases 3 and 4.

3.4.2.1 Comparative case study

A comparative case study is a method of inquiry that involves the use of qualitative and/or quantitative methods to investigate a social phenomenon across two or more cases in their situated context. Comparative case studies usually examine typical cases, rather than "outlier" cases (Mills et al. 2006). Unlike single case studies, the core objective of a comparative case study is to investigate the patterns, similarities and differences across selected cases. For this reason, comparative case studies are particularly useful for understanding and explaining how social context influences the effectiveness of a strategy or program. They also enable the development and study of particular interventions that may create greater possibilities to achieve intended outcomes.

Mills et al. (2006) suggest this type of case study research still strives for a "thick description" recommended in single case studies. Thick description is a process in qualitative research that involves a thorough investigation not only of individual actions

and behaviour but also of the social context and circumstances that drive these actions (Geertz 1973). For this reason, qualitative methods, such as interview, observation and fieldwork are preferred by researchers. The use of multiple cases and rich descriptions enabled in-depth analysis to determine patterns in the data, contributed to the development and confirmation of theory and enable the investigation and refining of the theoretical framework for the study.

The findings from the national review survey (Phase 1) informed the selection of programs to be part of comparative case study and to answer research questions 2 and 3 of this study (Section 1.5). Selection of cases was undertaken through a targeted approach and involved the use of set inclusion criteria. These criteria related to programs that:

- actively monitor waterways (wetlands, rivers and estuaries);
- have been operating for more than five years;
- are of similar size (i.e. sites monitored and volunteer numbers);
- implement training, and quality assurance and quality control procedures;
- have established partnerships and interactions with government, non-government organisations and other community groups;
- advance goals and objectives relating to influencing local policy and decision-making;
- have demonstrated impacts of catchment decision-making through data contributions.

Initially, the study aimed to include three cases from different socio-cultural contexts. However, in considering the extensive conceptual, analytical and synthesising work required in comparative case study research, a decision was made to reduce the number of cases. In the end, two programs (Mill Stream Waterwatch and Regional Highlands Waterwatch) were selected for further inquiry. Due to ethical consideration of the research design (described in Section 3.8), pseudonyms are used to ensure the anonymity of programs and participants. In the following paragraphs, the key characteristics of each case are described, and are summarised in Table 3.

The first case, *Mill Stream Waterwatch* is funded by a large water utility company responsible for the management and protection of waterways across an urban and peri-urban region. Mill Stream Waterwatch began in 1993 and currently operates in a governance context that emphasises community capacity-building under the region's waterway management strategy. The strategy provides direction for a regional vision of waterway health, with goals to elevate the importance of citizen science, promote environmental stewardship, improve community connections to waterways, strengthen community-government relations and build community leaders. The program comprises five coordinators employed by the funding agency with each coordinator responsible for one priority portfolio (water quality, platypus, macroinvertebrates, frogs and litter) and a region for coordinating water quality monitoring activities. The number of volunteers was not able to be accurately determined but is in the range of 250. The number of sites monitored is approximately 180.

The second case, *Regional Highlands Waterwatch*, is partly funded by a state government, with funding assistance from a state-owned water utility company. Regional Highlands Waterwatch was launched in 1995 and at the time of this research was guided by policy that supports the integration of Waterwatch in government monitoring to enable better understanding of water resources in the region. The program also has objectives to promote increased community awareness of waterways issues. Approximately 200 volunteers participate in the program and monitor approximately 250 sites. Volunteers are coordinated by four regional catchment committees, each employing a single coordinator. The role of the coordinator is to interface with communities in their respective region. A program facilitator who is employed by the state government oversees the activities of the coordinators and promotes the program internally.

Table 3. Key attributes of the two case studies

	Mill Stream Waterwatch	Regional Highlands Waterwatch
Initiated	1993	1995
Program size	Approximately 250 volunteers monitoring 180 sites	Approximately 200 volunteers monitoring 250 sites
Environmental context	Predominantly urban	Predominantly rural
Coordination	Five coordinators from within funding agency, supported by 2 coordinators from a council and catchment management committee	One program facilitator overseeing activities in four catchment coordinating committees each comprising one coordinator
Program objectives	Capacity-building, awareness raising	Regional reporting of catchment condition, awareness raising

3.4.2.2 Social network analysis

As described in Chapter 2, social network analysis is a conceptual and methodological tool that allows the mapping and investigation of social networks. In this thesis, the social network analysis was conducted using a mixed method approach, with quantitative and qualitative methods integrated according to a sequential explanatory research design (See Section 1.7). A sequential explanatory design involves two more or less distinct phases, beginning with the collection and analysis of quantitative social network data followed by the collection and analysis of qualitative data. A key advantage of sequential explanatory design was the ability for targeted selection of participants for the interviews after preliminary analysis of social network data. Sources of data for the quantitative strand was a survey to map network connections and understand actor characteristics. For the qualitative strand, interviews were conducted with a range of actors participating in, or interacting with, each study case. The purpose of the quantitative strand was to map the structural characteristics of the social network, whereas the subsequent qualitative data generated deeper understanding of the content of ties and the meaning actors have attached to those ties within the network (Fuhse and Mützel 2011).

Any social network study must first determine how they define what an actor in the study is, the relations and actor attributes of interest, and how they determined the network

boundary. In the following sections, I define these key dimensions to establish how the social networks in each study were constructed.

Actors

In social network studies, actors can comprise individuals, groups or organisations. These actors are otherwise termed "nodes" who are linked together through various relations or "edges". This study focuses on individual actors. An actor was defined as an individual who participates in, or interacts with, the study case and that shapes its planning, implementation and/or outcomes. An interaction was defined as a one-off or ongoing exchange of ideas or advice, training, collaboration on projects or monitoring activities, sharing data and resources or receiving funding. Examples of actors included volunteers, coordinators or program leaders, scientific advisors, environmental managers, policymakers and other stakeholders, such as education professionals or council representatives.

Relations

Relations in network studies can be of many different kinds, each capable of producing a different network structure. Borgatti et al. (2009) describes four broad categories of relations: (1) similarities (memberships in the same group, physical proximity); (2) social relations (e.g. kinship, friendship, cognitive awareness); (3) interactions (e.g. speaking with, gives advice to); and, (4) flows (e.g. unidirectional or bidirectional exchanges or transfers of information, resources or influence). In this thesis, I draw on the latter two categories, interaction and flows, and specifically focus on collaboration between actors and data sharing relationships. Collaboration and data sharing relations were selected since they are key relational processes in citizen science networks and critical to environmental governance arrangements more broadly.

Attributes

While the focus of network studies is primarily on social relationships, actor attributes are also important considerations (Robins 2015). Attributes can be used to group actors into

categories and establish the patterns of relations between them. Attributes relevant to this study were limited to the role each individual plays in the study cases, as described above.

Network boundary

Determining the network boundary in social network analysis studies is a critical consideration (Wasserman and Faust 1994). In organisation studies, the network boundary is relatively well-defined e.g. list of employees. However, in natural resource management studies, the network boundary is not as straightforward to define (Bodin and Prell 2011). This is a particular challenge since environmental governance arrangements have a cross-scale and multifunctional nature and so determining who is involved in a given network is a difficult task. For citizen science, determining the network boundary is relatively straightforward for those actors inside the program boundaries i.e. volunteers and coordinators, but more difficult for understanding those outside the program boundaries. The approach to establish the network boundary in this study was therefore achieved through a snowball sampling approach. In theory, this approach samples actors in multiple rounds until no new actors are identified by others. In other words, the network boundary is determined by the actors in the network itself.

3.4.2.3 Data collection methods

Network mapping survey

The survey to map network connections among actors was administered from April to September 2019. The survey was available as an online questionnaire accessed through a web-link provided to participants. The approach to sampling was conducted through a snowball sampling approach, starting with program coordinators (Doreian and Woodard 1992). Coordinators were asked to nominate potential participants who were then asked to nominate others. This approach continued as the central mechanism for working to achieve the required sample size. To assess volunteer connections, it was necessary to rely on coordinators to recruit volunteers for this study due to ethical considerations constraining

direct recruitment. Invitations to volunteers to participate in the research were sent out by coordinators on behalf of the student researcher with a link to an online survey.
The questionnaire to map network structure followed a name generator and interpreter method and is presented in Appendix B. Respondents were asked to recall up to ten individuals with whom they: (1) share citizen science monitoring data; and, (2) collaborate on monitoring activities and projects. A second section of the survey asked respondents attribute-based questions on their group affiliation, role and their duration of employment or participation. The focus was on following up survey responses from people who were named frequently as a way to maximise limited resources and obtain a network characterised by the most important individuals.

Interviews

A total of twenty interviews were conducted for each study case using a cross-cultural sampling approach (Robinson 2014), which selects participants in diverse roles and acquires a heterogenous sample. To select participants, five coordinators from each program were initially interviewed as key informants. A purposive sampling approach was then followed (Mason 2006) to interview additional actors in professional roles (e.g. scientists, land managers, policymakers, community engagement professionals). These Individuals were those discussed by coordinators as being important in the planning, development and implementation of Waterwatch. In addition, ten volunteers were interviewed from each case to capture differences between key informant, professional and community member perspectives (McKenna and Main 2013). In total, participants included volunteers (n=20), coordinators (n=10), catchment managers, policymakers and scientists (n=3), and community engagement professionals (n=3). Despite best efforts to interview a similar diversity of roles in each case, a policymaker from the Mill Stream case was not captured within this cohort.

Participants were asked a variety of questions about the nature of their collaboration with other people and organisations, the contributions of citizen science to understanding and managing waterways, enablers and constraints to building new, and strengthening,

existing relationships and visions for an ideal citizen science program in their respective region. Interviews lasted between thirty and ninety minutes and were digitally recorded and transcribed. The interview schedule is presented in Appendix C.

Program outcome data

A key concern for social network researchers is the ability to link network structure with an outcome of interest, which requires another data set in addition to network connection data (Groce et al. 2018). The outcome measure of interest in this study was each program's contributions to natural resource management and policy decisions as evidenced by data uptake in, for example, reports, policies or management actions. Carr et al. (2012) and Groce et al. (2018) both suggest that such outcomes are "intermediate," and can be considered a precursor to broader impacts on environmental improvement.

A secondary analysis of survey data collected during Phase 1 was conducted to understand the effect of different network structures on the outcomes of citizen science initiatives. Instances of data uptake for each study case were then categorised along two axes: (1) the scale of data use (local, sub-catchment, catchment, regional), and (2) the relevant part of a typical adaptive management cycle. Drawing on relevant literature network characteristics of each study case were then related to the type and scale of data uptake to determine the potential role of social network on citizen science outcomes. Therefore, in this case, social networks were treated as an independent variable.

3.4.2.4 Data analysis

Social network analysis

The research design allowed for the generation of two networks: data sharing and collaboration. Respondents were grouped into six categories: volunteers, coordinators, scientists, catchment managers, policymakers and other stakeholders, which included educators and individuals from non-government organisations. Relationships were symmetrised (Borgatti et al. 2013), meaning that a tie was included if one actor in a dyad

reported a connection. Thus, each studied relation resulted in an 'undirected' network where all relations are bidirectional.

To investigate the network characteristics, UCINET software (Borgatti et al. 2002) was used to quantify four network-level measures relevant to the research focus. The metrics included density, network centralisation, core-periphery analysis and cross-boundary exchange. *Density*, which indicates level of cohesiveness in a network, was assessed by calculating the number of connections a participant has, divided by the total possible connections within the network. *Network centralisation* calculates the extent to which the network conforms to a classic star network where all ties are concentrated on one or a few members. *Core-periphery* analysis (Borgatti and Everett 2000) calculates the degree to which the network conforms to an idealised core-periphery structure and assigns each actor to either the core or periphery of each network. A core-periphery structure is characterised by densely connected groups of core actors and a sparsely connected periphery and are recognised as a typical feature of social networks in general and useful for understanding the effectiveness of environmental organisations (Ansell 2003, Ernstson et al. 2008). Finally, *cross-boundary exchange* is a measure of network heterogeneity and measures the number of ties connecting actors in different roles divided by the total number of ties in the network. Cross-boundary exchange is therefore a measure of 'bridging ties', known to be an important indicator for how knowledge and resources are distributed across a network. Cross-boundary ties between volunteers and coordinators were excluded to uncover effects of program interactions with other stakeholders occupying different roles. Networks were illustrated using the social network visualisation software NetDraw (Borgatti 2002).

Interview analysis

Analysing the interview data was achieved through thematic analysis (Braun et al. 2019). Thematic analysis is a flexible method of analysing qualitative data, which systematically identifies meaningful patterns of ideas of concepts across a data set. The first step involved reading the transcripts multiple times to enable a process of familiarisation with the data. Following this, transcripts were segmented into "chunks" of information in NVivo 12

software (QSR International). Segments were coded to depict a core idea or concept that produced numerous descriptive and analytical categories (Appendix D). Coding of interview data was conducted through application of both an inductive (i.e. data-driven) and deductive (i.e. theory-driven) approach (Fereday and Muir-Cochrane 2006). This approach acknowledges that my observations were, to varying extents, informed by pre-existing concepts and theories, such as social networks, boundary work and key issues in citizen science literature. That is, I did not enter the coding process with a 'clean slate', as similar methods in grounded theory might assume (Glaser and Strauss 1967). The benefits of a hybrid approach to qualitative analysis relates to the ability to form both a close connection to the theoretical foundations that had thus far guided the research questions, but also an openness to emerging ideas and concepts. Being guided by theory and allowing the data to enable a process of "theorising" is akin to the adaptive theory approach developed by Layder (1998).

Coding of interviews was also achieved through multiple iterations. As I continued to code the interviews, the descriptive and analytical categories that were in use were sometimes renamed, collapsed or expanded into different categories. This occurred when the initial codes (or ideas and concepts) were exposed to new data. In such cases, I was careful to return to previous interviews and adjust codes where appropriate or necessary. After coding for each interview was complete, I created memos for each participant that summarised their role, perspectives and challenges they faced in the context of citizen science. This process was crucial to building a thorough awareness of similarities and differences between participants and actor roles. It also enabled me to take notes and reflect on the connections between the incoming data and existing theory for subsequent analysis of coded data.

The next stage of the qualitative analysis was constructing themes and subthemes that capture patterns of ideas or concepts that occurred within and across the study cases. Theme construction is a creative, active process (Braun et al. 2019), as the researcher makes choices about how best to structure and make sense of the coded data. Categories of codes were reviewed and clustered when they appeared to share some underlying similarity or unifying

feature. Theme construction was facilitated by exploring different ways to cluster codes into themes and drawing many thematic maps that illustrated connections between codes and candidate themes. As was the case with coding the interview data, constructing themes was achieved through an iterative process and done in close connection with the research questions, existing theories and the orienting concepts. In particular, existing theories were foundational in structuring the final analysis, as they grounded the constructed themes in social theory but also promoted a capacity to critique, adapt and develop new theory. Figure 3 illustrates the process of qualitative analysis conducted in this thesis.

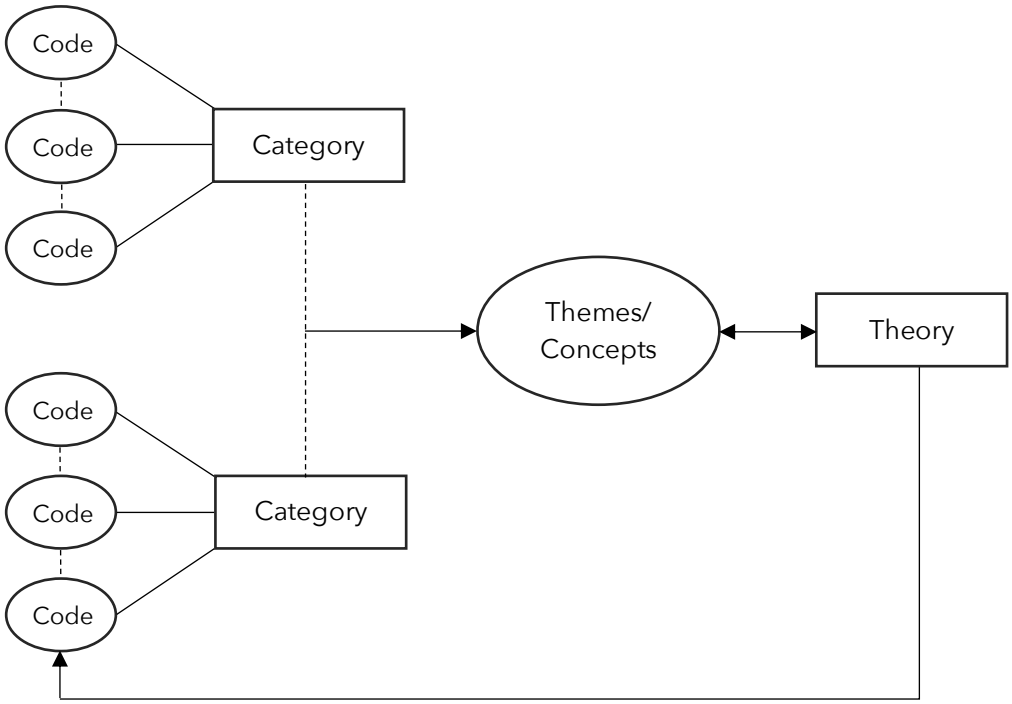

Figure 3. Process of qualitative analysis illustrating the development of codes to theory. Diagram adapted from Saldaña (2016) with additional consideration to Layder's (1999) contention that existing theory informs both theme generation and the initial coding process.

3.4.2.5 Validity and reliability

Validity and reliability are key concepts used to establish the quality of social network research. In network studies, validity is the extent to which the instrument to map network connections accurately captures the relevant network partners (Robins 2015). A key issue for

network studies is the challenge of missing data, which can have a strong influence on network validity. A key strategy implemented to reduce the possibilities of non-response was the development of rapport with research participants prior to conducting network data collection (Borgatti et al. 2013). Furthermore, as some network characteristics are sensitive to missing data, such as ideas that capture brokerage through betweenness centrality (Guerrero et al. 2020), only measures relatively robust to missing data were calculated. The insights from the qualitative strand of the research also enabled a mechanism to validate, contextualise and better interpret the findings from the social network analysis.

Reliability is the extent that the data collection procedures of a study can be repeated with the same results. For network studies, reliability refers to the degree researchers can be sure that network actors will nominate the same network partners if the study was repeated. Strategies to maximise reliability included detailed guidance provided to participants on how to complete the questionnaire and what constituted a network connection. For the interview data, cross-checking of codes and interview transcripts was conducted by the student researcher and two members of the supervisory team to assess the reliability of coding efforts and theme construction.

3.4.3 Phase 3 – Synthesising

The goal of Phase 3 was to meaningfully integrate and interpret the different methods and phases to understand the core research objective in this thesis. This was to arrive at richer and more insightful conclusions regarding the role and importance of 'relationality' in citizen science, particularly as it relates to its interactions in environmental governance contexts. Integration was achieved at the method- and interpretation-level (Fetters et al. 2013). At the method-level, the quantitative and qualitative databases were integrated through a process of "merging." In this case, the merging of data was conducted after the analysis of both quantitative social network analysis and qualitative analysis of interview data. At the interpretation-level, integrating and interpreting quantitative and qualitative research findings can be achieved through narrative, data transformation and joint displays (Fetters et al. 2013). In this case, I took a narrative approach and did this in a staged way. A

staged approach to integration is common in multiphase mixed method research designs when the results of a project are reported in stages and discussed separately. The process of integration occurs in the discussion of this thesis (Chapter 9).

3.4.4 Phase 4 – Theorising

Based on study findings (Phase 1 and 2) and subsequent synthesis (Phase 3), in the final phase of this research I engaged in a process of theorising to reconsider how researchers, practitioners and other stakeholders come to know and practise citizen science. The notion of theorising is a contentious issue in sociological literature, with a core concern relating to differences in opinion about definitions and approaches to theory and theorising (Hammond 2018). Swedberg (2014) challenges us to conceive theory (or the process of creating theory) not as something formal, logical, stable, but rather unstable, fluid and not yet established. In short, theorising is the search for explanation.

This process of theorising was supported by reading widely and far beyond citizen science literature. The relatively recent emergence of citizen science opens ups possibilities to search for new explanations, experiment with novel methodologies and, ultimately, view the practice in a new and (potentially) more productive light. Hammond (2018) highlighted three broad steps in a typical process of theorising: (i) identifying a gap in knowledge, (ii) providing an alternative explanation and (iii) justifying this alternative logically and empirically. In this thesis, so far, I have engaged in the first two steps: identifying that the relational dimensions are largely unexplored in citizen science research and proposed that citizen science is best conceived as a relational practice that considers issues of structure, meaning and boundaries. Informed by the research findings, the final part of this process—the logical justification of this alternative—will be described in the discussion (Chapter 9).

3.5 The role of the researcher

Making explicit the role of the researcher is especially important in studies taking a relational perspective. This is because the researcher enters a relationship with the research subjects who are themselves embedded in a network of relationships and networks

(Bradbury and Bergmann Lichtenstein 2000). Relational researchers thus take a reflexive approach with respect to his or her capacity to exert influence on, or be influenced by, the particular culture under study. For the purpose of this thesis, reflexivity refers to the act of acknowledging one's own biases, values, assumptions and theoretical views in order to highlight the influences that have shaped the design, conduct and outcomes of the research.

In this thesis, my role as a researcher could be described as "observer as participant" (Baker 2006). This means that while I actively participated in some citizen science activities (e.g. water monitoring, planning days and seminars), I have maintained a strong research-oriented approach to these relationships. Furthermore, any personal relationships I formed as a researcher extended mainly to participants in professional roles, particularly program coordinators, who were important individuals in facilitating many of the logistical aspects of the research. Despite maintaining an appropriate level of distance from research participants, I have still endeavoured to maintain a closeness to practice. In other words, not only am I concerned with 'how' to conduct this research as creative and rigorous pursuit, but also with practical questions, such as 'why' and for 'what purpose' (Ulrich 2001).

3.6 Ethical considerations

The ethical considerations in social network research have been addressed by several authors (Borgatti and Molina 2005, Kadushin 2005, Robins 2015). The most common issues related to confidentiality and anonymity of respondents. Since social network data typically comprises the identification of an individual's connections with others, data cannot be collected in anonymous forms. Therefore, additional considerations were given to ensure the privacy and confidentiality of participants and other identified individuals, as followed:

- Once data is entered participants were guaranteed that identifiable information will be de-identified, as is typically best practice in social network research.
- Each participant was coded with a unique ID number, therefore the list of names identified was destroyed once data was entered.

- The researcher sought informed consent from participants and assured anonymity and confidentiality of all participants upon publication of this research.
- A verbal or signed agreement between monitoring programs and the researcher about how the data was handled was included in the consent documents for participants.

It was made clear in cover statements and prefaces to interview questions that care would be taken to ensure the confidentiality of participants. The decision to rename the case studies with pseudonyms was part of the process of maximising the capacity for participant anonymity. Commitment to ensuring all ethical considerations, including issues of confidentiality and anonymity, were adhered to, was formalised through the fact that this research has gone through the appropriate ethical considerations of an independent body. The approval number granted by the Federation University Australia Human Research Ethics Committee is A18-006. Attached to this thesis, as Appendix E, is the final report to the Ethics Committee of Federation University Australia verifying that all ethical requirements put in place for the conduct of this research study have been met at project completion.

3.7 Conclusion

This chapter has outlined the methodology and data gathering techniques used in the development of this thesis. Its purpose was to connect the research paradigm to the strategies of inquiry and methods for collecting empirical data on freshwater citizen science in order to answer the aim and objectives of the research in a meaningful way. It has described four stages of the research that were used to answer the core research question in this thesis. In the following chapter, I summarise and describe the links between the four research articles that constitute the main findings of this research. The full articles are then presented in Chapters 5-8 before a synthesis and discussion in Chapter 9.

4 Articles and findings

This doctoral thesis is written as a thesis by publication, with four articles published, under review or written in preparation for submission to peer-reviewed journals (Table 4). The following section describes each paper, including the main findings contributing to the thesis objectives and answering the research questions. Given the nature of a thesis by publication, each of these chapters will repeat some aspects of the literature review and methods chapters. This is an inevitable consequence of this type of thesis format. However, wherever possible, measures were taken to minimise excessive repetition.

Table 4. Summary of papers

Article	Relational dimension	Methods	Theories
Article I (Chapter 5) 'Citizen Science in Australia's Waterways' *Status: Published*	Exploratory study	Closed- and open-ended questionnaire; Document analysis; Secondary analysis	Citizen science (Bonney et al. 2009)
Article II (Chapter 6) 'Advancing Citizen Science Practice Through Social Network Research' *Status: Submitted*	Structure	Literature review	Social network theory (Wellman 1988); Social network analysis (Wasserman and Faust 1994)
Article III (Chapter 7) 'Exploring the Citizen Science-Policy Interface' *Status: Submitted*	Structure; Meaning	Social network mapping survey; Semi-structured interviews	Social network theory (Wellman 1988); Social network analysis (Wasserman and Faust 1994)
Article IV (Chapter 8) 'Citizen Science in the Making' *Status: In preparation*	Meaning; Boundaries	Semi-structured interviews	Boundary work (Gieryn 1983); Boundary objects (Star and Greisemer 1989)

4.1 Article I: Citizen science in Australia's waterways: investigating linkages with catchment decision-making

Citation Bonney, P., A. Murphy, B. Hansen, and C. Baldwin. 2020. Citizen science in Australia's waterways: investigating linkages with catchment decision-making. Australasian Journal of Environmental Management 27(2):200-223

Contributions Bonney, P. developed the idea for this article, designed the data collection instrument, collected and analysed the data and wrote the article. Co-authors equally provided comments and suggestions on improving the manuscript for submission.

Article I (Chapter 5) was an exploratory study that aimed to create a baseline understanding on the role and utility of citizen science in the context of Australian waterway governance. The paper acknowledged the longstanding policy support for freshwater and estuarine citizen science in Australia, but also a distinct shortfall of research on the program extent, characteristics, contributions and challenges. Three methods were used to address these objectives: (1) a survey of program coordinators across Australia (see Appendix A); (2) analysis of program and policy documentation for contextual understanding and to verify coordinator reports; and, (3) secondary analysis of program data records from two longstanding freshwater citizen science programs to understand temporal dynamics of volunteer participation. A further aim in relation to this thesis was to use this foundational data in the selection of suitable programs for the subsequent comparative case studies.

The key findings were:

i. Freshwater and estuarine citizen science programs in Australia typically combine participatory learning with scientific inquiry under the support of government agencies at local, regional and state levels. Programs vary widely in their size, characteristics and the extent of interactions and partnerships with other groups and organisations.

ii. Verified scientific impacts on decision-making included impacts on policy planning and development, monitoring and reporting on management actions, and reporting

and evaluation of resource condition. Programs with evidence of data uptake in catchment decision-making were more likely to be larger programs, collecting water condition data for long periods of time and with a broad network of partnerships and interactions;

iii. Coordinators reported that several social, organisational and scientific barriers currently limit data uptake in government decision-making. Key issues included difficulties connecting and coordinating with data end-users, funding challenges and a lack of interest in volunteer-collected data. The scientific accuracy of volunteer data was a low-level concern for coordinators;

iv. Coordinators indicated volunteers were actively engaged in water resource management. Beyond their involvement in data collections activities, volunteers contribute to advisory groups, partner with local stakeholders to address waterway problems and actively advocate for local waterway issues and concerns.

Article I responded to calls in academic literature for improved understanding about the position and influence of citizen science in natural resource management (Conrad and Hilchey 2011; Stepenuck and Green 2015). The findings illuminate the various ways citizen science data can be used to inform management and policy decisions and the barriers that limit further uptake. The paper also contributes to a nascent literature on how citizen science encourages opportunities for the public to actively participate in decision-making processes beyond their involvement in data collection. In addition to these insights, the findings fill a geographic gap in knowledge about the extent and influence of freshwater citizen science in Australia. Additionally, they provided the foundations for further exploring and explaining contemporary issues in citizen science in natural resource management contexts. From a practical perspective, this paper assists citizen science practitioners working at the interface of community and waterway governance and provides three recommendations. A call is made for increased institutional support for citizen science; it is recommended that programs embrace new possibilities for collaboration; and the importance of demonstrating and communicating program achievements is highlighted.

4.2 Article II: Advancing citizen science practice through social network research

Citation Bonney, P., A. Murphy, B. Hansen, and C. Baldwin. 2020. Advancing citizen science practice through social network research. *Submitted to Citizen Science: Theory and Practice*

Contributions Bonney, P. developed the idea for this article, conducted the literature review and wrote the article. Co-authors equally provided comments and suggestions on improving the manuscript for submission.

Article II (Chapter 6) set out to explore the conceptual and methodological utility of a social network research perspective for citizen science theory and practice. The paper draws on a growing body of environmental governance and sustainability sciences literature documenting the role and importance of social networks in collaborative initiatives and bottom-up approaches to environmental management. The benefits of applying a social network perspective to citizen science was reinforced by the insights gained in **Article I**, which suggested an enduring challenge to connect citizen science with waterway governance is as much a social and organisational issue as it is a scientific one. **Article II** is separated into two main parts. The first section systematically reviews literature to understand how citizen science researchers have discussed social networks in order to conceptualise their various functions. The second section draws on social network analysis, social network theory and environmental governance literature to describe the potential applications of a social network perspective, including how the conceptual and methodological tools of social network analysis can aid in this understanding.

The review found:

i. Relationships built and maintained in citizen science, and the networks they form, play a crucial role as structural foundations for critical social processes, social attributes and a range of individual and program outcomes.

ii. Despite acknowledging the importance of building and sustaining social networks in citizen science, researchers have rarely treated the relationships and networks that underpin citizen science as objects of empirical study in their own right.

iii. Researchers have seldom considered possible negative consequences of social networks. Social networks, and the processes that shape, and are shaped by, social networks, have both enabling and constraining characteristics and qualities.

In exposing current limitations in citizen science literature regarding social networks, **Article II** describes the conceptual utility of a social network perspective and presents three possible applications for linking knowledge with action, social learning, and building community empowerment. Realising the full potential of citizen science in environmental governance contexts requires attention to how individuals are connected, the purposes of these interactions and their influence within a larger web of interactions. The following article (**Article III**) is a demonstration of the potential of one of these applications, linking knowledge with action, in two state-sponsored freshwater citizen science programs.

4.3 Article III: Exploring the citizen science-policy interface: a social network perspective

Citation	Bonney, P., A. Murphy, B. Hansen, and C. Baldwin. 2020. Exploring the citizen science-policy interface: a social network perspective. *Submitted to Society and Natural Resources*
Contributions	Bonney, P. developed the idea for this article, designed the data collection instruments, collected and analysed the data and wrote the article. Co-authors equally provided suggestions on improving the manuscript for submission

Management and policy-oriented citizen science programs often involve diverse stakeholders working together in broad social networks (**Article I**). However, the structure, function and consequences of these networks has received little research attention. In **Article III** (Chapter 7), the principles and research opportunities of social network research for

citizen science that were put forward in **Article II** are applied and examined in a comparative case study of two longstanding freshwater citizen science programs (Regional Highlands Waterwatch and Mill Stream Waterwatch). The study employed mixed methods recognised to be suitable for the study of social networks (Hollstein 2014). Here, quantitative methods (questionnaire) allowed for a mapping of network structure and qualitative methods (interviews) provided a rich layer of understanding of how actors navigate tensions involved in the network function and development.

The findings revealed important insights into the nature of collaboration and knowledge sharing in the two study cases:

i. For both the collaboration and data sharing relations, Regional Highlands Waterwatch and Mill Stream Waterwatch created different network structures, with each structure found to be appropriate for its primary objectives. Mill Stream Waterwatch was characterised by a decentralised structure that reflected its capacity-building goals, and enabled participants to control the processes and outcomes of data collection activities. Regional Highlands Waterwatch was characterised by a core-periphery network structure with connections among a dense core of coordinators, scientists and catchment managers and a sparse periphery mostly comprising volunteers who had limited network connections. This network structure reflected the program's recent goals to create a broad-scale monitoring program that was relevant to government decision-making.

ii. The network structure created by each program was found to match the type and scale of program contributions to catchment decision-making. The decentralised structure of Mill Stream Waterwatch aligned with local instances of data uptake whereas the more centralised structure of Regional Highlands was linked to data contributions to regional-level policymaking and government monitoring frameworks.

iii. Insights from the qualitative analysis revealed how actors navigated several network tensions inherent in citizen science practice. The findings showed how prioritising

some aspects of network governance over others influences the capacity to achieve certain social and knowledge outcomes. For instance, the flexible and inclusive approach of Mill Stream Waterwatch was able to quickly respond to changing local conditions but this approach lacked efficiency and consistency in actions over time. By contrast, Regional Highlands Waterwatch prioritised efficiency and stability in order to maximise the program impacts for regional-level policy making. However, this same structure has simultaneously limited the program's capacity to address local environmental problems.

As with previous research on the role of social networks in collaborative environmental initiatives, this study illustrates that not all citizen science networks are created equal. Different network structures created by different patterns of relations enable and constrain certain outcomes and tensions. This research extends citizen science literature by understanding the additional factors that enable productive connections between citizen science and environmental governance. The article highlights the importance of appropriate selection of network partners to achieve desired goals and suggests that practitioners should encourage a networking mindset to realise the potential in their program's network.

4.4 Article IV: Citizen science in the making: boundary work, participation and linking knowledge with action

Citation	Bonney, P., A. Murphy, B. Hansen, and C. Baldwin. 2020. Citizen science in the making: boundary work, participation and linking knowledge with action. *In preparation for submission to People and Nature*
Contributions	Bonney, P. developed the idea for this article, designed the data collection instrument, collected and analysed the data and wrote the article. Co-authors equally provided suggestions on improving the manuscript for submission.

Article IV critically examines the practices and strategies used by citizen science programs and actors to maximise their legitimacy in waterway governance. Taking 'boundaries' as the starting point for empirical inquiry, this paper discusses boundaries as critical sites that

constrain the formation of social networks and govern the inclusion and exclusion of citizen-based knowledge. This comparative case study of two freshwater citizen science water monitoring programs in Australia used a framework of three distinct boundary work practices and strategies employed by actors participating in and interacting with each program (Langley et al. 2019). Each practice was described in the context of its role in shaping useable citizen science knowledge in terms of credibility, salience and legitimacy. The practice and strategies explored within Article IV, as described by Cash et al. (2003) were

i. *Constructing boundaries.* This referred to the efforts by actors to defend or maintain boundaries between citizen science and expert communities. The form of boundary work was performed by scientists to limit the integration of Waterwatch into decision-making based on negative perceptions of the scientific utility of Waterwatch. The maintenance of boundaries was also enacted by program coordinators in various ways to promote its credibility, salience and legitimacy through dividing tasks, roles, and responsibilities for separate scientific and education goals and protecting local autonomy community assets;

ii. *Aligning boundaries.* This acknowledged the "permeability" of boundaries that were aligned and intentionally coordinated by coordinators for improved uptake of citizen science and localised knowledge, and involved the use of boundary spanners and boundary objects;

iii. *Reconfiguring boundaries.* This highlighted the efforts by actors to manipulate or arrange boundaries to bring people, ideas or practices into new alignments. This was achieved through the creation of spaces for learning and interaction. This form of boundary work was practised in cases where low levels of institutional support for citizen science required novel strategies to improve the practice's legitimacy in waterway governance.

The findings suggest that the ways in which boundaries between community and government are brought together can have implications for the scientific and transformative

potential of citizen science. Furthermore, the comparative nature of this study highlights the socio-cultural, environmental and organisational factors that create more or less permeable and rigid community-governance boundaries. The article concludes with practical recommendations in thinking about boundaries in citizen science, including a call for more in-depth studies on the relational dimensions of citizen participation in science.

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In the following chapters (5-8), the full research articles are presented. Together, the insights gained from this body of work validated the application of the relational research framework developed in Chapter 2. Importantly the insights and understandings captured and presented in these articles provided a mechanism to answer the core research question set for this study.

5 Citizen science in Australia's waterways: investigating linkages with catchment decision-making

5.1 Abstract

Citizen science can be a viable mechanism to foster productive linkages between community and government for sustainable water resource management. In Australia, this potential has longstanding policy support but research into program extent, characteristics or impact on decision-making processes has been lacking. This article draws on a temporal analysis of data records from two citizen science programs and a nationwide survey of program coordinators (n=47) representing 43 freshwater and estuarine citizen science programs to examine these knowledge shortfalls. Results indicate that program activity has contracted in Victoria but increased in the ACT, with additional evidence indicating a nationwide contraction. Survey results revealed programs operating nationwide and largely implemented as a community-government partnership combining data and educative-priorities. Despite 70 per cent of programs having goals to inform catchment decision-making, data use was verified for less than half of programs. Program coordinators reported several social, organisational and technical barriers that limit this uptake. In highlighting these issues, we make three recommendations for enhancing linkages between citizen science and catchment decision-making: (1) increasing institutional support; (2) improving coordination and embrace new possibilities for collaboration; and (3) demonstrating and communicating program achievements.

5.2 Introduction

The need for practical and effective links between the public, science and policy is a widely discussed theme in sustainability and water resource management literature (Carr 2015; Reed 2008). In Australia, the past three decades have witnessed the emergence of diverse participatory programs and strategies that include the public in the management of natural resources (Curtis et al. 2014). These initiatives range from those that provide information to, or seek input from, interested or affected stakeholders, to more resource–intensive programs that build active and connected communities (Dean et al. 2016). As part of this broader development are longstanding efforts to support public involvement in the collection and analysis of water condition data, commonly referred to as 'citizen science' (Irwin 1995, Bonney et al. 2009). In recent years, citizen science has grown in prominence as a viable mechanism to improve water resource management and foster productive linkages between community and government (Buytaert et al. 2014, McKinley et al. 2017, Nascimento et al. 2018, Turrini et al. 2018). However, whether and how these linkages form is an under-researched area, particularly in Australia.

In water environments, citizen science has historically functioned to build skills and raise community awareness around waterway issues through a combined process of participatory learning and scientific inquiry. This form of citizen science is otherwise labelled 'volunteer monitoring' or 'community-based monitoring' (Buckland–Nicks, Castleden, and Conrad 2016; Deutsch and Ruiz–Cordova 2015), and has been informed by the principles and practices of 'participatory action research' and 'community science' (Carr 2004; Cooper et al. 2007). In recent years, the popularity of citizen science has brought about a wide array of new projects in a variety of environmental contexts (Pocock et al. 2017), largely driven by advances in technology to support data collection, management and dissemination (Newman et al. 2012). The current suite of citizen science projects reveals a diversity of approaches, methods of data collection and multifaceted objectives, including the provision of data, policing environmental threats or education and engagement (Kinchy et al. 2014). Projects enlist participants at varying levels of engagement, ranging from 'contributory' projects that involve volunteers in data collection, to 'collaborative' and 'co-

created' forms, which involve participants in more steps of the research process and tend to produce deeper engagement due to their focus on local issues (Shirk et al. 2012).

Despite an increasing body of research demonstrating citizen science can make significant achievements in advancing ecological research (Dickinson et al. 2012), its uptake in environmental decision-making has been slow (Conrad and Hilchey 2011, Hecker et al. 2018a). As such, the issues and opportunities of citizen science at the science-policy interface have become a critical point of exploration and review (Ballard et al. 2017; Carlson and Cohen 2018; Chapman and Hodges 2016; Hyder et al. 2015; McKinley et al. 2017). A central focus in this research is on the potential for data collected by volunteers to shape policy and resource management outcomes. If volunteer data collection is supported by sufficient training, data validation and effective quality control, then the data have the potential to identify environmental problems, assess conservation activities, inform and evaluate policy, and meet legislative and statutory agreements (Stepenuck and Genskow 2018a). While not all citizen science projects will have such goals, nor will they be suitable for these purposes (Bonney et al. 2016), emerging research shows particular promise for contributions within place-based projects aiming to affect local decision-making (Newman et al. 2017).

Beyond its scientific dimensions, citizen science is regularly promoted as a tool for empowerment and behaviour change, with the potential to lead to more transparent and inclusive government processes (Nascimento et al. 2018). Public engagement in research and monitoring activities can raise environmental awareness, strengthen connection to 'place', improve scientific literacy and build social capital, among other benefits (Haywood 2016). These opportunities can empower communities to use the tool of science as an effective and structured method for communication of local environmental concerns (Pfeffer and Wagenet 2007). For example, a study by Storey et al. (2016) on volunteer stream monitoring in New Zealand showed participants became more confident and better equipped to engage in conservation action as a result of their participation. In addition to enhanced civic engagement, volunteers are increasingly recognised as possessing valuable local knowledge that can guide program operation, such as choosing relevant and accessible sites for

monitoring, and influencing the development of research questions in a way that aligns with community interests, needs and expectations. (McKinley et al. 2017).

The data- and engagement-related benefits of citizen science described above represent two distinct, but mutually reinforcing, pathways through which citizen science can impact environmental decision-making (McKinley et al. 2017). However, the realisation of each pathway is not supported by a substantial body of evidence, leading several researchers to call for more focused attention on the contributions of citizen science decision-making, including the factors that permit meaningful and effective citizen participation and data contributions (Conrad and Hilchey 2011, Stepenuck and Green 2015). These knowledge shortfalls are particularly acute in Australia, despite longstanding investment and strong rates of participation in community-based monitoring (Thomson 2007). Australia, therefore, provides a rich case study to examine the issues and knowledge gaps identified above and is the focus on this article.

5.3 The historical context of freshwater and estuarine citizen science in Australia

In Australia, the history of freshwater citizen science is largely a story of Waterwatch3, a community-based water monitoring initiative that has operated for about three decades. The national Waterwatch program emerged in 1993 due to both rising public environmental concern and also government policy to educate and engage the community in water management issues. The program was underpinned by two interconnected themes: participatory learning for sustainability and community-based monitoring of water quality and aquatic habitats (Thomson 2007). It was built on a flexible framework so that it responded to the local biophysical and social contexts in the respective region of implementation with regional coordinators employed to support monitoring activities.

[3] While Waterwatch is the main focus in this historical account, the paucity of documentation on similar programs limits discussion of new or existing programs.

Waterwatch has maintained a longstanding commitment to educate and involve the public in the management of water resources by raising environmental awareness and promoting positive stewardship behaviours. Program goals extended beyond these educative dimensions to include the collection of useful, credible and accepted data to underpin catchment decision-making several years after its establishment (Waterwatch Victoria 2000). Interest by scientists and government agencies in exploring the utility of volunteer-collected data can be traced as early as the year 1999. For example, Finlayson and Mitchell (1999) advocated for wetland conservation to explore the use of community participation in monitoring wetland condition, not only to act as an early warning for pollution impacts but also to improve communication between wetland researchers, managers and the local communities. More recently, government environmental policy at all levels explicitly states a commitment to support community-based water monitoring initiatives for its knowledge generation benefits (DEPI 2013; ACT Government 2014). However, efforts to link data with management actions and policy development have historically been hindered by perceptions that community-collected data is inferior to professional data (Wilson 2002). In response, Waterwatch has worked to improve the alignment between community and professional data by implementing data confidence plans, regular training and quality assurance and quality control (QA/QC) procedures. Moreover, the level of resistance to the use of volunteer-collected data does not align with emerging evidence demonstrating citizen science water quality data can be comparable to professional approaches (Fore et al. 2001, Nicholson et al. 2002, Storey et al. 2016).

In 2008/9, changes to federal natural resource management funding arrangements meant Waterwatch programs were supported through a regional delivery model, which had a significant initial impact on program stability (Thomson 2007). These changes were felt across the spectrum of community-based natural resource management programs, weakening engagement and reducing support from natural resource management (NRM) bodies (Robins and Kanowski 2011). Ongoing funding challenges have highlighted the necessity of strong partnerships with local, regional and state government agencies, non-government organisations and industry (Hardie et al. 2009). These partnerships not only

assist in funding opportunities, but they also provide programs with greater credibility and capacity to integrate within monitoring and decision-making frameworks.

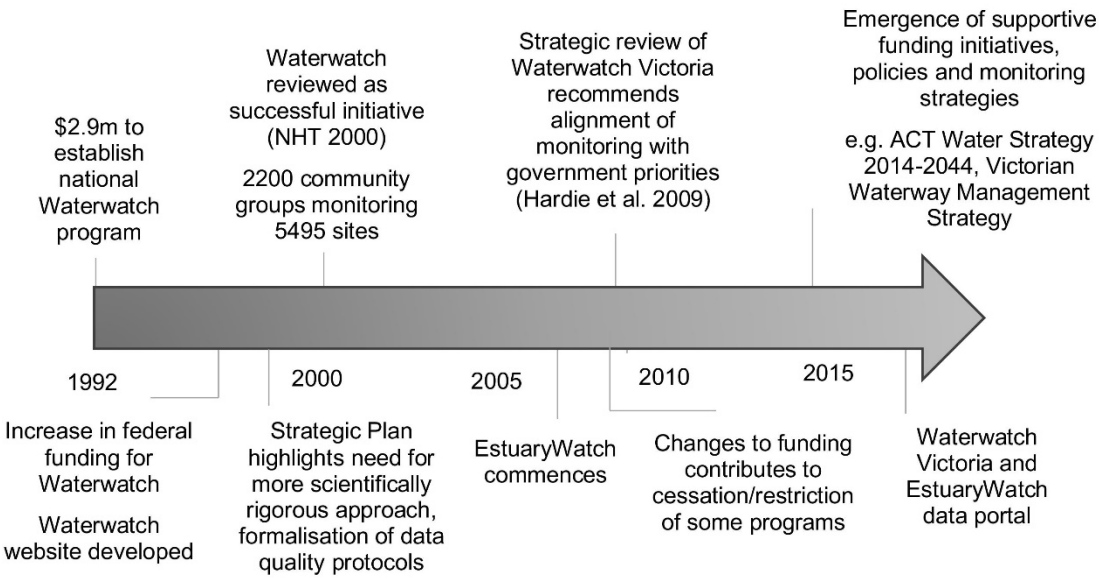

Figure 4. A timeline of major events in the history of the community-based water monitoring program, Waterwatch.

Despite undergoing various developmental phases (Figure 4), Waterwatch has not been supported by sufficient research attention on program characteristics, spatial extent and influence within catchment decision-making. Some early studies investigated the principles and conditions of effective environmental stewardship, including community-based monitoring programs (Carr 2002), the experiences and empowerment of volunteers in catchment groups (Gooch 2004), and the community-agency interactions that influence community research activities (Thomsen 2008). However, these studies predate the recent and widespread interest in citizen science (e.g. Pecl et al. 2015), including the associated advances in technology to support participation and improve data management (Newman et al. 2012). Therefore, renewed investigation into the extent and influence of freshwater and estuarine programs is critical if programs are to realise their full potential in contemporary water resource management that is increasingly characterised by community partnerships and multi-actor coordination.

5.4 Methods

The central aim of this research was to conduct a comprehensive assessment of freshwater and estuarine citizen science programs in Australia using an approach comprising two methods. First was an analysis of program data records from two freshwater citizen science programs to establish how program activity and volunteer participation has changed over time. The second was an online survey distributed to all freshwater and estuarine citizen science program coordinators with three key aims:

i. to build a baseline understanding of the extent, characteristics, diversity of objectives and partnership structure across the network of programs in Australia;

ii. to document and review examples of data contributions to catchment decision-making, including factors that influence data uptake,

iii. to explore the extent to which volunteers, through their participation, influence program operation and actively participate in catchment decision-making.

5.4.1 Program activity analysis

An initial investigation to determine how program activity has changed over time was conducted on two longstanding freshwater citizen science programs, in Victoria (*Waterwatch Victoria*) and the Australian Capital Territory (*Upper Murrumbidgee Waterwatch*). Both programs consist of multiple sub-programs hosted by regional natural resource management (NRM) bodies, water utilities or catchment coordinating committees. The ten sub-programs in Victoria and the four sub-programs in the ACT provide their data to centralised databases for storage and analysis. We collated these data and examined temporal trends in monitoring activity for each program using the total number of data records and unique monitoring sites annually since program inception as a proxy for program activity and volunteer participation over time. Data records were analysed only if they were from natural waterbodies e.g. lakes, rivers, wetlands and estuaries. Sites were excluded if they were marked as groundwater sites, household dams, rainwater tanks, constructed channels or stormwater drains.

5.4.2 Survey

To understand the characteristics and contributions of freshwater and estuarine citizen science programs, a survey of individuals in coordinating roles was conducted between March and April 2018. Coordinators were chosen as participants since they occupy a central position citizen science networks and hold comprehensive insights into project issues and opportunities. To recruit participants, emails were sent either to organisations supporting freshwater or estuarine citizen science initiatives or directly to coordinators, as identified through an extensive web search and existing professional networks. These were the most effective recruitment methods since, at the time of the survey design and implementation, a comprehensive list of known freshwater and estuarine citizen science projects in Australia was not available. The study was also promoted through other channels, including natural resource management email lists and newsletters and through the professional networks of program coordinators. In cases where a coordinator or organisation did not answer the survey request, two rounds of follow-up requests were sent via email at two-week intervals after initial survey deployment. The survey was available online using the software LimeSurvey (LimeSurvey GmbH).

Survey requests were sent to 61 freshwater and estuarine citizen science programs across Australia. Of these, 47 coordinators representing 43 programs from all states and territories in Australia responded to the survey, for a response rate of 77 per cent. It was most common for a program to have one coordinator facilitating monitoring and research activities. However, one program had five dedicated coordinators (four of whom took part in this study) each coordinating activities in separate regions. These four coordinators were treated as separate respondents unless otherwise stated. Another program involved a network of four subprograms located within separate catchment groups.

The survey comprised 38 questions seeking coordinator responses on three categories: (1) general program characteristics, (2) program interactions and partnerships, and (3) program and volunteer contributions to catchment decision-making (Table 5). The program characteristics analysed included monitoring duration, goals, number of volunteers, number of monitored sites, water condition indices collected, geographic focus and training and

quality assurance and quality control (QA/QC) protocols. Questions related to interactions and partnerships sought information from coordinators about the organisations and institutions with whom their program interacted in the past year. For the purpose of this study, an interaction was defined as a 'one-off' or ongoing exchange of ideas or advice, training, collaboration on projects, sharing data and resources or receiving funding. Respondents were asked to name up to three organisations within seven organisational categories and report the importance of these interactions for achieving their program's goals. We limited responses to three organisations per category to reduce survey burden and expected this would capture a majority of their interactions. The final questions assessed the ways in which volunteers influence program design and implementation, and actively participate in decision-making processes.

Table 5. Survey categories and questions for coordinators of freshwater citizen science programs in Australia.

Survey category	Survey questions
General program characteristics	Monitoring years Goals Number of active volunteers Number of sites monitored in the past year Geographic focus Biological, chemical or physical indicators collected Level of volunteer involvement in monitoring steps Implementation of training, QA/QC protocols
Interactions and partnerships	Program interactions with organisation or institution (federal or state environmental management department, local council non-government organisation (NGO), NRM board or Catchment Management Authority (CMA), other community or citizen science group, TAFE or University, museum or zoo, primary or secondary school, and 'no interactions') Nature of interaction (exchange of ideas or advice, training, collaboration on projects, sharing data and resources or receiving funding) Importance of interactions and partnerships for achieving goals
Contributions to catchment decision-making	Data uptake in decision-making Type(s) of data uptake Perceived influence on decision-making Barriers to data uptake Volunteer participation in decision-making processes Volunteer influence on program operations

Data contributions to catchment decision-making were assessed using three measures. First was the assessment of claims of data uptake from coordinator reports as part of the survey. Second, the provision of evidence of data uptake (in the form of documentation, links to web pages etc.) was sought from coordinators. This provided a mechanism to overcome the potential influence of social desirability bias among respondents (Nederhof 1985), which was identified as a methodological issue in a similar study on citizen science uptake in natural resource management (Stepenuck and Genskow 2018b). Social desirability is the tendency for respondents to report positively about their program's impacts on decision-making even if no, or tenuous, linkages were achieved. The third measure was an independent web search of program websites and program-specific documentation to investigate additional instances of data uptake. The purpose of this third measure was to (1) cross-validate statements about data use by coordinators that lacked detail or were not supported by any form of documentation and (2) ensure the capture of a comprehensive assessment of the use of volunteer data for water and catchment decision-making. To explore factors important in determining data uptake, we established relationships between the uptake of program data in decision-making (i.e. yes versus no) and (1) number of volunteers per program, (2) number of sites monitored per program, (3) longevity of monitoring and (4) number of organisational interactions. We excluded schools from this assessment because these interactions were not considered important in determining a program's capacity to contribute data to inform decision-making. We did not undertake statistical testing to confirm these relationships as this was an exploratory study, and we lacked adequate statistical power given the limited sample size.

5.5 Results

5.5.1 Program activity

Trends in program activity over time were found to differ between Waterwatch Victoria and Upper Murrumbidgee Waterwatch. For Waterwatch Victoria, total records and number of

monitoring sites showed an initial increase from program inception in 1993 to 1998, then plateaued for approximately eight years before reaching a peak in 2007 for 10,063 total records and 1571 unique sites monitored across the state (Figure 5a). During the past decade, program activity has declined and, as of 2017, Waterwatch Victoria is operating at approximately 40 per cent of the peak period. In contrast, the Upper Murrumbidgee Waterwatch program had relatively slow uptake in its first ten years of development showing a notable increase in total records and sites monitored after 2006, reaching 1887 total records and 231 sites monitored in 2017 (Figure 5b).

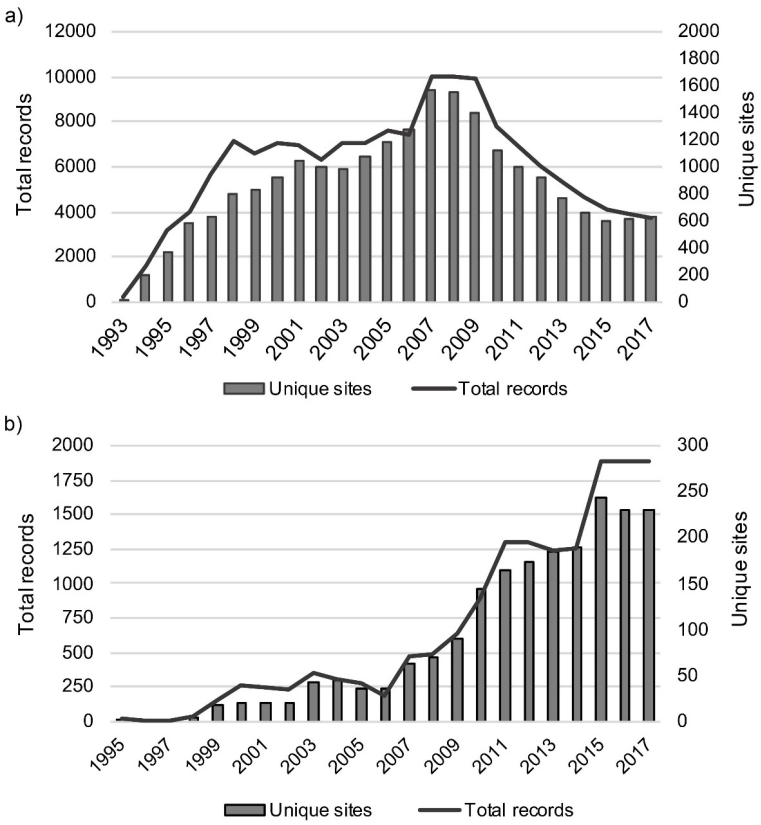

Figure 5. Total number of records and unique sites monitored per year for (a) Waterwatch Victoria and (b) Upper Murrumbidgee Waterwatch since inception.

5.5.2 Survey

5.5.2.1 Program characteristics

Findings show programs are mainly affiliated with local, regional or state government (51%) and catchment groups and coordinating committees (31%). Approximately 10 per cent were

community-led programs and one program emanated from a university. Programs were largely concentrated along the eastern and south-eastern coast of Australia (Figure 6).

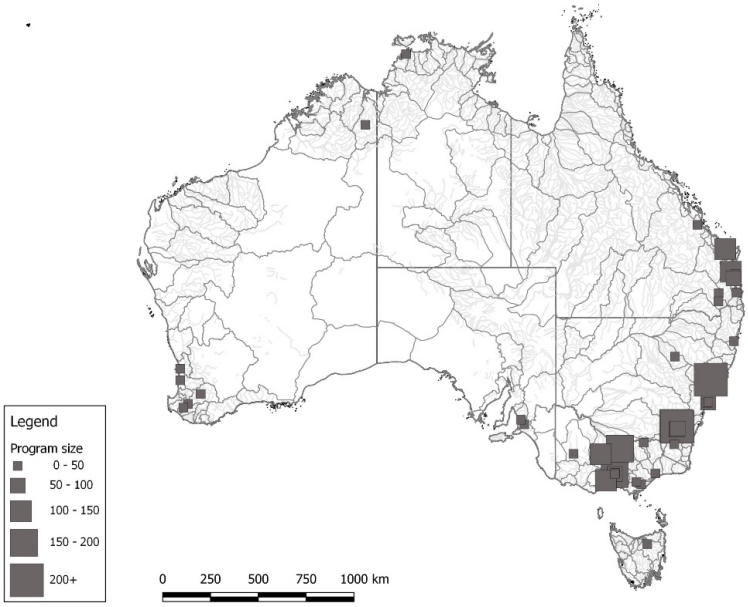

Figure 6. Location and size of programs across Australia by postcode. Size of squares represents the number of sites monitored in 2017.

Program size varied considerably, with total active volunteers and sites monitored reported to range from 2 to 240 and 1 to 300, respectively. Approximately half of coordinators reported their program have been collecting water condition data for more than 20 years while ten programs (21%) had been in operation for five years or less (Figure 7a). Most programs were focused on monitoring at a local to regional level with no programs operating nationally or internationally at the time of data collection (Figure 7b).

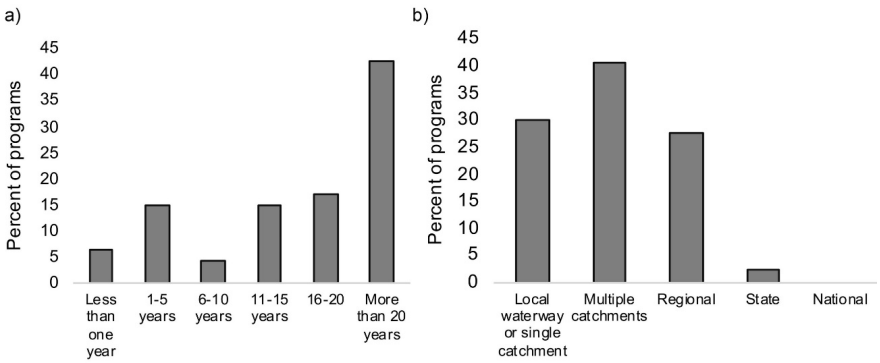

Figure 7. (a) Program longevity and (b) geographic focus of monitoring of freshwater and estuarine citizen science programs in Australia (n = 47).

Many programs monitored more than one type of waterway. Most programs were found to monitor rivers (89%), followed by lakes/reservoirs (53%), wetlands (51%) and estuaries (23%). There were also some reports of programs monitoring groundwater and constructed waterbodies. Coordinators reported data collection for a wide range of water condition indices, with the most common being physicochemical parameters (Figure 8). Almost half of coordinators reported that their program monitored the physical and riparian habitat (e.g. flow, sediment size or riparian cover) (51%) and macroinvertebrates (51%), while the monitoring of other aquatic taxa (frogs and platypus) was less common.

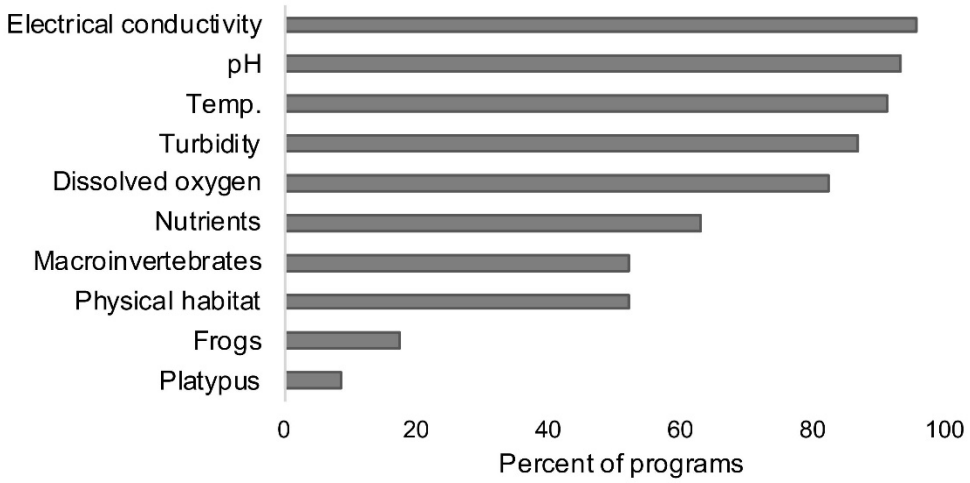

Figure 8. Water condition indices collected by freshwater and estuarine citizen science programs in Australia (n = 47).

5.5.2.2 Program goals

Table 6 shows the priorities of programs, with all but four coordinators reporting multiple goals. A majority of coordinators identified a combination of education and data-related goals. Educating and engaging the community was reported to be the main priority for a majority of programs (87%), followed by goals relating to the collection and use of waterway monitoring data. Nineteen coordinators reported their program had priorities to investigate the outcomes of a management effort (40%) while answering a particular research question was reported by just seven programs (15%).

5.5.2.3 *Training, data quality assurance and control and monitoring protocols*

Many programs had in place processes to ensure the collection and delivery of high-quality data. These included volunteer training (96%) with its frequency varying across programs, from once per year to on a needs basis i.e. as new groups/projects begin. A high proportion of programs were found to implement data quality assurance and quality control procedures (83%) and use of government (or government-endorsed) data collection standards (60%).

Table 6. Goals of freshwater and estuarine citizen science programs as reported by program coordinators.

Program goals	Number of programs	Percent (%)
To educate and engage the community	41	87.2
To obtain data useful to inform management decisions and policy	33	70.2
To create long-term data sets on a particular waterway	29	61.7
To address a lack of monitoring / waterway data	25	53.1
To monitor a perceived environmental threat (e.g. pollution, impacts of a development)	22	46.8
To investigate the outcome of a restoration or other management efforts	19	40.2
To use monitoring data to obtain funding for natural resource restoration and protection	14	29.8
To answer a research question	7	14.9
To investigate an environmental crisis	4	8.5

5.5.2.4 *Program interactions and partnerships*

Table 7 reveals the program interactions and partnerships with other organisations and institutions, including the purposes of these connections. Programs most commonly interacted with primary and secondary schools (81%) followed by local councils (72%), federal and state environment departments (60%) and other community environmental groups or other citizen science programs (60%). Less common interactions were with private companies (32%) and museums and zoos (15%). Three programs reported no interactions. Interaction purposes varied according to organisation type. For example, it was more

common for programs to receive funding from federal or state environmental departments than it was for local councils to provide financial support. Moreover, programs exchanged ideas and advice with other community and citizen science groups at greater extents than with government departments.

Table 7. The extent and purposes of organisational interactions and partnerships

Organisation	n	%	Purpose of interaction (as a percentage of n)				
			Exchange of ideas or advice	Training	Collaboration on projects	Sharing data and resources	Receiving funding
Primary or secondary school	38	80.9	31.6	55.3	34.2	42.1	0
Local council	34	72.3	67.6	17.6	50.0	52.9	23.5
Federal or state environmental management department	28	59.6	53.6	21.4	50.0	60.7	50.0
Other community or citizen science group	28	59.6	76.0	40.0	56.0	44.0	4.0
NRM board or Catchment Management Authority	25	53.2	57.1	17.9	53.6	46.4	32.1
TAFE or university	25	53.2	60.0	40.0	48.0	56.0	12.0
Non-government organisation (NGO)	23	48.9	53.6	25.0	53.6	46.4	3.6
Private organisation or company	15	31.9	47.8	17.4	43.5	39.1	13.0
Museum or zoo	7	14.9	20.0	0	20.0	20.0	0

5.5.2.5 Types and extent of data uptake

To investigate linkages between community data and decision-making, coordinators were asked questions about their program's contributions to, and perceived influence on, catchment management and policy development. For programs whose coordinator claimed data-related priorities (n=45), approximately half reported 'some' influence (n=23) on catchment decision-making while 38 per cent reported having 'little' or 'no influence' (n=17).

No coordinators reported that their program had 'extensive' influence on catchment decision-making.

Coordinators from 24 programs claimed their program's data was used in catchment decision-making, while approximately 11 program coordinators reported no data uptake and eight coordinators were "not sure." After collecting and collating data use instances through documentary analysis and independent web searches, a revised total of 19 programs had verifiable evidence of data uptake. Evidence of data use came in the form of management reports, internal and program-specific reports, policy and planning documents, monitoring frameworks and webpages. There were instances in which positive claims about data uptake were unsubstantiated (n=5), as well as instances in which examples of data use were found for programs whose coordinators reported 'no' or 'not sure' when asked whether their program had achieved data uptake (n=5). One respondent was unwilling to provide evidence of data use even though this program had on a number of occasions identified an environmental problem that was raised with stakeholders for resolution. Their reasoning was that it was not appropriate to publicise examples as it would undermine the "pro-active, non-regulatory approach" undertaken by the organisation.

Instances of data uptake were categorised as per a typical adaptive management framework, with findings as follows: (1) strategy and planning (9 per cent of total programs with data-related priorities), (2) monitoring and implementation (27%) and (3) reporting and evaluation (24%) (Table 8, for full list see Appendix F). In the evaluation and reporting category, volunteer data were used for resource condition reporting, impact evaluations against policy targets and annual reporting of management activities. Data uptake for monitoring and implementation related to the testing of assumptions and resource condition change due to external influences included several examples were reported where findings from program investigations triggered action by authorities e.g. pollution impacts. Data uptake in strategy, planning and policy development was least common.

Table 8. Data use by freshwater citizen science programs in Australia and applications in catchment decision-making. For a full list of impacts see Appendix F.

Data use category	Elaboration	Percent of programs (n=45)	Examples of documented cases
Strategy and planning	Regional planning Project/program planning Policy development	8.8% (n=4)	ACT Waterwatch (incorporating data from four subprograms) integrated citizen science data with government monitoring frameworks within the ACT Government's Environment Division for the Biodiversity, Research and Monitoring Program, the Conservation Effectiveness Monitoring Program and the ACT Integrated Water Monitoring Plan. Data from Waterwatch Manningham City Council used data collected across 20 sites in seven catchments to shape water policy including A Cleaner Yarra River and Port Phillip Bay Action Plan, Manningham Water Cycle Management Plan and Generation 2030. Platypus management plan used volunteer-collected data from the Melbourne Water Waterwatch program through an eDNA approach.
Monitoring and implementation	Monitoring and research to test assumptions Monitoring condition change and external influences	26.6% (n=12)	Use of data in a targeted monitoring program by Waterwatch South Australia Murray-Darling Basin investigating the effectiveness of Water Sensitive Urban Design (WSUD) infrastructure. Data collected by volunteers from Melbourne Water Waterwatch program on water quality in drought refuges important for the preservation of a vulnerable fish species, triggering emergency watering actions as dissolved oxygen levels in refuges reached critical levels. Waterwatch Goulburn-Broken Region undertook an intensive program of water quality monitoring in the Murray River upstream and downstream of the Barmah Forest to record the potential impact of management activities from the Barmah Forest floodplain. Volunteers measuring estuarine salinity levels and tracking mouth condition to inform estuary closure management. Measurement of environmental flow effects by Melbourne Water Waterwatch program influenced management actions to reduce public health risks following extensive blue-green bloom in a Victorian River. A citizen science projected conducted by FrogWatch investigated the relationship between frog species and habitat relationships in urban and peri-urban wetlands used data collected by hundreds of citizen scientists collected over more than ten years.
Reporting and evaluation	Resource condition reporting Impact evaluation against targets Annual reporting of management activities	24.4% (n=11)	Multiple programs prepare water quality information reports that detail catchment condition across a region commonly through a report card system. User of volunteer data in regional government annual reports. North Central Waterwatch used citizen science data to establish water quality trends to track the success of policy to improve fish numbers and habitat quality. Citizen science data from multiple Waterwatch Victoria subprograms has been used to supplement monitoring information for state of environment reporting such as Argent (2017), Index of Stream Condition (Ladson et al. 1999), Index of Estuary Condition and the Yarra and Bay Report Card (*https://yarraandbay.vic.gov.au/report-card).*

5.5.2.6 Factors influencing data impacts on decision-making

To understand which factors might influence the uptake of program data in decision-making, we explored the relationship between program data uptake and four factors: (1) volunteer numbers, (2) sites monitored, (3) program longevity and (4) extent of partnerships and organisational/institutional interactions. Our findings reveal that, generally, programs with greater numbers of volunteers and sites monitored have delivered impacts on catchment decision-making than smaller programs (Figure 9a, b). Additionally, program longevity appears to be important in determining whether a program has achieved data uptake (Figure 9c). Of the 20 programs that have been in operation for more than 20 years, 80% (n=16) have achieved some form of data use in catchment decision-making compared to only one in nine programs (11%) that have been in operation for less than 5 years. Finally, programs with a greater number of interactions were more likely to achieve data uptake than those programs with fewer interactions (Figure 9d).

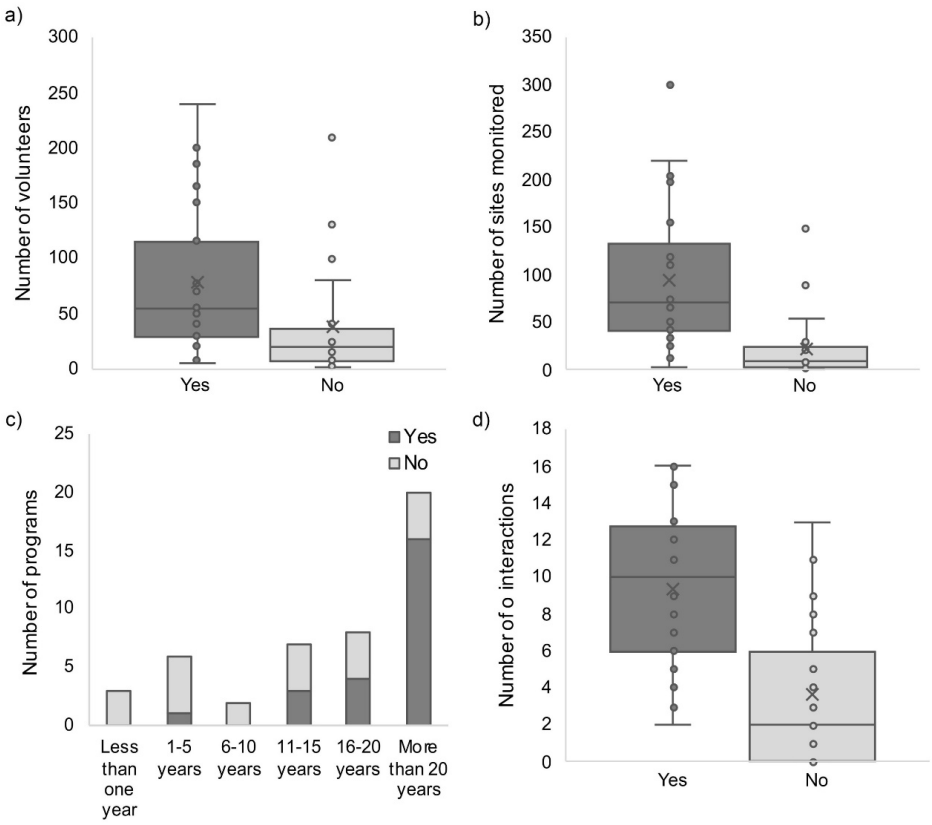

Figure 9. The relationship between the uptake of program data in decision-making (i.e. yes versus no) and (a) number of volunteers per program, (b) number of sites monitored per program, (c) longevity of monitoring and (d) number of organisational interactions.

5.5.2.7 *Barriers to uptake*

Of the 29 coordinators who reported the presence of barriers to data uptake, most common was the presence of funding and financial constraints and difficulties connecting and coordinating with decision-makers, followed by a lack of interest by decision-makers in volunteer-collected data (78%) (Figure 10). Data quality aspects of the programs that may limit uptake, such as accuracy, frequency of sampling and management procedures were lower level concerns. Many coordinators (46%) claimed that their data are viewed "somewhat receptively" by decision-makers, eight (17%) indicated that decision-makers were "very receptive" towards their data, and 37% responded with "neutral" or "somewhat sceptical." However, one coordinator cited an example of funding restrictions for their monitoring program due to a perceived lack of value of volunteer-collected data by the funding body.

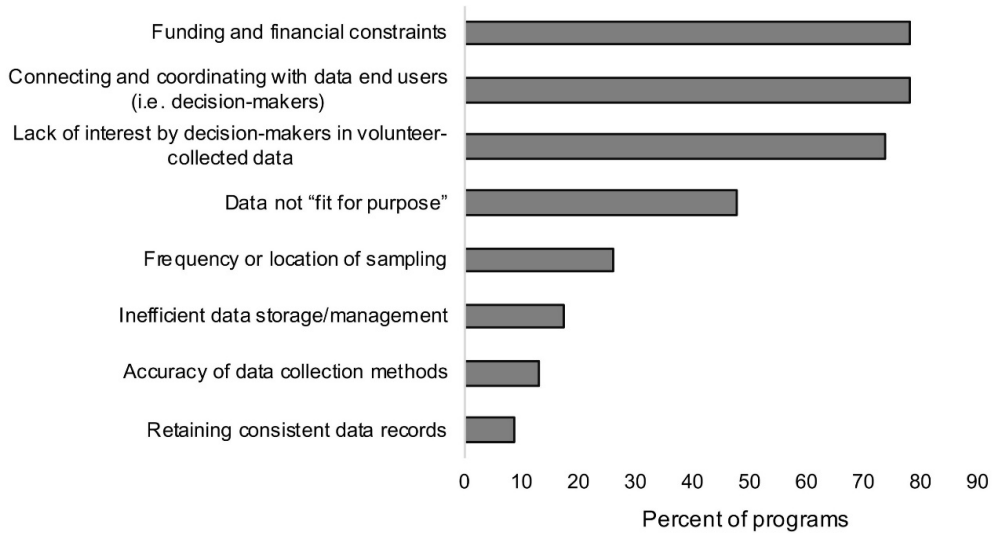

Figure 10. Barriers to data uptake as reported by program coordinators (n = 29).

5.5.2.8 *Volunteer impact and influence on program operations and participation in decision-making*

All programs involved volunteers in data collection, with site selection and data management a feature for more than half of programs (Figure 11). Participation in other aspects of the research process was less common. Approximately, 18 per cent of programs involved volunteers in developing research questions and 26 per cent participated in data

analysis. Only three coordinators reported that volunteers in their program were involved in all steps of the research process from developing research questions, collecting data to analysing and dissemination monitoring results.

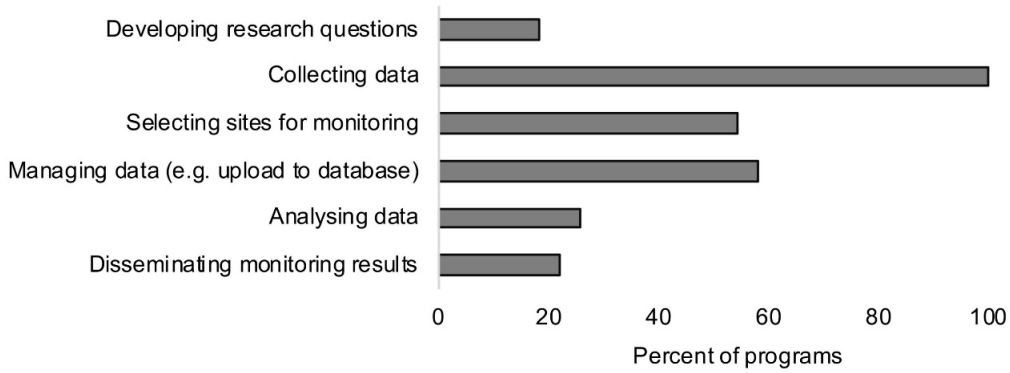

Figure 11. Extent of volunteer participation in the research/monitoring process.

The active involvement of volunteers in program operation and catchment decision-making was reported by coordinators in two open-ended questions, eliciting the following examples:

- volunteers' local knowledge was important in the selection of safe, accessible and/or scientifically relevant monitoring sites (23 of 43 programs);
- volunteers have prompted investigation by raising concerns about local environmental issues, including logging coups, septic leaks, pollution and excessive sediment impacts (5 of 43 programs);
- the presence of volunteers on advisory committees, working groups and leading community engagement initiatives (7 of 43 programs);
- instances of volunteers contacting environmental regulatory agencies, local council or water management authorities about their concerns (8 of 43 programs);
- one case involving a volunteer lobbying government for more funding for the monitoring program to continue and be able to disseminate results to the rest of the community.

5.6 Discussion

This broad review of citizen science projects conducting research and monitoring in Australia's waterways finds a diversity of projects operating nationwide. Despite this, evidence suggests a contraction in the size and scale of activities over the past decade. This claim is substantiated by analysis of program data records which revealed a steady decline in monitoring effort in Victoria since 2008. While the same analysis found monitoring effort in ACT to be increasing, the claim of a nationwide contraction is furthermore supported by previous reports on the extent of community-based monitoring activities that highlighted strong rates of volunteer participation in monitoring a large number of sites across Australia (Thomson 2007). This finding contrasts with studies in the United States and Canada where similar activities have increased in recent years (Jalbert et al. 2014, Carlson and Cohen 2018, Stepenuck and Genskow 2018b). The decline in program extent in Victoria appears to coincide with changes to federal funding, which has put pressure on the delivery of regionally-administered community-based programs (Robins and Kanowski 2011). This is a particular challenge for water-based citizen science projects whose activities are usually centred on the long-term collection of water condition data, which conflicts with governments having a short-term focus for community-based programs.

While programs differed considerably in their size and scope, a number of consistent characteristics were found in a majority of programs. First, many are affiliated with government environmental agencies and catchment committees with an expanded network of interactions and partnership with other organisations, including schools, universities, and local councils, among others. Second, volunteers are primarily involved in the long-term collection of water condition data, particularly physico-chemical and biological indicators in lakes, rivers, wetlands and some artificial waterbodies, such as storm water drains and irrigation channels. Third, many programs display considerable longevity with over half of programs collecting data in waterways for more than 15 years. Finally, over two-thirds of surveyed programs had goals of informing catchment management and policy in addition to the educative priorities that have long formed their primary remit. We uncovered few programs that emanated from universities, aimed to advance ecological research or were

entirely educational. Instead, the predominant model of freshwater and estuarine citizen science has not deviated substantially from the foundational principles and practices in early initiatives.

Perhaps the most significant development in freshwater and estuarine citizen science in Australia has been the increased attention towards integrating volunteer data within catchment decision-making. Despite this, less than half of programs with data-related priorities have experienced uptake of their data. Where it existed, data use for reporting and evaluation of resource condition and the investigation of management efforts was most common form. Programs have developed 'report cards' detailing baseline water quality or catchment condition (e.g. Bunn et al. 2010). Report cards provide a valuable communication tool about the status of water quality for future decision-making, but it is often unclear how they are subsequently used to inform 'on-the-ground' management practices or shape policy (Stem et al. 2005). More tangible links with decision-making were revealed in instances where programs triggered action, such as emergency watering of drought refuges, and local investigations of management efforts and external environmental influences. Engaging monitoring groups in place-based projects with clear aims and outcomes builds on the strong volunteer interest in the management decisions that affect local areas (Newman et al. 2017). It was far less common for programs to contribute data for strategy planning and policy development. Some examples showed volunteer data being integrated within government monitoring frameworks and being used to shape various environmental policies and underpin species management plans. In these cases, volunteer data were mostly used as a supplementary, rather than standalone, data source at a regional to state scale. The lower levels of data uptake for strategy planning and policy development could be related to recent evidence that suggested volunteer data is viewed less receptively for policy decisions than for natural resource management decisions, due to the perceived risks associated with relying on volunteer data for large-scale or long-term policy decisions (Stepenuck and Genskow 2018a).

Data uptake was found to be most common in larger projects, which have monitored water environments for a longer period of time and have developed a broad network of

interactions and partnerships with other organisations. Larger, long-term projects may have more resources, extensive datasets and time to develop productive connections that improve their capacity to make positive impacts on decision-making. We did not consider other factors known to be important in delivering positive impacts on decision-making, such as program objectives, level of financial support, data quality assurance plans and level of volunteer participation in the research process (Stepenuck and Genskow 2018a). We suggest continued investigation into the factors that enable citizen science contributions to catchment decision-making as a critical avenue of future research. Such investigations would likely benefit from in-depth studies using qualitative methods that engage with a wider breadth of actors in citizen science networks.

Our study provides evidence that volunteers actively participate in water management issues by, for example, raising environmental concerns with local agencies, participating on advisory committees and lobbying government for additional funding. These examples of civic engagement were reported by coordinators and opportunities to elicit information and experiences directly from volunteers should be pursued in future research. Further, this study is unable to provide clarity on the mechanisms related to this civic engagement and whether they are directly caused by participation in citizen science. Nevertheless, these emerging indicators are important to furthering the discussion about the extent to which citizen science promotes active engagement in environmental decision-making and strengthens relationships, which remains a key question for public participation advocates. This is particularly crucial since water policy in Australia specifies community engagement in water management and policy processes as a key priority (e.g. DEPI 2013; ACT Government 2014).

5.6.1 Enhancing linkages between citizen science and decision-making

The goals, characteristics and strong associations with NRM organisations shared by many freshwater and estuarine citizen science projects highlight their potential for productive linkages with water management and policy. While this study has provided evidence to suggest some programs are making positive impacts, the extent of data uptake remains

limited relative to the duration of community-based water monitoring and citizen science activities in Australia. This has been recognised as an issue for similar programs in other parts of the world and suggests that significant barriers limit data uptake for programs in Australia (Chapman and Hodges 2016). Respondents in this study identified difficulties connecting and coordinating with data end users and funding and resource constraints as the two main barriers to data uptake. Moreover, a lack of interest in volunteer-collected data was rated a significant barrier, suggesting continued hesitation in the use of citizen science in decision-making processes. This result is supported by over a third of coordinators indicating decision-makers were neutral or somewhat sceptical of citizen science data. The presence of strategies to assure high data quality in a majority of programs, and coordinators considering data accuracy as a relatively low-level concern, both suggest that social and institutional factors impeding the uptake of citizen science are just as relevant as scientific or technical barriers.

Based on these findings and building on insights in the citizen science literature, we propose three recommendations to enhance linkages between freshwater and estuarine citizen science and catchment decision-making: (1) increasing long-term institutional support and (2) improving coordination and embracing new possibilities for collaboration and (3) demonstrating and communicating program achievements.

First, the strong rates of participation in community-based monitoring and citizen science activities demonstrates a willingness by communities to act as stewards for their local areas but their efforts require adequate resourcing and supportive institutional cultures. Community-based programs in Australia have historically been challenged to undertake their work in the face of short-term funding arrangements, with an expectation to expend additional efforts to acquire further sources of funding (Ross et al. 2002). Program stability is therefore critical for project success and the satisfaction and empowerment of participants. As citizen science becomes increasingly accepted and institutionalised, the challenge will be how to maximise its contributions to decision-making while maintaining the diverse and distinctive benefits afforded to participants who often contribute large amounts of time and resources.

In Europe and the United States, the emergence of policies and strategies to facilitate citizen science contributions are examples of significant developments in the effort to build more supportive institutions (Shanley et al. 2019). For example, the C*rowdsourcing and Citizen Science Act of 2016* (15 USC 3724) is recent legislation that provides clarity to decision-makers about whether an agency can use citizen science for their work (Guerrini 2018). Similar developments are nascent in Australia and will be necessary steps if citizen science is to reach its full potential for policy. Some positive signs in this area include a recent citizen science funding initiative established by the Australian federal government's *Inspiring Australia Science Engagement Programme* (Sinodinos 2017). While the projects emerging from these new initiatives are encouraging, government departments should also maintain commitment to pre-existing freshwater and estuarine citizen science programs since they already comprise high stocks of human and social capital.

Second, our findings indicate that more effective coordination is needed between existing citizen science projects and decision-makers. Similar issues have been highlighted by other researchers who have consistently recommended communication between programs and decision-makers at early stages of project development to ensure data are collected within, rather than apart from, the decision-making frameworks (Aceves-Bueno et al. 2015, Chapman and Hodges 2016). This recommendation acknowledges the limitations of a 'linear or technocratic model of communication' and recognise that contemporary decision-making is a complex, multidimensional and social process (Young et al. 2014 p. 387). Improving coordination between citizen science projects and decision-makers requires clear articulation of the roles and responsibilities of all participants, sensitivity to stakeholder interests and motivations, the development of a shared vision with realistic expectations (Tulloch et al. 2013, Weston and Conrad 2015, McKinley et al. 2017). Further, this requires willingness on the part of policy makers to work collaboratively with new and existing citizen science projects (Conrad and Daoust 2008).

Furthermore, we echo calls for programs to improve collaboration by experimenting with new forms of participation (e.g. Hecker et al. 2018a). This study found that few programs enlisted volunteers in all phases of the research process, from devising research

questions, to collecting data and interpreting and disseminating results. One possibility to increase volunteer engagement is to undertake activities under the principles of 'co-created' citizen science (Shirk et al. 2012). Co-creation brings together scientists, decision-makers and community in a 'bottom-up', collaborative arrangement throughout the entire research or monitoring process, which can improve the social relevance of research efforts, strengthen relationships between stakeholders and may lead to stronger policy (Chapman and Hodges 2016, Hecker et al. 2018a). Despite having potential for greater depth of engagement, particularly for small, local catchment groups (Wilderman and Monismith 2016), practitioners should be aware that well-conceived and well-designed co-created citizen science can be time consuming, require significant levels of trust and can be difficult to implement if engaging with large numbers of participants (Chapman and Hodges 2016).

Finally, demonstrating and communicating program achievements should be integrated into program development to justify funding, attract additional resources, promote the development of new partnerships and reinforce the value of existing ones. This should also involve communicating how data were collected and the quality assurance and control procedures that promote confidence in the data. Furthermore, research suggests volunteer motivation is enhanced when they see that their efforts are valued by researchers, NRM bodies and private industry (Alender 2016), thereby increasing the stability of the program into the future. Instances of data uptake reported in this study are not likely to be a comprehensive list due to an underreporting by coordinators and a lack of documentation of all data contributions. It is also possible that when data are used for catchment decision-making, program coordinators and volunteers may not be aware of this use (Carlson and Cohen 2018). Therefore, the communication of data contributions, and program achievements more broadly, is critical and requires a two-way knowledge exchange between programs (including volunteers) and decision-makers (Jacoby et al. 1997).

5.7 Conclusion

With support for citizen science increasing in Australia, the present study responds to calls for increased understanding about the position and influence of citizen science in catchment

and water resource management (Conrad and Hilchey 2011; Stepenuck and Green 2015). We find that freshwater and estuarine citizen science in Australia is primarily a community capacity-building initiative with widespread potential for integration in government monitoring and community engagement policy frameworks. Our evidence shows citizen science data has been used for catchment decision-making, particularly for short term investigations and reporting on resource condition. Yet, program coordinators reported significant barriers that limit increased data uptake, which were largely social and organisational in nature rather than scientific and technical. We recommend that to improve the standing of citizen science in the context of water resource management, practitioners will benefit from focusing on the processes underpinning environmental decision-making, including coordinating activities to meet the data requirements of decision-makers, embracing new modes of collaboration i.e. co-creation, maintaining and furthering the development of partnerships with supportive organisations and institutions and demonstrating and communicating program achievements. By shedding light on the characteristics and contributions of programs monitoring water environments, we highlight the possibilities of citizen science as a meaningful and effective participatory approach to lessen the chasm between environmental management and the public.

6 Advancing citizen science practice through social network research

6.1 Abstract

Citizen science programs can be conceptualized as social networks involving the interactions between a variety of people and organisations. Studies across diverse research areas have consistently demonstrated that the social networks underpinning collaborative initiatives have important consequences. Yet, few studies have shown how citizen science actors are embedded in a social network and the implications of different network patterns and characteristics. This review discusses the conceptual and analytical utility of social network research for enabling investigations of the structure and function of citizen science social networks. We argue that this research perspective, which places relations and networks at the centre of investigations, can add novel insights into three critical issues in citizen science: (1) achieving data uptake; (2) promoting social learning; and (3) building empowered communities. In presenting these possibilities, we provide several entry points for future research. In practice, we envisage that social network research will help inform strategies to build influential and resilient citizen science programs. This potential is particularly relevant for those initiatives where partnerships exist between multiple actors working across different scales of governance.

6.2 Introduction

Recent decades have witnessed the emergence of citizen science as a key public engagement mechanism that involves members of the public in science learning and discovery (Irwin 1995, Bonney et al. 2009). The practice adds to a developing scientific culture that promotes transparent, participatory and socially relevant science and decision-making (Gallopin et al. 2001, Nowotny 2003). At the same time, the potential for citizen science to augment professional research and contribute to public education has led to further integration and support in government policy (Mackechnie et al. 2011, McKinley et al. 2017). Citizen science has been growing steadily in recent years with projects studying diverse environmental contexts and engaging volunteers at different levels of participation in the research process (Pocock et al. 2017). In parallel, social and scientific research continues to bolster interest and uptake of citizen science through demonstrating important outcomes for individuals, science and society (Conrad and Hilchey 2011, Dickinson et al. 2012, Stepenuck and Green 2015, Groulx et al. 2017).

Increasingly, citizen science involves a wide range of people and organisations who need to act collectively, often across well-established boundaries. Göbel et al. (2016) illustrated this diversity by conducting a qualitative stakeholder analysis of 16 citizen science projects and identified six stakeholder groups who regularly engage in project development and knowledge generation: (1) Civil society organisations, informal groups and community members; (2) Academic and research organisations; (3) Government agencies and departments; (4) Participants i.e. citizen scientists; (5) Formal learning institutions such as schools; and, (6) Businesses or industry. Similarly, Skarlatidou et al. (2019) demonstrated the utility of prospective and retrospective stakeholder mapping as a tool to enhance identification and engagement of multiple stakeholders in co-created citizen science. Both studies highlighted the similarities and differences in stakeholder groups and the importance of ensuring individual needs, interests and capacities are understood in project planning and development. However, recent research investigating social networks in environmental governance suggests that generalizing group membership in such a way

fails to capture the influence of complex patterns of informal relationships within and between groups (Bodin et al. 2011).

If citizen science is to succeed in developing stronger linkages between science, society and policy, then building and maintaining effective social networks becomes central to this effort. A vast body of sociological research has demonstrated the importance of social networks in shaping the lives of individuals, from their attitudes and behaviour, to their access to resources and information (Pescosolido 2006). Social networks enable people and organisations to communicate, coordinate activities and share knowledge. They are a key element of trust and social capital and support collective action, social movements and voluntary associations (Diani and McAdam 2003, Bekkers et al. 2008, Henry and Vollan 2014). This literature also underscores their potential negative consequences, whereby social ties can 'imprison actors in maladaptive situations or facilitate undesirable behaviour' (Borgatti and Foster 2003 p. 994). Despite the role and importance of social networks, how they form and function in citizen science to shape programs and participants is poorly understood and presents an important avenue for future research.

A social network perspective offers a promising way forward to examine citizen science networks, for example, by investigating how patterns and characteristics of social relations in a given network enable and constrain actors and their actions (Bodin et al. (2011). These patterns of relations are systematically quantified and visualized using the tools afforded by social network analysis (Wasserman and Faust 1994). Social network analysis has demonstrated significant utility in studying and explaining various social phenomena across numerous disciplines, such as anthropology, criminology, public health and organisational practice (Freeman 2004). The recent uptake of social network analysis in environmental governance has advanced understanding on information diffusion, power relations, and different group structures and their influence on individual behaviour (for a review on outcomes see Groce et al. 2019). Its use in citizen science has the potential to bring about similar advances since both citizen science and environmental governance study related concepts, such as participation, collaboration, capacity-building, social-ecological resilience and learning for sustainability.

A social network perspective offers researchers an alternative lens through which to study citizen science – one that centres investigations on the structure, meaning and consequences of social relationships. Practically, its use provides a way to understand the degree of connectivity in citizen science programs, identify relevant stakeholders and the implications of different network patterns and characteristics. In building this insight, key questions could include: How does network structure affect the quality and quantity of volunteer participation? How do social networks influence data flows and application? How can social networks be strengthened to increase participant learning, behaviour change and civic engagement? Answers to these types of questions can help inform the delivery of strategies that ensure ideal program design and performance (Holman 2008). Social network analysis may be particularly valuable for placed-based citizen science projects where in-person participation and collaboration between multiple individuals and organisations are characteristic features (Bliss et al. 2001, Newman et al. 2017, McKinley et al. 2017). However, empirical work and methodological guidance in this area is currently lacking.

In this paper, we provide an overview of a social network perspective and its potential for citizen science research and practice. We begin by conducting a literature review on citizen science studies that emphasise the role and importance of social networks to consider their present use and conceptualise their functions (section 2). We then provide background to the key principles and concepts of a social network perspective (section 3). The final section considers how the application of this perspective can benefit investigations of three current issues in citizen science: achieving data uptake, promoting social learning, and building empowered communities (section 4). This overview of social network approaches does not intend to be exhaustive, but rather illustrative of the strong potential of a relational perspective to shed light on critical questions within citizen science.

6.3 Citizen science and social networks

6.3.1 Review process

To examine how social networks have been conceptualized in citizen science research, we reviewed relevant literature up until September 2019 using Scopus and Web of Science

online databases. We used the advanced search function of these databases and combined two sets of terms:

> TS = ((“citizen science” OR “community-based monitoring” OR “participatory monitoring” OR “volunteer monitoring” OR “community science” OR “community-based research” OR “public participation in scientific research”) AND (“social network” OR “network analysis” OR “social relationship*”, OR “social capital” OR “social learning” OR “collective action” OR “partnership” OR “collaboration” OR “collaborative governance” OR “co-production”))

The abstracts of each paper were scanned for key words and included if they met the following criteria: (1) studied citizen science as it relates to the involvement of members of the public in scientific research or monitoring; and, (2) emphasised the emergence, role and importance of social networks and/or relational processes and concepts. We excluded papers that discussed social media networks. Further, we confined papers to those documenting environmental citizen science, since it is environmental and natural resource management contexts where social network analysis has recently demonstrated significant utility (Bodin and Prell 2011).

6.3.2 Review findings

Our review discovered that social networks in citizen science shape a program in diverse ways. Three categories appeared most relevant: (1) facilitating social processes, (2) achieving individual and program outcomes and (3) building social attributes (for examples see Table 9; for full list of studies see Appendix G). First, social networks were considered to lay the structural foundations for critical social processes such as promoting social learning (Fernandez-Gimenez et al. 2008), enabling coordination and collaboration (Nerbonne and Nelson 2008), communicating results to others (Sayer et al. 2015), and facilitating information exchange (Becker et al. 2005, Nerbonne and Nelson 2008, McGreavy et al. 2016). Second, social networks were important to a range of individual and program outcomes. At the individual level, social networks were linked to attitude and behaviour change (Chase and Levine 2018), motivations (Cappa et al. 2016, Carballo-Cardenas and Tobi 2016, Martin and Greig 2019), self-efficacy (Johnson et al. 2014), and access to actors in positions of power (Overdevest et al. 2004). At the programmatic level, social networks improved uptake of

community data into decision making (Fernandez-Gimenez et al. 2008, Nerbonne and Nelson 2008, Villaseñor et al. 2016, Stepenuck and Genskow 2018a), support for conservation initiatives through information diffusion (Forrester et al. 2017), and program stability, longevity and recruitment (Bell et al. 2008). Finally, the building and strengthening of social networks were considered to have important implications for the attributes of citizen science networks as a whole, namely for trust and social capital (e.g. Becker et al. 2005, Pollock and Whitelaw 2005, Conrad 2006, Nerbonne and Nelson 2008, Bremer et al. 2019).

Researchers conceptualised social networks rather loosely and rarely as an object of empirical study. It was most common for researchers to use social networks as a metaphor whose presence (or absence) had important consequences. Few studies sought to actively describe or quantify specific patterns of relations that make up a social network. Only one study to our knowledge has investigated citizen science by giving primacy to social relations and their influence on individual and program benefits (Richter et al. 2018). This study examined the embeddedness of individuals in a butterfly monitoring scheme to understand drivers of long-term participation. Using social network analysis, their findings highlighted the vital role that central coordination and peer support played in personal satisfaction and engagement. Other studies have been less analytical and more descriptive in highlighting specific network characteristics that positively shaped activities. For example, Overdevest et al. (2004) described how volunteer stream monitoring programs create more 'dense' networks of participants that served to build social capital and enable individual political participation and promote program stability.

Our review also revealed that researchers seldom examined the negative consequences of social networks. Instead, the functions of social networks were regularly considered in a positive light with the exception of two studies. First, Conrad (2006) discussed possibilities for a breakdown in social cohesion when structural barriers limit community-based monitoring groups' ability to communicate and deliver monitoring results to decision-makers. Second, Ellis and Waterton (2004) showed that project organisers and collaborators were highly prescriptive in the nature of volunteer participation by limiting volunteer

interactions to data transfer only. They suggest that prescribing the boundaries of participation may limit other opportunities for volunteers to be 'active agents in science and decision-making.' These limited examples flag a bias in the literature promoting the positive benefits of social networks. Researchers must be aware that social networks, and the processes that shape and are shaped by social networks, have both enabling and constraining qualities.q

Table 9. Examples of citizen science studies that link social networks to relevant social processes, social attributes and outcomes.

	Example from reviewed studies	**Reference**
Social process e.g. communication, social learning information sharing (n=9)	A citizen science program monitoring ephemeral pools created new social networks that functioned to enhance information flow, bring together diverse views and form new learning processes.	McGreavy et al. 2016
	In a review of five citizen science projects engaging in landscape scale conservation, social networks among stakeholders working at different hierarchical levels were critical for social learning and communicating results.	Sayer et al. 2015
	Shows citizen science as an effective mechanism to create support for conservation in the wider community through information diffusion to wider social networks.	Forrester et al. 2017
Individual/Program outcome e.g. behaviour change, data uptake (n=20)	Some participants in eight citizen science natural resource monitoring projects indicated that exposure to other volunteers strengthened pro-environmental attitudes.	Chase and Levine 2018
	Citizen science promotes the development of 'environmental opinion leaders' who develop a 'sense of self-efficacy' through interactions with others and by acquiring new skills and knowledge.	Johnson et al. 2014
	Data use in multiple volunteer macroinvertebrate monitoring projects was correlated with a 'group's feeling of connection to a social network of engaged citizens and professionals'	Nerbonne and Nelson 2008
Social attributes e.g. trust, social capital (n=13)	Participation in a snowfall monitoring citizen science project strengthened participant social networks by creating 'a sense of comradery.'	Appels et al. 2017
	Community-based monitoring led to shared understanding, trust and social learning among diverse stakeholders in the management of forests in the United States.	Fernandez-Gimenez et al. 2008

Participation in a water-related citizen science program was associated with dense networks that served to build social capital and enable political participation.	Overdevest et al. 2004

Overall, this review found social networks to play a crucial role as the structural foundations for critical social processes, social attributes and a range of individual and program outcomes. We show this influence via a simple conceptual model (Figure 12). This model explicitly highlights the enabling and constraining qualities of social networks, which emerge from the critical awareness that not all social networks are created equal (Bodin et al. 2011). With limitations in current research regarding a lack of analytical specificity and the tendency to report positive benefits of social networks, we see significant potential for a social network perspective to advance the knowledge on key issues in citizen science.

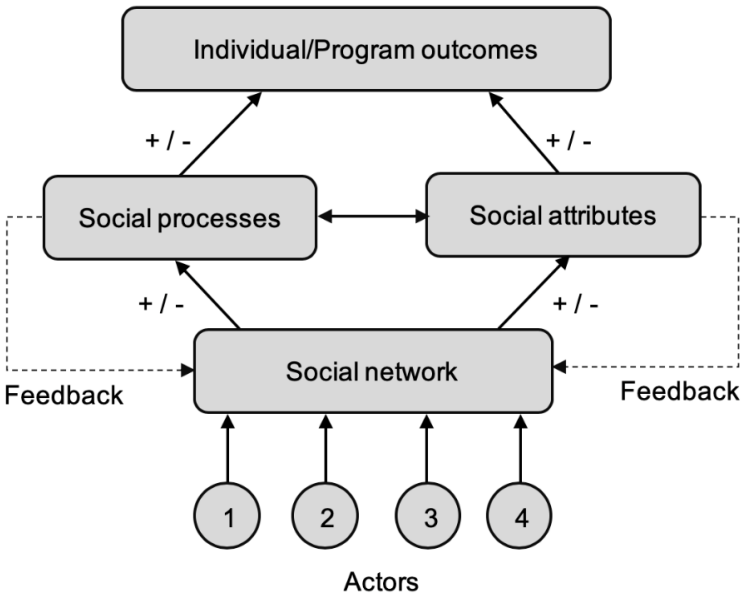

Figure 12. Conceptual model linking citizen science networks to program and individual outcomes. Plus-sign (+) indicates an enabling influence on desired processes/attributes /outcomes. Minus-sign (-) indicates an inhibiting/constraining influence.

Before reviewing these possibilities, we discuss key research principles of a social network perspective, including their representation and analysis, in the following section.

6.4 Key principles and concepts of social network analysis

6.4.1 Principles of a social network perspective

Social network analysis differs in fundamental ways to non-network explanations of social phenomena understood through traditional social science methodologies (Wasserman and Faust 1994). Three principles thus guide network analysts: (1) 'relations' between actors become the priority unit of analysis, not actor attributes; (2) there are no assumptions about the presence of uniformly bounded groups; and, (3) the broader relational context is critical in enabling and constraining individual actions (Marin and Wellman 2010, see also Wellman 1988). The following section discusses these principles in more detail.

The first principle of a social network perspective posits that the 'relation' as a unit of analysis is a more powerful way to explain social phenomena than actor attributes (Marin and Wellman 2011). Typically, social science studies employ an 'attribute-based' approach which groups actors based on a set of common characteristics to understand which attributes disproportionately determine particular outcomes. However, this approach tends to neglect the broader network of relationships in which such individuals are embedded. By contrast, network analysts account for a relational world to consider actors and their actions as 'interdependent rather than independent, autonomous units' (Wasserman and Faust 1994 p. 4). Thus, the goal of social network analysis is to understand the larger web of interactions, and how different structural or relational processes influence actors and their actions. Such an approach enables a simultaneous view of a social system as a whole and of its parts. Although priority is given to the relation in social network analysis, studies do not completely ignore actors' attributes since it is useful to investigate attribute data alongside network data to enhance explanatory insights (Robins 2015).

The second principle of a social network perspective posits that we live in a world composed of networks, rather than discretely bounded or mutually exclusive groups (Marin and Wellman 2011). While in social network research it is critical to determine what counts as the study's population of interest, or the 'network boundary' (Borgatti et al. 2013), a network perspective avoids shortfalls associated with pre-defining group membership (Marin and Wellman 2011). In other words, social network analysis allows groups to be defined empirically, rather than through a priori assumptions. This approach allows researchers to describe communities by the patterns of relations between actors and groups

of actors who each hold divergent values, perceptions and influence. It avoids oversimplifying group membership as something that has a uniform influence on group members. Actors' differing levels of group membership, their membership in multiple groups, and their ties between groups are subject to different opportunities and constraints. Furthermore, viewing society as composed of networks allows the study of less easily identifiable sets of people that structure social relations; for example, experienced versus novice volunteers in citizen science (e.g. Overdevest et al. 2004, Alender 2016).

The third principle of a social network perspective states that the meaning and consequences of social relationships can best be realised if these relations are understood as part of a larger social structure (Marin and Wellman 2011). In other words, just as network researchers do not consider actors as independent, autonomous units, neither do they consider each pair of interactions as independent of a larger web of interactions. The resources that flow between a pair of actors are greatly influenced by the surrounding social system. This principle can be illustrated using the phenomenon of 'brokerage' (Burt 2004). This network concept refers to the presence of an individual or organisation (a broker) that holds exclusive links which bridge otherwise disconnected groups, such as a citizen science project coordinator. A broker is usually considered a powerful actor able to guide information flows, control group behaviour, promote trust, and create new opportunities at a greater extent than other actors (Bodin et al. 2006). As such, the broker's significance in providing opportunities for, and constraints on, individual action only emerges once the overall patterns of relations are considered.

6.4.2 Social network analysis

Over the past several decades, social network analysis has developed into a distinct field of research (Freeman 2004). The mathematical treatment of social networks draws heavily on social network theory and graph theory, characterising social structure in terms of nodes (e.g. individual, organisation) connected by relations, or 'edges', in a network. Relations can be of many different kinds, with each relation capable of giving rise to a corresponding network (Borgatti et al. 2009). For example, we may be interested in how citizen science data

flows through a policy network and ask respondents to list the names of people with whom they share citizen science data. In this case, the resulting network can be described as a data sharing network. Other studied relations could be communication networks, collaboration networks or networks based on trust. Overall, the combination and characteristics of nodes and edges results in a network configuration composed of particular patterns and measurable features for subsequent analysis and visualisation.

In conducting a social network analysis, researchers can employ two main research designs: a whole-network or an egocentric design (Robins 2015) (Figure 13). A whole-network, or 'sociocentric' design aims to understand all social ties in a pre-specified population of interest by collecting relational data from every actor. Alternatively, an ego-centric research design is where a set of actors is sampled from a population (the 'Ego') who then provide information about their immediate network partners (the 'Alters'). While collecting relational data is most commonly conducted through quantitative surveys, it can also be complemented by qualitative data collection and analysis techniques (Crossley 2010). This approach allows respondents to expand on their network partners, which provides a rich insight into how actors attach meaning to relationships within their network. A mixed methods approach has been identified as critical to overcoming insufficiencies of purely quantitative designs (Hollstein 2014).

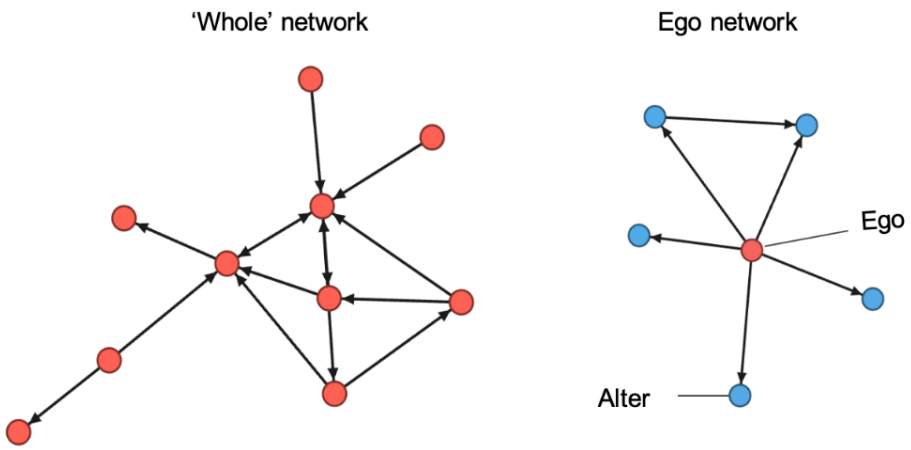

Figure 13. Social network diagrams showing the two main social network analysis designs: 'Whole' networks and Ego networks. Graphs are directed.

By collating relational data, different insights can be gleaned through analysis of a wide range of network measures, which can be quantified at the individual, sub-group and network level (Borgatti et al. 2013) (Table 2). Common measures include the presence of strong and weak ties, homophily (shared attributes among actors), degree centrality (actors with contacts to many others), betweenness centrality (actors that link disconnected parts of the network), and centralization (actors holding a majority of ties). In addition to these quantitative aspects, social networks can also be visualised using specialised software, such as NetDraw and Gephi, which adds qualitative insight into network structure. Visualised networks are referred to as sociograms, and can assist in understanding how a network operates, helping to communicate insights to others and encouraging reflexivity among network actors so that efforts can be directed to influence network function (Beilin et al. 2013).

6.5 Potential applications of social network analysis

The following section shows the analytical possibilities of a relational network perspective for advancing three key issues in citizen science: (1) achieving data uptake in decision-making; (2) promoting social learning; and, (3) building community empowerment. In addition to these issues being substantial focal points in contemporary citizen science research, the selection of these issues also follows the recent work of Turrini et al. (2018) who, from an environmental perspective, considered knowledge generation, learning opportunities and civic engagement/empowerment as the 'threefold potential' of citizen science.

6.5.1 Linking knowledge with action

In recent years, the possibility for citizen science to influence policy development through data uptake has become a topic of serious consideration (Hyder et al. 2015, Chapman and Hodges 2016, Hecker et al. 2018a). Generally, the use of volunteer-collected data in decision-making has been limited, despite some examples of successful linkages (Conrad and Hilchey

2011, McKinley et al. 2017). In examining this issue, researchers have commonly framed slow uptake of citizen science data as a scientific or technical issue. Although both studies are justified in stressing the importance of ensuring citizen science generates robust data for policy decisions (Bonney 2014), they also consider social processes, such as knowledge co-production and trust, as necessary elements to achieve improved citizen science-policy linkages.

Despite this, the social dimensions impacting the citizen science-policy interface remain poorly understood. A social network perspective offers a useful framework in which to assess this relationship. The approach acknowledges the many and varied relations that exist across different scales of governance which shape policy decisions (Chilvers 2008). Moreover, it recognises that data collection, dissemination and application is immersed in a wider social and political context where trust, inclusiveness and power are critical to how scientific information is understood and perceived (Wynne 1992). Thus, the unique combination of citizen science being both a participatory initiative and knowledge producing practice requires that the outputs of data collection, relevant actors, social processes and context are assessed together (van den Hove 2007).

For citizen science, we contend that a social network perspective can be applied across two phases of the research and monitoring lifecycle: (1) strategy and planning, and (2) synthesis and delivery. First, in the early stages of project development, several researchers highlight that early and active engagement of relevant stakeholders is critical if citizen science data are to be translated into effective actions (Sharpe and Conrad 2006, Chapman and Hodges 2016). This ensures data are collected and shared within, rather than apart from, decision-making frameworks. Since certain relational variables, such as communication, cooperation and trust, are critical for sharing knowledge (Henry and Vollan 2014), social network analysis provides both a means to identify relevant stakeholders and to map these variables (Prell et al. 2009). With this understanding, citizen science programs can identify how information flows through their network and the extent to which information is delivered to data end-users with the authority to act—whether policymakers or on-ground

managers. Programs may then be better equipped to target efforts at appropriate scales and develop relationships with those not properly engaged.

Second, the way in which actors form a global network structure may have a profound influence on the synthesis and delivery of citizen science data. Recent research shows that community-based water monitoring programs can comprise a dispersed network of participating groups, which can form either centralised or decentralised networks (Kinchy et al. 2014). Studies in environmental governance have demonstrated that more centralised networks ease information flow and are well suited to solving simple and easily identified tasks (Janssen et al. 2006). However, they can be vulnerable to network collapse and asymmetries in power due to a strong reliance on a few key individuals (Crona and Bodin 2006). Conversely, decentralised network structures are more stable, promote deliberation and enable the generation of information across different parts and scales of the problem. Thus, social network analysis and investigating network concepts, such as centralisation, could provide key insights into how different network structures influence the ways in which citizen science data are shared and applied. This knowledge could be used to inform an understanding about who benefits from this application as well as the types of environmental issues and policies these data are capable of addressing.

In summary, a social network perspective offers a novel lens through which to view data uptake. Critically, the approach reframes the issue as a social process situated in participatory modes of decision-making, rather than being constrained by issues of data and data quality. The following lists a series of research possibilities:

- Describing network structure through data sharing ties to identify whether appropriate actors are engaged from the outset and at a scale relevant to the environmental issue(s) of interest;
- Exploring how different network structures (e.g. centralised, decentralised) shape the synthesis and application of citizen science data;
- Examining the extent to which trust and credibility are influenced by the presence of program connections with policymakers and on-ground managers;

- Using centrality measures to reveal the presence of 'gatekeepers' facilitating or constraining information flow;
- Describing how data are shared among and between citizen science and other stakeholders with respect to the level of reciprocity or unidirectionality of data transfer.

6.5.2 Promoting social learning

In addition to generating useable knowledge, learning and promoting pro-environmental behaviours are core premises of citizen science and contribute to its importance in policy. With respect to learning, recent research suggests many projects do not evaluate learning outcomes (Bonney et al. 2016), whether that be its cognitive, affective or behavioural dimensions (Jordan et al. 2012). Those studies that conduct evaluations largely concentrate on factual (or instrumental) learning. Moreover, studies have mostly confined research participants to volunteers, overlooking learning that can happen among scientists or institutions (Bela et al. 2016). In recent years, there has been growing interest in the capacity for citizen science projects to promote social learning (Jordan et al. 2016). Social learning refers to learning that occurs through social influence and connections with others, that is, through observation, imitation and dialogue (Schusler et al. 2003). This form of learning is increasingly viewed as central to achieving sustainable environmental governance (Pahl-Wostl et al. 2007, Reed et al. 2010).

Social networks offer a natural organising concept to examine social learning in citizen science. While we acknowledge that learning can occur through an individual's internal cognitions (Henry 2009), social networks facilitate individual learning through exposure to others because they enable and constrain the flow of information and promote deliberation (Newig et al. 2010). The concept of social learning is relevant to citizen science because information gathered is used in collaborative settings and encourages multiple perspectives toward shared goals (Jordan et al. 2016). What individuals learn in collective settings can also feedback to reinforce or alter network structure (Henry 2009, Newig et al. 2010). This

concept reflects research in learning literature on single- and double-loop learning (Reed et al. 2010). Single-loop learning involves factual learning that may instigate a change in individual attitudes or behaviour but does not challenge the underlying assumptions of the knowledge-making process. Social learning encompasses double-loop learning and relates to groups reflecting and acting on the assumptions that underlie actions, which may lead to changes in attitudes, beliefs and social norms known as triple-loop learning (Reed 2010). Double- and triple-loop learning has been recognised to cause fundamental changes in network structure as groups or organisations shift towards new ways of working (Newig et al. 2010).

Newig et al. (2010) approach learning from a network perspective and propose a series of whole-network structural characteristics hypothesised to enable or constrain learning processes. For example, greater proportions of strong ties promote trust in a network and facilitate learning processes, whereas weaker network ties promote uptake of new ideas and knowledge. Similarly, the extent of network cohesion has differential effects on learning. A dense, cohesive network is one in which actors have a high connectedness that eases information transmission and deliberation, both prerequisites for social learning (Schusler et al. 2003). By contrast, high network cohesion might be less able to adapt to change, if actors become "trapped" in their own groupthink.

Social network analysis offers researchers a novel method to examine learning in citizen science. Key research areas could examine how one's network partners shape acquired knowledge or describe how learning reconfigures network structure. The following summarises key research possibilities:

- Investigating actors' network partners and how they influence learning processes at the individual level;
- Using cohesion as a network measure to examine how social learning processes influence network structure;

- Employing a multiple case study design to assess the social networks formed by different project types and how these differentially affect learning and behaviour outcomes; and
- Using a social network perspective to help inform the development of strategies to improve individual and social learning for enhanced education and engagement outcomes in citizen science.

6.5.3 Building community empowerment

A growing area of research emphasises the potential of citizen science to build empowered communities, especially those communities that have been previously marginalized or excluded (Ottinger 2016). Empowerment refers to the capacity of people, organisations and communities to shape their own actions in the context of others. Zimmerman (2000 p. 44) considers that in addition to empowerment being about efforts to exert control, 'participation with others to achieve goals, efforts to gain access to resources, and some critical understanding of the socio-political environment are basic components of the construct.' This conceptualisation reveals empowerment to have a substantial relational component (Christens 2011), with researchers recently examining the structural aspects of empowerment through social network analysis (Neal and Neal 2011, Neal 2014).

Empowerment in citizen science can take many forms (Strasser et al. 2018). The concept has been associated with community participation in decision-making and environmental protection (Storey et al. 2016), the building of local leadership (Fernandez-Gimenez et al. 2008), social and environmental justice (Ottinger 2010), and community stewardship of local natural resources (Stevens et al. 2014). Yet, the relationship between citizen science and empowerment remains poorly understood compared to studies of learning and scientific outcomes due, in part, to the lack of formal frameworks to guide investigations (Strasser et al. 2018, Turrini et al. 2018). Moreover, many projects may not have empowerment as a stated objective. Some researchers have considered such goals, including promises of democratising the knowledge-making process, unnecessary in some

projects (Bonney et al. 2016). Phillips et al. (2019) agree that the potential for empowerment through citizen science should not be expected but should still be designed to foster its potential.

The connection between citizen science, social networks and empowerment relates to how new knowledge, skills and confidence acquired through participation build volunteer and group capacity to actively address their concerns (McKinley et al. 2017). Realising such outcomes strongly relies on the presence and quality of volunteers' relationships to others, which can be understood by examining their bonding, bridging and linking social capital (e.g. Larsen et al. 2004). For example, empirical work in environmental governance has shown that local fishers are more likely to report illegal fishing if they had participated in conservation planning and if they have linking ties to management officials in information sharing networks (Alexander et al. 2018). The same may be true for citizen science volunteers where access to individuals in positions of power, i.e. linking social capital, may increase their likelihood to participate in decision-making processes. However, this could also have negative consequences, since powerful individuals or high levels of government involvement may exert influence to stifle or frame out opportunities for deeper engagement (Irwin 2001, Ellis and Waterton 2004, Nerbonne and Nelson 2004).

This potential for social networks to both enable and constrain opportunities for empowerment points to the critical importance of ensuring effective coordination between actors. Coordinators in citizen science play a crucial role in enabling learning, recruiting and retaining volunteers, acquiring resources and facilitating connections between on-ground action and policy (Richter et al. 2018). Moreover, coordinators are often research participants in citizen science studies precisely because they occupy a central position in programs and hold comprehensive insights into project issues and opportunities (e.g. Crall et al. 2011, Stepenuck and Genskow 2018b). In this way, coordinators are the 'brokers' of citizen science initiatives. Coordinating projects and program participants to enable empowerment will be best achieved when the interconnectivity of a network is understood. This knowledge provides volunteers and practitioners guidance on points in the network that can be leveraged for purposive action (Henry and Vollan 2014). This practical dimension of social

network analysis highlights its opportunities as not just a diagnostic and explanatory tool, but a method to shape and build networks in practice (Holman 2008).

Social network analysis offers an exciting way forward to examine how relational structures enable or inhibit empowerment processes and, from this, greater active involvement in decision-making. In considering a network perspective for these issues, the following research possibilities are proposed:

- Investigating the extent to which bridging ties enable or constrain the capacity for individuals to participate in decision-making processes;
- Examining different citizen science program types to show how associated network structures shape community empowerment;
- Describing the connectivity between government organisations and citizen science programs to reveal leverage points that facilitate pathways for influence;

6.6 Conclusion

In citizen science, building strong and productive relationships is critical across all stages of the research and monitoring process. The capacity to recruit and coordinate volunteers, collaborate with others, collect and share data, and influence people in positions of power strongly depends on the nature and quality of these connections. In this review, we have proposed that a social network perspective offers an alternate lens through which to study citizen science practice – one that reframes key issues by placing social relationships and networks at the centre of investigations. Social network analysis and visualisation provides a means to systematically measure and map citizen science networks to examine what might enable or constrain individual experiences and program outcomes. We envisage knowledge gained through this approach to assist communities and practitioners in understanding how their network operates and how it might be strengthened.

Based on a review of citizen science studies, we showed that social networks influence a range of social processes, attributes and outcomes relevant to citizen science practice. However, we expose limitations in current conceptualisations and highlight significant

potential for citizen science researchers to treat social networks as an object of empirical study in their own right. We have argued that applying a social network perspective can advance understanding of data uptake in decision-making through reframing this issue as a social process situated in participatory modes of science governance, rather than constrained by some technical barrier, e.g. data quality. Moreover, we see great potential for evaluating social learning through social network analysis, where new knowledge and behaviour change are viewed as being affected by one's relationships and the relationships within a broad social structure. Finally, taking a social network perspective holds promise for researchers interested in the barriers and enablers to community participation and empowerment in science and environmental governance.

This review is intended to stimulate a greater appreciation of the role and importance of social networks in citizen science research and practice and we encourage researchers to consider the research possibilities outlined in this paper. We believe social network analysis as a complementary knowledge practice will be necessary—as part of the suite of tools used by researchers—to propel citizen science research and practice forward in efforts to build resilient and influential programs.

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In the following chapter, social network analysis is applied to understand one possibility outlined in this paper—linking knowledge with action—and is understood through an investigation into the nature and quality of data sharing and collaborative social ties in two freshwater citizen science programs in Australia.

7 Exploring the citizen science-policy interface: a social network perspective

7.1 Abstract

In natural resource management contexts, citizen science programs often involve diverse stakeholders collaborating in broad social networks. However, the characteristics and features of these networks are largely unknown despite there being a well-known relationship between network structure and effectiveness of collaborative environmental initiatives. In this article, a mixed methods social network analysis of two longstanding freshwater citizen science programs in Australia is undertaken. The quantitative social network analysis revealed important insights into the characteristics and impact of data sharing and collaboration across the two cases. Despite both programs comprising similar actor diversity and conducting similar data collection activities (i.e. water quality monitoring), they have produced different network structures, which matched the scale of each program's data contributions to decision-making. Qualitative analysis complemented the structural analysis and provided insight into how actors navigate their relationships to manage several tensions inherent to network function. The article provides novel insights into the social relational factors that enable and constrain the benefits of citizen science in natural resource management and concludes by encouraging practitioners to adopt a networking mindset to realise the potential in their own networks.

7.2 Introduction

Citizen science is increasingly embedded in government policy as a means to improve the management of natural resources while building active, connected and informed communities. Academic literature highlights both the importance and potential of citizen science to meet various governance objectives but has so far tracked mixed success concerning its uptake and acceptance in environmental decision-making (Hecker et al. 2018a). There are emerging indicators that the uptake of citizen science in governance contexts depends on favourable institutional support and cross-scale relationships between programs and other stakeholders (Irwin 2015, Stepenuck and Genskow 2018a, Bonney et al. 2020). These insights align with a large body of environmental governance literature that has consistently demonstrated the importance of social networks in facilitating knowledge uptake, learning, trust and collective action (Innes and Booher 2004, Leach and Sabatier 2005, Groce et al. 2019).

Pollock and Whitelaw (2005) suggest that effectiveness of policy and management-oriented citizen science is associated with local and adaptive community structures, underpinned by functional coordination and pathways to facilitate the flow of information. However, few studies have sought to examine the structural and relational characteristics of citizen science networks beyond these descriptive accounts. Environmental governance literature suggests social networks are not uniform (Newman and Dale 2005), and that different social network structures can lead to different outcomes (Bodin and Prell 2011). Applying these insights to citizen science networks and understanding the factors that enable and constrain network development may create an opportunity for more informed assessments on the scientific and collaborative potential of the practice.

In this article, we assess the characteristics and influence of two longstanding freshwater citizen science networks in Australia. This is done using the conceptual and methodological tools of social network analysis, which has found increasing utility in the study of collaborative environmental initiatives (Bodin and Prell 2011). For the purpose of this research, *citizen science networks* refer to the various forms of relationships between stakeholders in citizen science (e.g. volunteers, coordinators, scientists and decision-makers)

who influence the planning, implementation and outcomes. In examining these networks, we are not only interested in how actors are embedded in a given social structure, but also how social structure shapes network function and program outcomes. This article presents a review of the literature discussing the social relational approach to collaborative environmental governance followed by the empirical research applying this perspective to citizen science.

7.3 Citizen science and social networks: towards a 'structurally explicit' approach

References to the role and importance of relationships and networks are frequently found in citizen science literature. For example, social networks have been cited as being critical to the development of various social processes, individual and program outcomes and social attributes, such as trust and social capital (see Chapter 6; Appendix G). However, few studies have sought to actively describe or quantify the specific patterns of relations that make up a citizen science social network. Rather, researchers have tended to conceptualise social networks in citizen science as a metaphor whose presence (or absence) have important consequences. Only one study (Richter et al. 2018) has taken a quantitative approach by examining the embeddedness of individuals in butterfly monitoring project to understand drivers of long-term participation. Through social network analysis, their findings highlighted the vital role that central coordination and peer support played in personal satisfaction and engagement.

To fully grasp the role of social networks in citizen science, it will be necessary to adopt a 'structurally-explicit' approach that draws attention to social structure. This approach is informed by a social network perspective and views that not all networks are created equal (Newman and Dale 2005). Different patterns of relations can lead to different—and not always positive—outcomes. This means social networks can have a "dual nature" (Ernstson et al. 2008), which may create maladaptive situations or facilitate unproductive behaviour (Borgatti and Foster 2003). Indeed, Conrad (2006b) discussed possibilities for a breakdown in social cohesion when structural barriers limited the ability

of community-based monitoring groups to communicate and deliver monitoring results to decision-makers.

7.3.1 Social network analysis

Social network analysis provides a set of tools through which to study the structure, meaning and consequences of social relationships. The methodology is underpinned by three main principles: (1) 'relations' between actors become the priority unit of analysis, not actor attributes; (2) there are no assumptions about the presence of uniformly bounded groups; and, (3) the broader relational context is critical in enabling and constraining individual actions (Marin and Wellman 2011, see also Chapter 6). In recent years, social network analysis has proven useful in studying key issues in environmental governance, such as information diffusion, power relations, and different group structures and their influence on individual behaviour (for a review on outcomes see Groce et al. 2018). Its use in citizen science has the potential to bring about similar advances, since both citizen science and environmental governance deal with related concepts like participation, collaboration, capacity-building, social-ecological resilience and learning for sustainability.

More specifically, social network analysis draws heavily on social network theory and graph theory to characterise social structure in terms of nodes (e.g. individual, organisations) connected by relations, or 'edges', in a network. Relations can be of many different kinds, such as communication, information sharing or trust, with each relation capable of giving rise to a single network (Borgatti et al. 2009). The combination of nodes and edges results in a network configuration composed of particular patterns and measurable features for analysis and visualisation. Common network-level measures include the level of centralisation (actors holding a majority of ties), core-periphery structures (a dense core of actors with a sparse periphery of actors connected only to the core) and cross-boundary exchange (a measure of network heterogeneity). Drawing on network theory and other sociological concepts, such as social capital theory and social movements, these network characteristics can then be used to understand how social structure shapes, and is shaped by, the processes and outcomes of a phenomena of interest.

In addition to these quantitative aspects, social networks can be visualised using specialised software, such as NetDraw and Gephi, which adds qualitative insight into network structure. These visualisations are called sociograms, and can assist in understanding how a network operates, helping to communicate insights to others and encouraging reflexivity among network actors so that efforts can be directed to influence network function (Beilin et al. 2013). Figure 14 illustrates three typical network structures: shared network (the number of ties equally distributed across the network), decentralised network (multiple "hubs" of relational connectivity) and a centralised (ties connected to a single or (few) actors) network.

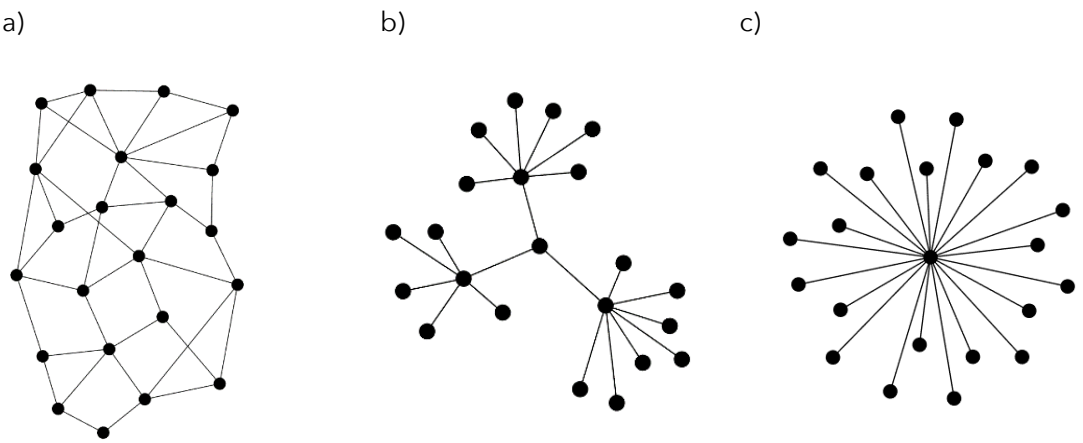


Figure 14. Examples of common network structures: a) distributed b) decentralised and c) centralised networks.

7.3.2 Linking networks to outcomes

A key concern for social network researchers is the ability to link network structure with an outcome of interest. Such an investigation requires an additional data set alongside network connection data and beyond a single case (Groce et al. 2018). For citizen science projects monitoring natural resources, environmental improvements such as improvements in water quality are usually the ultimate goal. However, demonstrating a link between citizen science and environmental outcomes is a difficult task and few studies make this link (Conrad and Hilchey 2011). In acknowledging a similar challenge in catchment groups in the United States, Floress et al. (2011) suggested a useful outcome measure is one that identifies

outcomes beyond social processes but prior to environmental outcomes, or so-called "intermediate outcomes" (Carr et al. 2012). For citizen science, an important intermediate outcome relates to a program's contributions to natural resource management and policy decisions. This could be evidenced by instances of data uptake in reports, policies or management actions. Both Carr et al. (2012) and Groce et al. (2018) suggest that intermediate outcomes can be considered a precursor to broader impacts on environmental improvement.

Insights from environmental governance literature highlight at least three ways networks enable and constrain the ability to link science and policy (Henry and Vollan 2014). First, networks enable and constrain information flows and, therefore, will influence the delivery of information to those end-users with the power to act. Second, social networks reveal the position of certain actors who control, facilitate or inhibit information delivery, and who have similar information needs or uses. Finally, the way in which actors and their interactions form an overall network structure can both enable and constrain the synthesis and application of generated information.

With respect to overall network structures, Jalbert et al. (2014) described how community-based water monitoring programs work in either 'centralised' networks, where "hub" organisations connect different groups, or 'decentralised' networks, where organisations shared resources and collaborated on projects without a central hub. This particular study led to the identification of important unanswered questions about the relationship between different citizen science network structures and knowledge exchange, resource sharing and collaborative potential. Environmental governance literature suggests more centralised networks, within which few actors hold a majority of the ties, are recognised to be more efficient in solving simple and easily identified task (Bodin and Crona 2009). However, they can be vulnerable to collapse due to a strong reliance on few key individuals. Alternatively, decentralised network structures which comprise more distributed network connections are known to have higher resilience, promote deliberation and generate information at different parts and scale of the problem, but may require more intensive coordination efforts.

7.3.3 Understanding network tensions through qualitative methods

While a purely structural focus to studying social networks has many positive benefits, it also has limitations when considering the content, quality and meaning of relationships (Hollstein 2010, Fuhse and Mützel 2011). Qualitative methods are therefore most appropriate for investigating the way in which actors navigate and experience their relations and how meaning shapes network structure, and vice versa (Hollstein 2014). Through a mixed methods approach, quantitative methods allow descriptions of the structural characteristics from an 'outsider' perspective, qualitative methods, such as in-depth interviews, enable understanding of the meaning relationships from an 'insider' perspective (Bolíbar 2016, Yousefi Nooraie et al. 2018). Additionally, triangulating quantitative and qualitative methods in data collection and analysis can enhance the validity of network data and the explanatory power of network studies (Bolíbar 2016).

The use of qualitative methods in social network analysis has the potential to provide important insights into various network tensions or "contradictory logics" (Provan and Kenis 2008). Provan and Kenis (2008 p. 14) describe three such tensions, which they describe as being an 'inherent and critical aspect of network life that network members must deal with.' The first network tension affecting network function can occur between *efficiency* and *inclusiveness*. This means that efforts to promote inclusive and equitable participation in decision-making (i.e. through collaboration and distributed network structures) can reduce a program's capacity to act as a collective, and vice versa. The second tension relates to *internal* and *external* legitimacy, which refers the need to satisfy potential differences in expectations among participants within a network, while being responsive to expectations from outside groups, such as funding agencies. Provan and Kenis (2008) suggest this tension is best addressed through a governance structure that comprises both a centralised administration, which promotes external legitimacy, and representative management that provides a mechanism to deal with the everyday work of interacting with participants. The final tension concerns a tension between *flexibility* and *stability*, which refers to the need to be adaptive in response to changing stakeholder needs but also maintain consistency in actions over time. In citizen science, flexible network structures may enable a program to respond

quickly to environmental threats and other opportunities, but this could lead to a focus on short-term, temporary engagements that impact on long-term stability.

7.4 Methods

7.4.1 Comparative case study approach

In this study, the relationship between network structure, function and outcomes is explored through a comparative study of two longstanding citizen science programs: Mill Stream Waterwatch and Regional Highlands Waterwatch[4]. Mill Stream Waterwatch, is funded by a large water utility company responsible for the management and protection of waterways across the region. The program employs five coordinators each responsible for one priority portfolio (water quality, platypus, macroinvertebrates, frogs and litter) and a region for coordinating water quality monitoring activities. Mill Stream Waterwatch began in 1993 and currently operates in a governance context that emphasises community capacity-building under the region's waterway management strategy, which provides direction for a regional vision of waterway health. Included in this strategy are goals to elevate the importance of citizen science, with key performance objectives aimed at promoting environmental stewardship and connections to waterways, strengthening community-government relations and building community leaders.

Regional Highlands Waterwatch is partly funded by a state government, with funding assistance from a state-owned water utility company. Volunteers are coordinated by four regional catchment coordinating committees, each employing a single coordinator whose role is to interface with communities in their respective region. A program facilitator, employed by the state government, oversees the activities of the coordinators and promotes the program internally. Regional Highlands Waterwatch was launched in 1995 and is at the time of this publication guided by policy that supports the integration of Waterwatch in government monitoring to enable better understanding of water resources in the region. The

[4] See Chapter 3 regarding the decision to maintain the confidentiality of study cases.

program also has objectives to promote increased community awareness of waterways issues.

The study cases were chosen due to several key similarities, which included (i) their long history in Australian natural resource management, (ii) established relationships with a wide range of other organisations, (iii) a demonstrated capacity to contribute data to inform the management of water resources and (iv) large numbers of volunteers and monitoring sites across large geographic areas (although exact numbers of volunteers were not able to be identified). Key differences between the two cases are their primary objectives (described above) and their focus in different environmental contexts. Mill Stream Waterwatch is largely focused on collecting waterway information in urban and peri-urban environments. Regional Highlands Waterwatch operates across more rural regions with some urban sites. Both programs are focused on delivery of multiple subprograms, such as collecting data on frogs, macroinvertebrates, platypus and other environmental indicators. In this study, we focus our attention on the long-term water quality monitoring component of each program.

7.4.2 Research design

The social network analysis was conducted using a mixed method approach following a sequential explanatory research design (Hollstein 2014). A sequential explanatory design involves two more or less distinct phases. It begins with the collection and analysis of quantitative social network data using an online questionnaire, followed by the collection and analysis of qualitative interview data. The purpose of the quantitative strand is to map the structural characteristics of the social network, whereas the subsequent qualitative data generates deeper understanding of the content of ties and the meaning actors have attached to those ties within the network. For this study, a key advantage of sequential explanatory design was the ability for targeted selection of participants for the interviews after preliminary analysis of social network data.

7.4.3 Network data collection

We followed a snowball sampling approach (Doreian and Woodard 1992) to survey actors participating in or interacting with each program, starting with program coordinators. The coordinators were then asked to nominate potential participants who were then asked to nominate others. This approach continued as the central mechanism for working to achieve the required sample size. The questionnaire to map network structure followed a name generator and interpreter method (Robins 2015), and is presented in Appendix B. Respondents were asked to recall up to ten individuals with whom they interact in citizen science activities. For the purposes of this study, an 'interaction' was defined as (1) sharing citizen science monitoring data and (2) collaborating on monitoring activities and projects. While many types of relations can be mapped and analysed through social network analysis, the decision was made to choose these particular relations because data sharing and collaboration have been consistently recognised as fundamental social processes in management and policy-oriented citizen science. A second section of the questionnaire asked respondents attribute-type questions on their group affiliation, role and their duration of employment or participation. We focused on following up survey responses from people who were named frequently as a way to maximise limited resources and obtain a network characterised by the most important individuals. To assess volunteer connections, we had to rely on coordinators to recruit volunteers due to ethical considerations relating to direct recruitment, which removed researcher control over the recruitment of volunteers. Invitations to volunteers to participate in the research were sent out by coordinators on behalf of the research team with a link to an online questionnaire.

A total of 29 emails were sent to individuals in professional roles in the Mill Stream case while 27 were sent out in the Regional Highlands case. A total of 21 and 22 questionnaires were returned, respectively, for a response rate of 72% and 81%. The response rate for volunteers was difficult to measure given the constraints on recruitment. We received responses from 43 volunteers from Mill Stream Waterwatch and 38 volunteers in the Regional Highlands case. Given both programs report that they coordinate around

200 volunteers per program, the response rate for volunteers is low at approximately 19% and 22%, respectively.

7.4.4 Social network analysis

Our research design allowed the generation of two networks: data sharing and collaboration. We grouped respondents into six categories: volunteers, coordinators, scientists, catchment managers, policymakers and other stakeholders, which included educators and individuals from non-government organisations. Relationships were symmetrised (Borgatti et al. 2013), meaning that a tie was included if one actor in a dyad reported a connection. Thus, each studied relation resulted in an 'undirected' network where all relations are bidirectional.

To investigate the network characteristics, we quantified four network-level measures relevant to our research focus and considered important metrics to understand collaborative environmental governance (Bodin et al. 2006, Bodin and Crona 2009, Prell et al. 2009). The metrics included density, network centralisation, core-periphery analysis and cross-boundary exchange. Table 10 describes each measure assessed in this study and its social meaning for citizen science. For measures of cross-boundary exchange, we excluded cross-boundary ties between volunteers and coordinators to uncover effects of program interactions with other stakeholders occupying different roles. Network measures were calculated using the software UCINET (Borgatti et al. 2002). We illustrated the networks using the social network visualisation software NetDraw (Borgatti 2002).

7.4.5 Program outcome data

To understand the effect of different network structures on the outcomes of citizen science initiatives, we conducted a secondary analysis of survey data collected during a previous study of freshwater citizen science in Australia to review, among other issues, the uptake of citizen science data in decision-making (Chapter 5). The two case studies that are the focus of this paper were involved in this previous study and reported various instances in which

their program's data had been used in management or policy decisions, which were later verified through documentary evidence. For this study, instances of data uptake for both programs were categorised along two axes: the scale of data use (local, sub-catchment, catchment, regional), and the relevant part of a typical adaptive management cycle (strategy and planning, monitoring and intervention, reporting and evaluation).

Table 10. Network measures analysed in this study and their social meaning for citizen science.

Network measures	Explanation	Social meaning
Density	The number of connections in a network divided by the total possible connections. A density score of 1 indicates that all actors in the network are directly tied to one another, and a score of 0 indicates the network is fully disconnected.	Networks of high density can promote trust in a network, facilitate common identity and collective action (Diani and McAdam 2003), but can also reduce the development of innovation (Bodin and Crona 2009).
Centralisation	The extent to which a network is organised around a central point scored from 0 to 1 where a score of 1 indicates a network conforms to an idealised 'wheel' or 'star' structure.	In highly centralised networks, few actors hold a majority of network ties. Centralised networks can be more efficient in coordinating activities, but program resilience and long-term problem-solving capacity is lower than in more distributed or decentralised networks (Prell et al. 2009, Mills et al. 2014).
Core-periphery fit correlation	A network with actors in a dense, cohesive 'core' and sparse periphery of actors connected only to the core. Like measures of centralisation, scores indicate the degree to which a given network conforms to an idealised core-periphery structure.	Core actors are considered to function as bridges to local (peripheral) actors and act as communication hubs to transmit information within and beyond the core. Can reflect a clear division of labour that assists in information acquisition and transmission (Bodin and Crona 2009).
Cross-boundary exchange	A measure of network heterogeneity. The number of ties connecting actors in different roles or affiliations divided by the total number of connections in the network (Sandström and Rova 2010).	Strong external links may promote "bridging" ties, which implies greater access to diverse resources (Newman and Dale 2005).

7.4.6 Interview data

To understand network function, a total of 40 in-depth semi-structured interviews were conducted following a preliminary social network analysis with a broad range of key stakeholders in each site (e.g. volunteers, coordinators, scientists, catchment managers and policymakers). Participants included volunteers (n=20), coordinators (n=10), catchment managers, policymakers and scientists (n=6) and other stakeholders, including community engagement professionals (n=4). Interview questions focused on: the nature of individual collaboration with other people and organisations; the contributions of citizen science to understanding and managing waterways; enablers and constraints of building new and strengthening existing relationships; and, visions for an ideal citizen science program in the respective region of the participant. The interview schedule can be found in Appendix C. Interviews were transcribed and ranged in length between 30 and 90 minutes. We adopted a hybrid approach to coding interviews (Fereday and Muir-Cochrane 2006; Layder 1999; see also Chapter 3). In this approach, interviews were assessed in relation to the three known tensions of network governance developed by Provan and Kenis (2008) while, at the same time, being guided by the interview data to ensure an openness to emerging ideas and potential contrasts with the network governance literature. Coding was conducted using the software NVivo 12 (QSR International). We completed several cycles of coding to identify consistent themes between interviewees and study cases. To maximise data accuracy, validity and consistency in coding the qualitative data was reviewed by three researchers. The analysis of interview data served a dual purpose: (i) to capture way in which different actors navigate and experience their relationships to manage tensions inherent to citizen science network governance, and (ii) to provide a mechanism to validate the quantitative social network analysis.

7.5 Results

Our results are presented here in three parts. First, we present and compare the whole-network properties of the data sharing and collaboration networks for each study case.

Second, we describe the type and scale of data contributions that each program has made to decision-making to enable interpretation of the correlation between structure and outcomes. Finally, we discuss insights from the interview data that detail how actors navigated and experienced their relationships to examine key network tensions that affected the functioning of each program.

7.5.1 Network structure

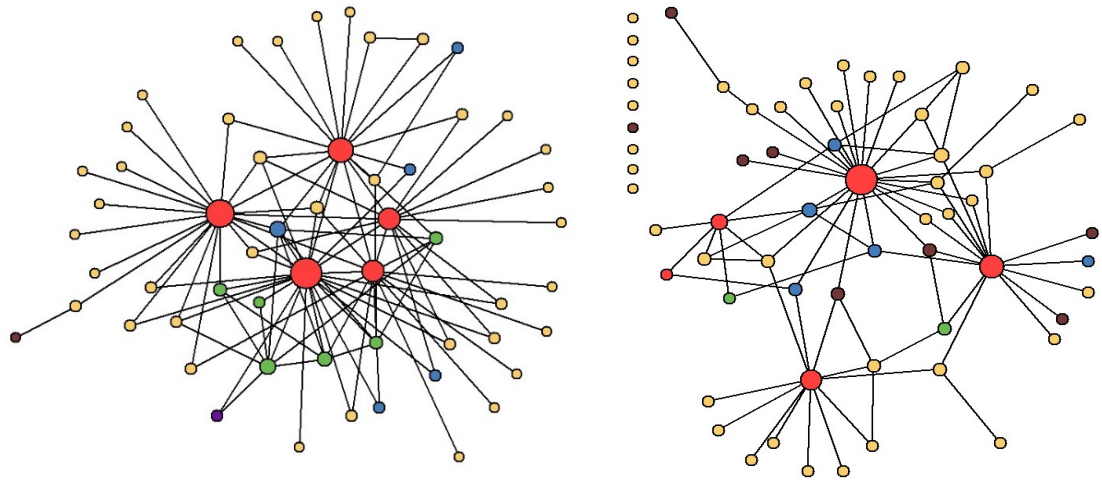
Figure 15 illustrates the data sharing and collaboration networks for the two citizen science programs. The size of networks was measured by the number of nodes in each network. Regional Highlands Waterwatch was smaller in size than the Mill Stream case but had a greater number of ties across both networks. While each program had similar actor diversity, the proportions of stakeholder groups varied across programs and network relations (Table 11). For example, Regional Highlands Waterwatch was composed of more scientists than Mill Stream Waterwatch in all networks (green nodes in Figure 15). There was low policy-maker presence in both programs: only one policymaker was found to be involved in the Regional Highlands case compared to none in the Mill Stream case.

Table 11. Actor diversity in data sharing and collaboration networks

	Regional Highlands		**Mill Stream**	
Actor	Data sharing (n=56)	Collaboration (n=51)	Data sharing (n=61)	Collaboration (n=65)
Volunteers	38	30	41	43
Coordinators	5	5	5	5
Scientists	6	6	2	2
Catchment managers	5	6	5	4
Policymakers	1	0	0	0
Other stakeholders	1	4	8	11

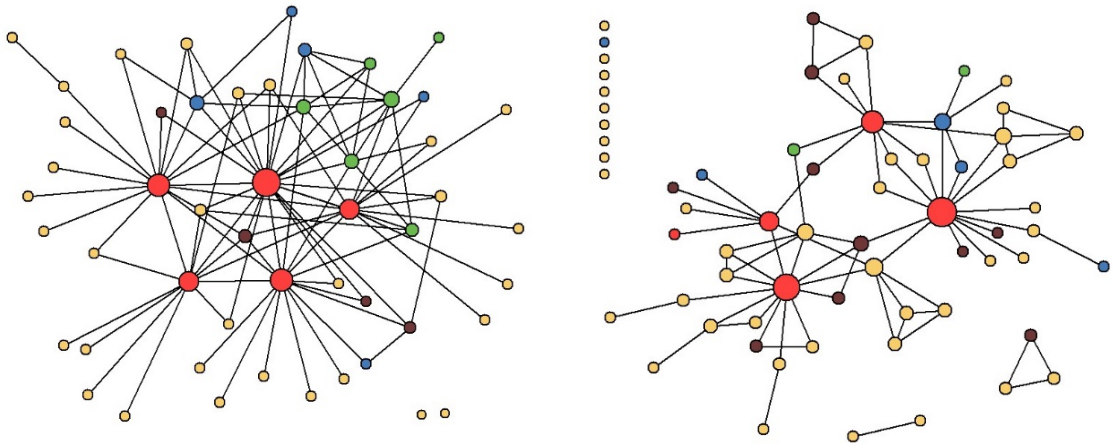
Data sharing network

a) b)



Collaboration network

a) b)



Volunteer Coordinator Scientist Catchment manager Policymaker Other stakeholder

Figure 15. Social networks based on data sharing and collaboration ties in a) Regional Highlands Waterwatch and b) Mill Stream Waterwatch. Size of nodes represents the number of ties of each node (degree) and the colour of the node denotes actor roles: yellow (volunteers); red (coordinators); blue (catchment managers); purple (policymakers); and brown (other stakeholders)

Mill Stream networks was more loosely connected than the Regional Highlands case (Table 12). This is evidenced by lower densities and lower average degrees in the Mill Stream case across both relations indicating fewer overall ties connecting stakeholders. Further, Mill Stream Waterwatch was more fragmented, having a greater number of isolates and components disconnected from the main network structure. By contrast, the Regional Highlands Waterwatch program was completely formed in the data sharing network while only two isolates were present in the collaboration network.

Table 12. Whole-network properties of data sharing and collaboration network in Regional Highlands Waterwatch and Mill Stream Waterwatch

	Regional Highlands		**Mill Stream**	
Network measures	Data sharing	Collaboration	Data sharing	Collaboration
Nodes	56	49	61	65
Edges	103	97	77	77
Avg. degree	3.68	3.96	2.53	2.37
Density	0.067	0.082	0.042	0.036
Network centralisation (%)	40	44	35	20
Core-periphery fit correlation (%)	73	70	46	37
No. of components	0	0	0	2
No. of isolates	0	2	8	10

In relation to network centralisation, Regional Highlands Waterwatch and Mill Stream Waterwatch had similar degree-centralisation scores for the data sharing network of 40% and 35%, respectively (Table 12). This means data are shared only moderately around a few central individuals when compared to that of a classic star network with a centralisation index of 100% (Valente 2015). However, for the collaboration network, Regional Highlands Waterwatch was much more centralised than Mill Stream Waterwatch at 42% and 20%, respectively, which suggests collaborative ties are more dispersed and evenly spread in the Mill Stream case.

A further measure of structural centralisation was the assessment of the core-periphery profile of each program. Unlike Mill Stream Waterwatch, the Regional Highlands case exhibited a strong core-periphery structure across both the data sharing and collaboration network with a correlation of 73% and 70%, respectively, compared to an idealised core-periphery structure. For the data sharing network, within-core density was 64% and within-periphery density was 0.003%, with core actors comprising coordinators (n=5), scientists (n=2) and a catchment manager (n=1). For the collaboration network, within-core density was 60% and within-periphery density was 0.007% with core actors similarly comprising coordinators (n=5), scientists (n=3) and catchment managers (n=2).

The heterogeneity of the two networks was assessed by calculating overall levels of cross-boundary exchange, which measures the extent of bridging ties between actors in different roles. Ties between volunteers and coordinators were excluded from this analysis since almost all volunteers reported a connection with their respective coordinator. For the collaboration network, the cross-boundary character of Regional Highlands Waterwatch was higher than Mill Stream Waterwatch of 39% and 33% respectively (Table 13). For the data sharing network, Regional Highlands Waterwatch had a much lower cross-boundary exchange than Mill Stream where 28% and 40% of total ties, respectively, were between actors holding different roles (Table 13). These results suggest that in Mill Stream Waterwatch, data are shared with a greater diversity of stakeholders than in the Regional Highlands case, which confirms the more distributed nature of the Mill Stream Network.

Table 13. Total cross-boundary exchange and volunteer within/cross-boundary ties across each network.

	Regional Highlands		**Mill Stream**	
	Data sharing	Collaboration	Data sharing	Collaboration
Cross-boundary exchange† (%)	28	39	40	33
Volunteer cross-boundary ties† (%)	4	5	13	12
Volunteer within-boundary ties (%)	1	1	11	27

† Excludes volunteer-coordinator ties

Volunteers across both study cases showed differences in the nature of their connections. In Regional Highlands Waterwatch, volunteers had few ties with other volunteers, suggesting they mostly conduct activities alone, whereas volunteers in Mill Stream case had much higher within-boundary (volunteer-volunteer) ties (Table 13). For example, 27% of all ties in the Mill Stream collaboration network were between volunteers compared to 1% in the Regional Highlands case. In the Mill Stream case, volunteers were also more likely to connect with stakeholders in other roles, with 13% of total ties in the data sharing network and 12% in the collaboration network.

7.5.2 Network outcomes

To understand the effects of different network structures in citizen science, we consolidated instances in which data from both programs have been used for management and policy decisions. Figure 16 places each instance of data uptake along two categorical axes. The x-axis describes instances of data uptake according to a typical adaptive management cycle: strategy and planning, monitoring and implementation and evaluation and reporting. The y-axis describes the scale of data uptake from the site to regional level. Results show both programs provided examples of citizen science data use across each point in the adaptive management cycle. However, Regional Highlands Waterwatch had more instances of data uptake at a regional scale whereas Mill Stream Waterwatch was more likely to demonstrate successful instances of data use at a local level. As will be described in the discussion, the differences in network structure, including levels of centralisation and cross-boundary exchange match the type and scale of the knowledge outcomes achieved by each program.

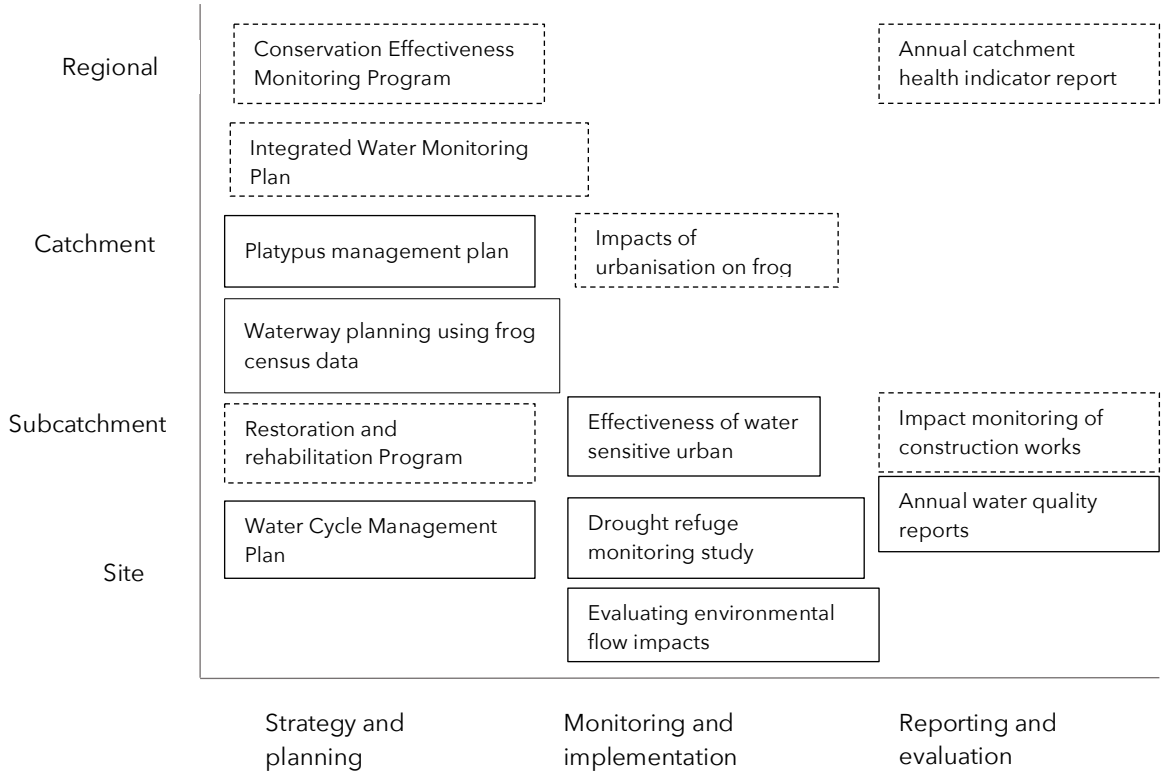


Figure 16. Instances of citizen science data uptake. Dashed line: Regional Highlands Waterwatch. Solid line: Mill Stream Waterwatch

7.5.3 Network tensions: insights from qualitative analysis

The quantitative findings described above are complemented with in-depth interviews conducted with a diverse set of people in each study case's network. Data are structured according to each network tension identified by Provan and Kenis (2008) and show how each program has prioritised or balanced different sides of each tension. Table 14 summaries the prioritisation and management of network-level tensions based on these insights.

Table 14. Prioritisation and management of network-level tensions based on qualitative insights that were found to influence network effectiveness (see Provan and Kenis 2008). Positive sign (+) indicates tensions favours one dimension (e.g. stability) over another (e.g. flexibility), indicated by a negative sign (-).

Network tensions	Explanation	Regional Highlands	Mill Stream
Efficiency / Inclusiveness	The need to act efficiently as whole while encouraging inclusive and equitable participation in decision-making	+/-	-/+
Internal / External legitimacy	Satisfying potential differences in expectations among participants (i.e. volunteers) while being responsive to expectations from outside groups (i.e. funding agencies)	-/+	+/-
Flexibility / Stability	Being adaptive in response to changing stakeholder needs and environmental conditions while maintaining consistency in actions over time	-/+	+/-

7.5.3.1 Efficiency versus inclusiveness

The first tension described is between efficiency and inclusiveness, which refers to the challenge of acting effectively as a whole while encouraging inclusive and equitable participation. In the Regional Highlands case, all program coordinators reported a recent shift in the program's primary objectives from community-directed participation and unstructured data collection activities towards developing a more scientifically rigorous and broadscale monitoring program that efficiently captured a picture of waterway condition across the region. The extent to which the network structure was viewed as essential to the overall effectiveness of the program is captured by the following quote by the program facilitator:

> I sit in the [government] but the four coordinators who work directly with the volunteers sit in the community. I feel this is a key to success as I can connect with policy makers and promote the program and its data while the coordinators can get on with their job and be more accessible to the public (program facilitator, RHW).

While Regional Highlands Waterwatch's model of governance has enabled efficient coordination and data management, it has simultaneously reduced inclusive and self-directed participation that once characterised the program. For most volunteers this was not a significant issue, since the improved efficiency of the program allowed them to feel part of "something bigger" (volunteer, RHW). Still, the prescribed nature of monitoring activities also presented some difficulties, as two volunteers highlighted:

> A lot of the testing dates, they would prefer you to do them on a special day…I can see that their data sets would be a lot better if everybody did their testing on a certain day…I just can't commit to that (volunteer, RHW).

> For most people, they will [monitor] when they can. When [the new approach] was mentioned, there was a groan that went around the room. You could see it wasn't a popular idea (volunteer, RHW).

Our interviews with the program facilitator and most regional coordinators highlighted that this tension between efficiency and inclusiveness was also manifest in the locations of volunteer monitoring. They described how several monitoring sites continued to be supported by the program despite their low scientific utility. The program facilitator reported that telling volunteers that their sites were "not meaningful to the broader monitoring program" was "not exactly going to win hearts and minds" (program facilitator, RHW). Instead, the program facilitator suggested it is about "finding a balance" between community ownership of monitoring sites and the scientific rigour of the program and negotiating a tension between the two.

By contrast, Mill Stream Waterwatch has created a program that decentralises control over the purpose, tasks and goals of data collection activities to the local level, thereby promoting inclusiveness over efficiency. The role of coordinators is to facilitate partnerships between volunteers and local stakeholders to deliver environmental outcomes relevant to these areas and that build on local environmental concerns, as one coordinator described:

> For volunteers, it's about making a connection with their waterways…I guess that has been an aim of the program for a while now to try and build people up in terms of their skills, in terms of their connections, so they can take a more active role (coordinator, MSW).

While promoting inclusiveness in the form of community-directed monitoring activities was assessed positively across this study cohort, data analysis found some divergence in views

relating to program efficiency as it related to regional cooperation. A consistent message from Mill Stream Waterwatch coordinators revealed that they generally work on their own projects in their respective regions. This finding reflects the social network analysis where coordinators did not report ties with other coordinators. This finding highlights a potential lack of efficiency in coordinating actions at a broader, regional level. Having highlighted this finding it is important to identify that, one coordinator described the relationships between coordinators as "really collaborative" where "everyone's trying to achieve the same thing" (coordinator, MSW). This coordinator perspective was found to be inconsistent with the findings in the social network analysis, and with the qualitative data drawn from the majority of coordinator participants. This discrepancy highlights the importance of exploring quantitative and qualitative feedback when examining social networks; both for enhanced data validity across qualitative and quantitative data and as an indicator of discrepancies or differences in perceptions. Identifying and exploring similarities and potential differences in views on particular issues provides an important insight into how individuals perceive the strengths and needs relevant to their network and their network outcomes. The type and scope of the strategies put in place when responding proactively and inclusively to enhancing outcomes within the citizen science program should be shaped by both the consistencies and the inconsistencies drawn from social network data.

7.5.3.2 Internal versus external legitimacy

The second network tension is between internal and external legitimacy, or the responsiveness of the program to the potentially conflicting needs and expectations of internal participants, such as volunteers, and external stakeholders, such as funding bodies and decision-makers. In the Regional Highlands case, a necessary task for the program has been to demonstrate scientific utility for decision-making. As described by one scientist, Regional Highlands Waterwatch has "generally has struggled from the point of view that they're not considered to be accurate, useful data, and just side-lined" (scientist, RHW). The program facilitator explained that delivering a robust monitoring program accepted

externally by decision-makers, and that could inform policy, was critical to ensure the program remained functional:

> Definitely that's been my biggest driver. The reason being though because we lost our funding in 2013. I was starting to talk to [an environmental agency] who looks at funding. I could tell there was this real ambivalence to Waterwatch, that it was this thing that just kept going on and on and on and they couldn't really see any clear tangible evidence of what they did and the effect they were having (program facilitator, RHW).

Demonstrating the "effect" of the program to improve external legitimacy was also assisted by an individual whose work at the science-policy interface was critical in easing the flow of information into the policy arena. The program facilitator of Regional Highlands Waterwatch considered this individual as their "greatest ally" who was able to shift the perceptions of some policymakers on the utility of citizen science.

While the program has been largely successful in shifting to the more policy-oriented approach to promote external legitimacy, it has tried to balance the needs and expectations among volunteers. There was a clear awareness of the potential cost to local identity and independence of gaining external validity. This awareness was captured in the fact that the program facilitator made a concerted effort to distinguish the program as a "'government-delivered program', not a 'government program'":

> I want [volunteers] to feel like they are still very much an independent person who is dealing with a coordinator in the field, that they're not beholden to the [the government] and can't speak their opinions (program facilitator, RHW).

This insight suggests that the program is actively trying to maintain the internal legitimacy among volunteers despite the program's increasing need to demonstrate its scientific value and meet government expectations.

In Mill Stream Waterwatch, one coordinator commented that finding uses for citizen science data at a regional policy-making level within the funding agency was a "harder sell", which the coordinator attributed due to overt resistance from scientists and decision-makers:

> The program is written off by some [who say], "it's citizen science; that's less valuable than the other data being collected across the business" (coordinator, MSW).

Unlike Regional Highlands Waterwatch, demonstrating the external legitimacy of Mill Stream was difficult for the coordinators, in part, because they lacked a contact able to assist in connecting their programs with decision-makers within the funding agency:

> I don't have someone who has a lot of time internally to make that link between the data and the research that's done by consultants. And then the potential with this to be a way to make data more meaningfully used (coordinator, MSW).

The program, according to one coordinator, has found "much more value in the small-scale projects and making these projects very specific and very relevant" (coordinator, MSW). For volunteers, this coordinator suggested that short-term engagements were much more effective at promoting inclusive engagement in water resources management because volunteers are "having a hands-on experience" and can "quickly build up a sense of ownership" (coordinator, MSW).

7.5.3.3 Flexibility and stability

The final tension inherent to network governance is between flexibility and stability, which refers to being adaptable to changing conditions while maintaining consistent actions over time. In Regional Highlands Waterwatch the recent efforts to embed the program within government decision-making has enabled the program to maintain consistency in data collection and reporting activities. Despite this, the program facilitator was aware that their centralised position was a risk to the program's stability if they were no longer able to run the program and that this, therefore, required careful management:

> I try to have processes in place that over-ride personalities so that if I left or if that other person left, that it isn't just dependent on a good personality relationship (program facilitator, RHW).

Despite the program's consistency in actions, it simultaneously lacked the flexibility and capacity necessary to address local environmental problems when they occur:

> It can be frustrating constantly getting that data and seeing something that's a problem and not being able to do anything about it; that's not our job to take that data and turn that monitoring into action kind of thing, because we don't really have the capacity to do that (program facilitator, RHW).

This lack of capacity to address local issues—while not consistently identified across the volunteer data—was verified by one volunteer who described a particularly frustrating experience. This volunteer revealed an instance where significant and frequent nitrate spikes were discovered and was raised with the local council. With assistance from a regional coordinator, the volunteer contacted the environmental regulator but was met with inaction over what was perceived to be an obvious pollution impact. The volunteer felt that this work was not being taken seriously by environmental agencies and was frustrated by the lack of feedback: "you think what's the bloody point of doing all this work if you're already not going to take any interest in what is obviously a problem" (volunteer, Regional Highlands).

By contrast, Mill Stream Waterwatch is structured and governed in such a way that it has a high level of flexibility, which enables rapid attention to changing local conditions. The following quote demonstrates this benefit as described by a volunteer from one group who worked with local stakeholders and the funding agency to address a pollution event in their local waterway:

> A local resident started complaining about a bad smell in the lake and then we took samples and that's when we realised that there was *E. coli* in the water. We sent that sample to [the funding agency] and after couple of days we understood that was there a sewage pipe had burst and then [the funding agency] sent some tankers of clean water to flush out that sewage water. And ultimately the problem was solved, but it was only because of the Waterwatch [Mill Stream] program that we were able to identify the issue and get rid of the pollutants and sewage water (volunteer, MSW).

For around half of the volunteers we interviewed from this cohort, a consistent message was that they were under the impression they were collecting data for use by the funding agency, as this representative quote describes: "It is our understanding that [the funding agency] use those results to ensure that the health of the waterways" (volunteer, MSW). However, a catchment manager working in the funding agency identified there was a disconnect between the expectations between volunteers and the funding agency. The catchment manager cited a survey conducted within the organisation to understand differences in perspectives, highlighting the stability of volunteer participation in the program is at risk:

> The information that is collected by Waterwatch [Mill Stream] wasn't the key value [as perceived by the funding agency], but the volunteers saw that the information that they were collecting was the most important thing they were doing…I think that's the risk with the program, because it made me feel like, if the volunteers knew this, all of their motivation might disappear because they're saying [data uptake] is really important, but little do they know, it's not that, and I think that's a problem (catchment manager, MSW).

These insights again highlight the importance of gathering qualitative data to better understand perceptions, motivators and discrepancies - and the potential impact of these on program outcomes and goal development into the future.

7.6 Discussion

7.6.1 The social complexity of citizen science

This study employed social network analysis to examine the characteristics and impact of data sharing and collaborative relations in two freshwater citizen science projects in Australia. These two projects advance different objectives: one with a focus on building community capacity (Mill Stream Waterwatch) and the other with a focus on data uptake for regional decision-making (Regional Highlands Waterwatch). The results of the study have shown that both programs were characterised by a diverse network of actors from government agencies, universities, community-based organisations, local councils and private industry. This study highlights the benefits of citizen science in bringing together diverse actors to address natural resource management issues. In addition, the use of social network analysis showed how these actors are connected in a social network structure. Programs were found to have created different social network structures across both studied relations, as understood through the analysis of key network measures including density, network centralisation, core-periphery analysis and cross-boundary exchange.

Regional Highlands Waterwatch revealed a more centralised and well-connected (i.e. higher density, higher average degree and less isolated components) than Mill Stream Waterwatch across the data sharing and collaboration network. Furthermore, the social networks of the Regional Highlands case were strongly correlated with a core-periphery structure, which have been observed in other environmental networks (Ansell 2003,

Ernstson et al. 2008). Core-periphery networks have been correlated with high efficiency in sharing knowledge, capacity to solve well-defined problems and collective action in environmental governance (Provan and Kenis 2008, Bodin and Crona 2009). This structure is suggested to be appropriate for the program's primary objective to create an efficient and robust water monitoring program, which was dependent on the coordination and prioritisation of data collection activities.

By contrast, the social networks of Mill Stream Waterwatch were characterised by more decentralised structures, particularly for the collaboration network that had a particularly low degree centralisation score (20%). Decentralised networks are recognised to enable programs to solve more complex tasks (Leavitt 1951), such as mobilising to address urgent environmental threats. Enqvist et al. (2014) similarly suggested that a distributed network approach is correlated with an openness to change and experimentation. Like the Regional Highlands case, the social networks of Mill Stream Waterwatch were a reflection of its primary objectives, which is to build the skills of volunteer groups to take action in their local areas.

Cross-boundary exchange also differed across the two programs. Cross boundary exchange measures the heterogeneity in a social network and indicates the level of resources available, and how these are exchanged (Sandström and Rova 2010). With respect to the overall cross-boundary exchange, Mill Stream Waterwatch was found to be more heterogenous for the data sharing network than in the Regional Highlands case. This finding suggests citizen science data are shared with a greater diversity of stakeholders at Mill Stream over Regional Highlands. However, the opposite was true for the collaboration network, with Regional Highlands Waterwatch displaying a slightly higher percentage of cross-boundary interactions. Most striking, however, were the differences in volunteer data sharing and collaboration ties with fellow volunteers (i.e. "bonding" ties) or actors in different roles (i.e. "bridging" ties). Volunteers from Mill Stream Waterwatch were much more likely to report ties both with other volunteers and also actors in roles other than their regional coordinator - i.e. having stronger both bonding and bridging ties. This is an important insight as Bonding ties at the community-level have been recognised as critical to

create a shared identity, maintain trust and work on complex tasks. Alternatively, bridging ties connect actors to new ideas and resources and gain access to people in positions of power. Dale and Newman (2010) suggest that a balanced mix of bonding and bridging ties is necessary condition for sustainable community development. Building insights into the extent of bonding and bridging capital, as allowed through the use of social network analysis of these two programs, provides important insights for program planners and funding bodies on effective strategies for working sustainably and effectively within a community-based setting.

7.6.2 Social networks and knowledge outcomes

Both Mill Stream Waterwatch and Regional Highlands Waterwatch have successfully contributed data to underpin policy and on-ground management actions. While each program has demonstrated a capacity to inform decision-making across a typical adaptive management cycle, the scale of these impacts differed between programs. Whereas Mill Stream Waterwatch was found to impact decision-making mostly at the site and sub-catchment-level, Regional Highlands Waterwatch was more effective at impacting decision-making at a regional level. A review of the data from which these insights were drawn suggest that by drawing on this additional dataset, I suggest that differences in network structures are related to the type and scale of each program's contribution to catchment decision-making. This relationship between network structure and policy outcomes has longstanding support in environmental governance literature (Howlett 2002), but is typically not considered in citizen science. There has been a tendency in citizen science literature to consider that the factors enabling positive connections are related to a program's inherent characterises and design features (Shirk et al. 2012), such as rigorous data quality standards or high levels of volunteer participation. While these insights are useful, they neglect the critical role of network structure in shaping program outcomes that was addressed in this study. Henry and Vollan (2014) suggest social networks reveal the position of certain actors who facilitate or inhibit information delivery, or actors who have the ability to apply this information. Differences in network structures are related to the type

and scale of each program's contribution to catchment decision-making. This relationship between network structure and policy outcomes has longstanding support in environmental governance literature (e.g. Howlett 2002), but is typically not considered in citizen science. There has been a tendency in citizen science literature to consider that the factors enabling positive connections are related to a program's inherent characteristics and design features (Shirk et al. 2012), such as rigorous data quality standards or high levels of volunteer participation. While these insights are useful, they neglect the critical role of network structure in shaping program outcomes. This is an issue that was addressed in this current study. Henry and Vollan (2014) suggest social networks reveal the position of certain actors who facilitate or inhibit information delivery, or actors who have the ability to apply this information.

In the Mill Stream case, limited connections were found between coordinators and decision-makers. Further, the limited connections among coordinators was an identified issue that has the capacity to pose additional difficulties in coordinating the entire network to achieve collective aims. Together, these deficiencies in the network were found to reduce possibilities to achieve data uptake in policymaking at a regional level. Despite this, the local development of social networks in the urban environment where Mill Stream Waterwatch conducts activities was assessed as a suitable way to address local and acute environmental issues, such as pollution events or restoration activities, which are common in urban environments. At this scale, Mill Stream Waterwatch has generally been successful at achieving impacts on-ground management actions and this success was found to be a result of these local connections between volunteers, coordinators and other local stakeholders.

By contrast, the core-periphery network structure of Regional Highlands Waterwatch program is, as suggested in previous research (Bodin and Crona 2009), served an important role in coordinating activities and facilitating knowledge uptake. The capacity of Regional Highlands Waterwatch to link the program within policymaking at a regional level can be explained, at least in part, by the presence of a tightly connected group of scientists who actively collaborate and share data within the network. However, this same network structure was not efficient at addressing and solving local environmental concerns. This was

due to the fact that local network structures were not a main feature of the network. This insight highlights the dual nature of social networks and the tensions inherent to its proper function.

7.6.3 Navigating network tensions

The use of qualitative methods proved important to validate the structural analysis that was a central component of this study, but also to understand how actors navigated and responded to basic tensions that result from decisions to adopt a particular form of network governance (Provan and Kenis 2008). The Regional Highlands was found to prioritise network efficiency, external legitimacy and stability. As described, the program has been successful in developing an efficient and stable broad-scale monitoring program with consistent impacts on regional-level policymaking. However, as Regional Highlands has prioritised efficiency and stability, it has simultaneously reduced the inclusiveness and flexibility of the program. This was particularly evident in its lack of capacity to respond to the needs of volunteers and quickly changing environmental conditions. While the inability to address acute environmental threats was an issue for some volunteers, many others were encouraged that their efforts were acknowledged by government and were happy to be part of a broader monitoring effort. This finding aligns with research by Bodin and Crona (2009 p. 371) who suggest that core-periphery structures are less likely to suffer from "us-and-them" attitudes that might generate conflict among actors because 'there is only one "centre-of-gravity".'

By contrast, the Mill Stream Waterwatch encourages inclusiveness, internal legitimacy and flexibility. The decentralised network has enabled the program to quickly respond to changes in environmental conditions or engage in short term projects with local stakeholders or catchment managers. This approach is characteristic of flexible network structures. The program's focus on local activities presents an inclusive approach that draws on the strong volunteer interest in a local area to address waterway issues of mutual concern. Still, the lack of network connections between regional coordinators and between coordinators and scientists and decision-makers within the funding agency has limited

efforts to manage and share data collectively or collaborate on projects for regional level outcomes. Furthermore, the focus on inclusive participation raises important issues regarding the efficiency of coordination, as coordinators were tasked with managing many volunteer groups, each with different needs and objectives.

7.6.4 Practical implications

The results of this study have provided valuable insights relating to strategies that both programs could implement to maximise the strengths of their social networks, while minimising potential weaknesses. In the Mill Stream case, as identified, the limited data sharing and collaborative ties between coordinators, scientists and decision-makers appears to have constrained the program's capacity to achieve data uptake for regional level policymaking. Equally, the lack of connections at a local level in the Regional Highlands case constrained the capacity to address local environmental problems in an effective and timely manner. The identification of these shortfalls is the first step toward the development of a practical and targeted response to addressing them. This is true both for the case studies that were the focus of this paper, but also in terms of the lessons learnt and the transferability of these to citizen science programs more generally.

As a result of the insights gained in this study it is recommended that programs build understandings of the nature and scope of their social network structure. Importantly, once this is achieved programs should actively develop relationships with individuals currently absent from their network. as part of a strategy to expand their potential sphere of influence in decision-making for waterway governance. This strategy has the capacity to lead to more effective uptake and use of citizen science. It is acknowledged that these efforts can be difficult to achieve since developing more cross-boundary social relations takes considerable time and requires high levels of trust and deliberation (Bodin 2017).

Insights from the qualitative data highlighted the importance of key individuals who act as "bridges" between social groups. It is conventionally understood that citizen science coordinators will embody this role. While this was clearly the case in this study, other individuals were also important. For instance, the scientist in the Regional Highlands case

was critical in enabling greater use of volunteer data while simultaneously shifting the perspectives of decision-makers about the potential of citizen science in environmental governance more broadly. Consequent to this finding, it is suggested that citizen science programs actively recruit, as part of their program development processes, individuals who can act as knowledge brokers, community leaders or policy entrepreneurs.

Overall, the network analysis approach illuminates the role and importance of social networks in collaborative environmental initiatives. As a final recommendation, we suggest that citizen science programs actively foster a networking mindset among participants and build this into program planning and implementation. Programs could organise workshops to discuss and question the nature and quality of their social network. Who is involved and for what reason? Do network connections match individual and program objectives? Are there key individuals missing or other constraints? This type of overt acknowledgement of, and proactive response to, shortfalls in the nature, scope and type of network structure is an important step in building capacity to achieve program goals and objectives.

While it was outside the scope of this study, future research conducting a social network analysis of citizen science could present their findings back to programs to facilitate this reflection (e.g. Beilin et al. 2013). It is also possible for programs to undertake more informal exercises themselves, such as through participatory community network mapping (de Moor 2018), to collaboratively understand and assess their network and develop appropriate strategies moving forward.

7.6.5 Limitations

This study has provided some valuable insights relating to the role of social network analysis in enhancing and strengthening network ties, and through this, program potential. It Is however acknowledged that there were some limitations to the research design. While responses were captured from the majority of actors in professional roles across the case studies, the low response rate of volunteers limited that capacity to gain a full picture of their network connections. Ethical considerations that constrained the ability to contact volunteers directly played a significant role in suppressing the response rate of volunteers.

A valuable lesson was learnt relating to the importance of having prior connection to research participants to increase the willingness of individuals to participate in the study. This is an insight that has been reported by others (Borgatti et al. 2013).

A second limitation was the cross-sectional nature of the research design that captured only a snapshot of network connections at a single point in time. This limitation resulted in study findings related to the structure and outcomes being able to only provide insights on likely correlations, not causations. This limitation highlights the importance of longitudinal studies to address this shortfall although It Is acknowledged that such studies are difficult to achieve in real world settings. The comparative nature of our study, and the use of mixed methods, provided a way to, at least partly, offset the negative effects of these two limitations (Holstein 2011).

7.7 Conclusion

This study applied the conceptual and methodological tools of social network analysis to investigate how actors in two longstanding freshwater citizen science programs are embedded in a social network structure, and the relationship between structure, function and outcomes. This work thus illustrates that not all citizen science networks are created equal. Similar programs can create different network structures, which will influence how actors navigate and experience relationships within the network and the outcomes that can be achieved. These findings illustrate the social complexity in place for citizen science programs as they aim to influence policy and on-ground management outcomes. They suggest that the effectiveness of citizen science is dependent on patterns of relations in a larger network structure. This study extends previous research on the factors that enable productive connections between citizen science and environmental governance. The insights gained from the study reinforce the importance of encouraging practitioners to adopt a networking mindset which promotes the importance of giving consideration to their own relationships within and external to their program.

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In the following chapter, the final dimension of the relational framework is examined. This article draws on the concept of boundary work to provide further insights into the relational foundations of citizen science knowledge and practice. Boundary work shifts the attention from the connectivity between actors in a citizen science network, towards the social practices and contextual factors that shape and define the practice, particularly as it relates to maximising its credibility, salience and legitimacy in the wider environmental governance landscape.

8 Citizen science in the making: participation, boundary work and linking knowledge and action

8.1 Abstract

This article examines the social and organisational dynamics that facilitate the acceptance and uptake of citizen science in waterway governance. The research draws on semi-structured interviews with a broad range of actors who influence the processes and outcomes of two freshwater citizen science programs in Australia. Analytically, we employ the concept of "boundary work" to understand how the boundaries between citizen science and expert communities are defended, maintained or redrawn through social practice. The paper describes three types of boundary work: (1) constructing boundaries, (2) aligning boundaries and (3) reconfiguring boundaries, and examines how these practices shape the credibility, salience and legitimacy of citizen science knowledge and practice. The main contribution of this paper is illustrating how citizen science programs have overcome existing organisational boundaries and maximised their credibility, salience and legitimacy. This paper thus presents new insights on the micro-level interactions that enable and constrain the inclusion of citizen science knowledge in environmental governance contexts.

8.2 Introduction

Citizen science is a rapidly growing participatory knowledge practice that is commonly discussed as a way to overcome perceived "chasms" or "gaps" between science, society and policy (Pfeffer and Wagenet 2007, Vaughan 2007, Cavalier and Kennedy 2016, Hecker et al. 2018a). The basic argument is that by connecting the public with science, decision-making becomes more effective and responsive to local needs. However, citizen science currently faces several challenges that limit its acceptance and uptake in natural resource management contexts. One enduring challenge relates to perceptions by scientists and decision-makers that citizen science is an inferior source of knowledge for environmental decision-making (Freitag et al. 2016). Previous research has addressed this issue in various ways, such as demonstrating the accuracy of citizen science data, providing recommendations to improve project design, or describing new technologies that enable knowledge outcomes. While this work has provided valuable insights, considerably less research attention has been paid to *how* people and organisations work together to enable collaboration, align professional and citizen science and promote learning opportunities and supportive institutional cultures.

The premise of this article is that, to understand how and why citizen science promotes innovation at the science-society-policy interface, it is necessary to examine the social and organisational dynamics that shape and define the practice. Analytically, we employ the concept of "boundary work"—a concept drawn from STS literature that has proven useful to examine how fields of knowledge are constructed, defended and undermined (Gieryn 1983, Jasanoff 1987). In recent years, boundary work has been in a range of environmental governance settings to understand how boundaries between different social groups, such as researchers and policymakers, can be managed and practically aligned to promote more productive knowledge-action relationships (Cash et al. 2003). Boundary work shifts attention away from boundaries as being fixed and stable entities, which are crossed or connected as processes are improved or outcomes are achieved (Toomey 2017). Instead, boundary work highlights their fluid and evolving nature "made real" through negotiation and social practice (Tuinstra et al. 2006, Wehrens 2014).The premise of this article is that, to understand how and why citizen science promotes

innovation at the science-society-policy interface, it is necessary to examine the social and organisational dynamics that shape and define the practice. Analytically, we employ the concept of "boundary work"—a concept drawn from STS literature that has proven useful to examine how fields of knowledge are constructed, defended and undermined (Jasanoff 1987, Gieryn 1983). In recent years, boundary work has been used in a range of environmental governance settings to understand how boundaries between different social groups, such as researchers and policymakers, can be managed and practically aligned to promote more productive knowledge-action relationships (Cash et al. 2003). Boundary work shifts attention away from boundaries as being fixed and stable entities, which are crossed or connected as processes are improved or outcomes are achieved (Toomey 2017). Instead, boundary work highlights their fluid and evolving nature "made real" through negotiation and social practice (Tuinistra et al. 2006).

In this study, we are interested in how different types of boundary work divide and align citizen science and expert communities (Langley et al. 2019). Furthermore, we are also interested in how boundary work influences the credibility, salience and legitimacy of citizen science in different environmental and governance contexts (Cash et al. 2003). The current study was undertaken in 2019 and involves content analysis of interviews with key actors in two longstanding citizen science water monitoring programs in Australia. Before describing the findings from the study, the following section expands on theoretical and definitional issues of boundary work and describe three types proposed by Langley et al. (2019). The framework developed by these authors was foundational in structuring the qualitative analysis used for this current study and was used as a conceptual framework to understand similar practices that were identified within each of the case studies examined for this paper. Our findings show that boundary work is a useful concept to explain the challenges faced by citizen science programs to gain acceptance by expert communities in environmental decision-making. The implication of this research relates to the importance of viewing boundaries as subject to human agency. This insight not only enriches understanding of the social, contextual and political factors shaping the citizen science but also identifies key strategies to improve the acceptance and uptake of the practice.

8.3 Theory and practice of boundary work

8.3.1 Boundary work in theory

Boundary work was originally proposed by Gieryn (1983) to describe how scientists defended themselves and their work from "non-science." Gieryn's (1983) main contribution was showing that the credibility of science is not formed through its inherent set of rules and methods but, rather, through rhetorical strategies and social practices that cast science more favourably than other forms of knowledge. More recently, researchers have adapted boundary work not only to examine the exclusion of knowledge but also how knowledge-action relationships can be aligned and practically coordinated. In this context, the effective management of boundaries becomes foundational to linking knowledge and action.

According to Cash et al. (2003, p.8086, emphasis in original), 'scientific information is likely to be effective in influencing the evolution of social responses to public issues to the extent that the information is perceived by relevant stakeholders to be not only *credible*, but also *salient* and l*egitimate*.' Credibility refers to how actors perceive the technical accuracy of information and whether it meets the standards set by the scientific community, salience refers to the relevancy of information to meet the objectives of a given stakeholder in a timely manner, and legitimacy refers to whether a stakeholder perceives the processes of knowledge production to be fair and adequate. However, actors across different sides of a boundary may perceive and value the credibility, salience and legitimacy differently. Thus, the way in which boundaries are bridged or drawn requires careful attention and management to balance these tensions over time (Parker and Crona 2012).

Researchers have developed a number of boundary work concepts, including boundary organisations (Guston 2001), boundary spanning (Wenger 2000) and boundary objects (Star and Greisemer 1989). These concepts and organisational structures help to support efforts at linking credible, salient and legitimate knowledge to decision-making. Boundary spanning, for instance, refers to the way in which people work across existing boundaries to promote the use of science to inform decision-making. In citizen science, for instance, coordinators play a key role as boundary spanners, assisting in translating

information across boundaries—connecting individuals and processes—to promote collaboration and uptake of knowledge. They work to align the perspectives of different actors and may attempt to overcome and transform institutional barriers (Nederhand et al. 2019). A key aspect of boundary work is the creation and use of boundary objects, which are artefacts, such as maps, databases, modelling. Boundary objects can enhance the ability to span boundaries as they provide a common focus for different actors to recognise environmental problems and thus help fuel collaboration and cooperation by adapting to the diverse interests of those who employ them (Star and Greisemer 1989).

8.3.2 Doing boundary work

In practice, the relative rigidity and permeability of boundaries can arise through different types of boundary work. In a recent review of boundary work in groups and organisations, Langley et al. (2019) presents a useful framework that describes three types of boundary work: working *for* boundaries, working *at* boundaries and working *through* boundaries (Table 15).

Table 15. Three forms of boundary work (adapted from Langley et al. 2019)

Type of boundary work	Definition	Significance
Working *for* boundaries	The efforts by actors to construct, defend and extend boundaries to maximise social position, access to resources and legitimacy.	Creates, reinforces or disrupts power relations between groups of actors Can promote efficiency
Working *at* boundaries	The practices, objects and sustained patterns of interactions between groups and organisations to pursue collective aims.	Encourages collaboration, coordination and learning Can create tensions for actors meeting competing needs and demands across boundaries.
Working *through* boundaries	The efforts by actors to manipulate or arrange boundaries to bring actors, ideas or practices into new configurations i.e. through experimental spaces.	Promotes creativity, reflexivity and opportunities to experiment Often temporary, maintains status quo among power relations.

First, working *for* boundaries, or 'competitive' boundary work, refers to how actors construct, defend or extend boundaries to obtain particular benefits and influence (Langley et al. 2019). For scientists engaging in this form of boundary work, they may make use of technical language, which emphasises elements of rigour, objectivity and causality, or present work in a way that makes it appear authoritative. They may also decide on how tasks, roles and responsibilities are divided, thereby defining the scope of inclusions of other forms of knowledge. While this form of boundary work can promote efficiency and organisational stability, it can have consequences for other forms of knowledge. For instance, knowledge practices considered illegitimate can lose influence and access to political and cultural resources, which undermines its credibility in policy debates (Eden 2010).

Second, working *at* boundaries, or 'collaborative' boundary work, refers to the alignment of boundaries through negotiation and coordination to pursue collective aims. Collaborative boundary work acknowledges that at the same time as boundaries are defended, they may also need to be spanned for individual or collective action towards a shared goal (Hoppe 2010). Thus, this form of boundary work highlights boundaries as "junctures," or sites that enable cooperation and new ways of working (Quick and Feldman 2015). Collaborating at the boundaries frequently means developing shared understandings of problems and solutions, negotiating the divisions of tasks, roles and responsibilities and openly discussing problems and potential solutions. However, in collaborative boundary work, tensions may emerge as actors working at boundaries 'manage the ambiguities of belonging to and navigating different worlds' (Langley et al. 2019, p.35).

Finally, working *through* boundaries, or 'configurational' boundary work, refers to efforts by actors to manipulate or arrange boundaries to bring people, ideas or practices into new configurations. Langley et al. (2019) discusses several studies that document the creation of temporary, bounded spaces for interaction, or what Zietsma and Lawrence (2010) call *experimental spaces*. Such spaces enable actors to engage in practices that they would not normally be able to achieve in their regular environment, which can promote flexibility, trust and motivation to participate. While the temporary nature of these spaces means that

actors do not have to commit to building newly learned practices into their everyday work, it may maintain the pre-existing power relations. Studies of configurational boundary work highlights that boundaries are not just ways to maximise legitimacy (i.e. competitive boundary work) or align activities (i.e. collaborative boundary work) but also have potential to promote transformation by manipulating and rearranging these processes of exclusion and inclusion.

A current limitation in boundary work literature is lack of attention to how peripheral actors and marginal knowledge practices construct, align or break-down boundaries to maximise their social position and promote collaboration. Most research focuses on how boundary work is enacted by researchers and decision-makers as they negotiate the boundaries of science and policy. In citizen science, the few studies applying boundary work reveal novel insights into the processes of inclusion and exclusion in "social movement-based" citizen science (Epstein 1995; Kimura 2019; Ottinger 2010). For example, Ottinger (2010), while not explicitly using the term boundary work, demonstrated the importance of scientific standards in serving a "boundary-bridging" function to coordinate scientific work and a "boundary-policing" function that allowed scientists and regulators to exclude citizen science data because it did not meet professionally defined standards. Less research attention has been paid to boundary work in state-sponsored citizen science projects, or what has been termed "scientific authority-driven citizen science" (Ottinger 2015). This is despite similar epistemic struggles between professional science and citizen science also existing in these projects (Ellis and Waterton 2004, Cornwell and Campbell 2011). Thus, it is within the context of scientific-authority driven projects that we assess role of boundary work in citizen science.

8.4 Research context: freshwater citizen science in Australia

Waterwatch, a longstanding community-based water monitoring program in Australia, serves as our case study to examine the role of boundary work in citizen science. Beginning in the early 1990s, Waterwatch was delivered as part of several strategies to increase community involvement in the management of natural resources. The program has

maintained longstanding commitment to building local capacity and raising awareness of catchment health issues. A distinct advantage of Waterwatch lies in its flexible model, which enables regional programs to adapt to locally specific socio-ecological contexts (Thompson 2007). As a result, many programs have developed independently of each other and combine different objectives, methods of data collection and levels of volunteer involvement (Bonney et al. 2020; Chapter 5). In recent years, government agencies have expressed interest in exploring the scientific potential of Waterwatch to fill knowledge gaps and contribute to management and policy decisions.

Waterwatch serves as an ideal case study to examine boundary work in citizen science due to its prominence as a key participatory mechanism in Australian natural resource management, its goals in fostering productive community-government relations, demonstrated contributions to catchment decision-making and well established connections with government, non-government and community organisations (Bonney et al. 2020; Chapter 5). Two programs were chosen for this comparative study: Mill Stream Waterwatch and Regional Highlands Waterwatch[5]. Both programs have a long history, with a similar large number of volunteers and monitoring sites in their respective region. They are both funded by government and have demonstrated a strong capacity inform the management of water resources while building active community participation (see Chapter 3 for a full description of study cases).

The first case, Mill Stream Waterwatch, is funded by a large water utility company responsible for the management and protection of waterways across the region. The program has five paid coordinators each responsible for one priority portfolio (water quality, platypus, macroinvertebrates, frogs and litter) and a region for coordinating water quality monitoring activities. Mill Stream Waterwatch operates in a governance context that emphasises community capacity-building under the region's waterway management strategy, which provides direction for a regional vision of waterway health. Included in this

[5] While Waterwatch is the actual name of the longstanding community-based water monitoring program in Australia, we have used pseudonyms for the two case studies to protect the confidentiality of programs and participants as per our ethical obligation.

strategy are goals to elevate the importance of citizen science, with key performance objectives aimed at promoting environmental stewardship and connections to waterways, strengthening community-government relations and building community leaders.

The second case, Regional Highlands Waterwatch, is partly funded by a state government, with funding assistance from a state-owned water utility company. Volunteers are coordinated by four regional catchment coordinating committees, each employing a single coordinator whose role is to interface between community and the program facilitator who sits in state government. The facilitator overseas the activities of the coordinators and promotes the program internally. Regional Highlands Waterwatch is guided by policy that supports the integration of Waterwatch in government monitoring to enable a better understanding of water resources in the region. The program also has objectives to promote increased community awareness of waterways issues.

Despite several similarities, the two programs differ in two important ways. The first distinction relates to the broad focus of each program, as described above. The second distinction relates to the environmental context in which the programs are situated. Mill Stream Waterwatch conducts activities in urban and peri-urban environments and largely aims to address urban waterway issues such as stormwater and urban runoff, industrial pollution, development and threatened species protection. By contrast, Regional Highlands Waterwatch mainly involves volunteers in monitoring rural areas, with key waterway issues including drought, invasive species, riparian management, erosion and non-point source pollution.

8.5 Methods

The methods employed in this study draw upon those used in Chapter 7, whereby in 2019, semi-structured interviews were conducted with individuals participating in, or interacting with, the two programs. We employed a cross-cultural sampling approach (Robinson 2014), which selects participants in diverse roles and acquires a heterogenous sample. This approach enabled the comparison of perspectives across groups to search for key similarities and differences. To selected participants, five coordinators from each program were initially,

interviewed as key informants (Gilchrist 1992). We then followed a purposive sampling strategy (Mason 2002) to interview additional actors in professional roles (e.g. scientists, land managers, policymakers, community engagement professionals) who were discussed by coordinators as being important in the planning, development and implementation of Waterwatch. Additionally, ten volunteers were interviewed from each case to capture differences between key informant, professional and community members. In total, twenty interviews were conducted for each study case. Participants included volunteers (n=20), coordinators (n=10), catchment managers, policymakers and scientists (n=3), and community engagement professionals (n=3). Despite our best efforts to interview a similar diversity of roles in each case, we were unable to interview a policymaker from the Mill Stream case.

Interviews lasted between thirty and ninety minutes and were digitally recorded and transcribed. Participants were asked a variety of questions about the nature of their collaboration with other people and organisations, the contributions of citizen science to understanding and managing waterways, enablers and constraints to building new and strengthening existing relationships and visions for an ideal citizen science program in their respective region. The lead author coded interview data through both an inductive (i.e. data-driven) and deductive (i.e. theory-driven) approach (Fereday and Muir-Cochrane 2006). Coding was also guided by the research questions and concepts in boundary work and environmental governance literature. Once coding of interviews was complete, cross-checking results among co-authors was conducted to test for code reliability. The codes were then collated and analysed to identify several overarching themes (Braun and Clarke 2006). These themes captured the boundary work practices enacted by different actors as identified by Langley et al. (2019), and how this work influences the credibility, salience and legitimacy of citizen science (Cash et al. 2003) (Figure 17).

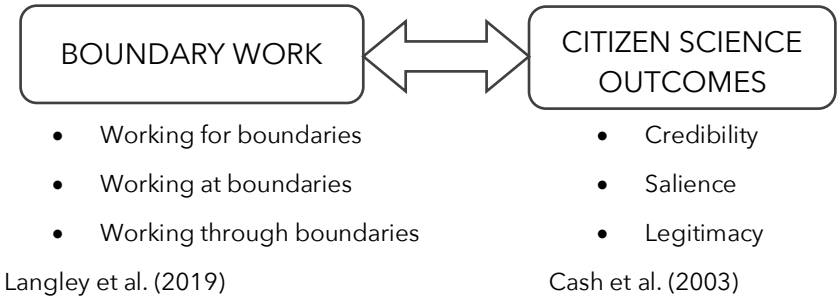

Figure 17. The analytical approach employed to assess (a) the role of different types of boundary work and how this influences (b) citizen science outcomes according to its credibility, saliency and legitimacy.

8.6 Setting the scene: shifting trajectories of citizen science

Before describing the role of boundary work in the identified citizen science case studies, it is important to set the scene relating to shifts that have occurred these case studies as this provides a context against which conceptualise the boundary work practices being discussed. The analysis of interview data revealed that both Waterwatch programs have in recent years shifted in their primary focus along seemingly divergent trajectories. These changes have been pivotal in the way boundary work was performed in each case to ultimately shape the credibility, salience and legitimacy of citizen science knowledge and practice. This makes exploration of these shifts integral to building an understanding of the ways in which boundary work occurs, and ultimately shapes and defines practice. Firstly, in Mill Stream Waterwatch, the program has transitioned from practising broad-scale community engagement and delivering public-facing events to instead adopting a community capacity-building approach as its primary objective. As one coordinator described:

> Whereas previously it was all about chasing targets in terms of the number of people that we've engaged…we had quite a big shift around building capacity in the community where they can take those next steps and be a lot more effective at protecting their waterways and taking actions (coordinator, MSW)

As part of this approach, volunteers involved in long-term water quality monitoring are required to decide on the purpose, tasks and reporting of their data collection efforts

with assistance from their regional coordinator. The role of the coordinator is to facilitate participant training, partnership building and resource delivery. As assessed by one coordinator, this change in objectives was a way to encourage community members to "do the same things that we do" and "spread the same message" as the funding agency (coordinator, MSW). A scientist from within the funding agency confirmed the coordinator perspective and added that these goals were to "invest in" community leaders and "champions" (scientist, MSW).

In addition to building the capacity of local monitoring groups, Mill Stream Waterwatch also delivers an increasingly diversified citizen science program combining a variety of projects that focus on different aspects of the environment, such as water quality, frogs, platypus, litter and macroinvertebrates. One coordinator indicated that this approach enabled the funding agency to meet "diverse community expectations" and volunteer capacities while generating different types of information to understand trends in environmental condition (coordinator, MSW). However, the state-wide Waterwatch coordinator that was interviewed raised concerns around how the recent enthusiasm for citizen science, and diversity of focus that resulted from this, had the potential to divert attention away from the long-term water monitoring groups, thereby limiting their capacity to deliver outcomes valued by community members and other stakeholders:

> The water quality monitoring stuff doesn't get too much development, or it doesn't seem to progress as far as innovation goes. It just sort of keeps doing the same thing, the same people. And then there's the citizen science stuff, which is very shiny. It's exciting. It's engaging a different audience, but I feel like there's a risk that we're not marrying those two worlds (state Waterwatch coordinator, MSW)

Regional Highlands Waterwatch has also shifted in its program objectives from community-directed and unstructured data collection. However, rather than focus on local-problem solving and community-capacity building, Regional Highlands Waterwatch has worked to develop a regional monitoring program that contributes to government policy and monitoring frameworks. This new direction was, at least partly, a consequence of a precarious funding situation that impacted the stability of the program in 2013. At this time, coordinators testified that the funding agency could no longer justify continued investment

of the program based on its education and engagement benefits alone, particularly when the credibility of their data could not be guaranteed. Our interview with the program facilitator highlighted that the rigorous collection and uptake of community data was a key objective driving the new focus and direction of Regional Highlands Waterwatch:

> Definitely that's been my biggest driver. The reason being though because we lost our funding in 2013. I was starting to talk to [an environmental agency] who looks at funding. I could tell there was this real ambivalence to Waterwatch, that it was this thing that just kept going on and on and on and they couldn't really see any clear tangible evidence of what they did and the effect they were having (program facilitator, RHW).

Following these changes, Regional Highlands Waterwatch became, as assessed by two regional coordinators, as less "volunteer-centric" and more "prescriptive" regarding where volunteers monitor (coordinator, RHW). This strategic approach was aimed at reducing instances where monitoring was redundant but also at enabling greater data coverage in other areas. To reinforce the scientific rigour of the program, Regional Highlands Waterwatch has placed several additional controls on volunteer participation, including (re)selecting monitoring sites, requiring attendance at quality assurance and quality (QA/QC) events, assisted macroinvertebrate data collections and designating specific days and times on which sampling takes place.

A comparative analysis of the interview data from each case study suggested that Mill Stream Waterwatch and Regional Highlands Waterwatch have both largely rejected broad-scale engagement and unstructured monitoring activities that had previously characterised the early iterations of the program. There were also indications that program has continued to operate in a fairly consistent way over the course of its development, which appears to have limited its innovation. Nevertheless, the recent changes to the programs highlight two different approaches taken to involve community members in citizen science, which differ according to the degree of diversification of activities and levels of power sharing. These differences provide valuable insights into boundary work in practice at each location, as discussed in the following subsection of this chapter.

8.7 Boundary work in practice

In this section, we describe our findings related to how individuals participating in, or interacting with, each study case enacted three distinct, but interlacing, forms of boundary work as identified in the framework developed by Langley et al. (2019). In highlighting these practices, we document their purposes, enabling conditions and implications for the credibility, salience and legitimacy of citizen science knowledge and practice. We note here that not all forms of boundary work were evident or equally prominent in each study case. For example, efforts to working at boundaries was a key strategy in the Regional Highlands case, whereas working through boundaries was most pronounced in the Mill Stream case.

8.7.1 Working for boundaries

8.7.1.1 An "edge case" and a "fringe thing"

Coordinators from both case study sites reported, and often expressed frustration, that their program had not been historically viewed by scientists and decision-makers as valuable source of environmental information. In the Regional Highlands case, the program facilitator testified that these perceptions have historically limited possibilities for cooperation and collaboration with expert communities:

> I was never getting invited to any meetings. I was not involved in any networks. It was this fringe thing. It was this community agent thing that no-one really knew much about…It was just not integrated at all (program facilitator, RHW).

In the Mill Stream case, a similar opinion among professional staff that, for instance, Waterwatch is "just a nice little thing that people go and do to keep an eye on their own backyard" (scientist, MSW), was assessed by one coordinator as justifying its exclusion from decision-making processes:

> [W]e are not having discussions around being involved in the [region's monitoring, evaluation and reporting framework]. I find that really disappointing and frustrating that we're not considered as useable data…It's always an edge case by certain sections of the organisation and its only for education and engagement purposes that you'd engage the services of Waterwatch (coordinator, MSW).

The use of terms "edge case" and "fringe thing" provided indications that both Waterwatch programs have historically occupied a marginal position in waterway governance that has ultimately limited the capacity of each program to reach a fuller potential.

Interviews with scientists, land managers and policymakers across both case studies consistently confirmed coordinator perspectives and additionally described the underlying mechanisms that constructed a boundary between citizen science and expert communities. Four key justifications were used: (1) citizen science lacks credibility; (2) volunteer-collected data are irrelevant to professional priorities (i.e. lacking salience); (3) citizen science is more appropriate as a community engagement mechanism (i.e. lacking legitimacy); and (4) there existed little demand for citizen science data in environmental decision-making. Table 16 provides a structured overview of each of these justifications, along with a representative quote that captures the views of interview participants and provides evidence on how these justifications were determined during the process of data analysis.

The fourth justification referring to a lack of demand for citizen science data was a consistent theme only in the Mill Stream case. In the Regional Highlands case, a government scientist stated that sources of professional water data were "starting to go missing", which required the adoption of other methods, including citizen science, to "pick up the slack" (scientist, RHW). As a result, government scientists and decision-makers described their increasing openness to developing a relationship with Regional Highlands Waterwatch. This was a notable development in the history of the program since one scientist described this relationship as being "really challenging in the past" (scientist, RHW). A policymaker in the Regional Highlands case confirmed this new willingness to engage with the program but assessed it as being a direct result of improvements to the scientific quality and design of the program rather than based on any particular need for citizen science data:

> I think in the last couple of years [Regional Highlands Waterwatch] has improved in a more coordinated fashion and I think it has been part of that process to get a better picture of water quality in [the region] (policymaker, RHW).

Thus, the cross-contextual analysis of interview data showed that the boundary between citizen science and expert communities was not only influenced by a form of exclusionary

boundary work enacted by scientists and decision-makers that cast citizen science less favourably than professional science. The relative rigidity and permeability of this boundary appears furthermore determined by the historically contingent socio-cultural context (i.e. the relative need for citizen science data in the face of human and financial resource constraints).

Table 16. Justifications for limited integration of Waterwatch data in decision-making from interview data.

Justification/ argument	Explanation	Representative quote
Credibility	Citizen science lacks demonstrated capacity to collect credible data that meets strict scientific standards associated with environmental decision-making	"I think Waterwatch generally has struggled from the point of view that they're not considered to be accurate, useful data and just sidelined." – scientist, RHW
Salience	Citizen science is irrelevant to professional priorities in water governance due to differences in goals, methods and values	"[T]he things that we'd be really wanting to look at are the things that the community can't monitor, like heavy metals, like E. coli, like the nutrient species" – scientist, MSW
Legitimacy	Citizen science is better placed as a community engagement mechanism that serves governments by building policy support and creating local leaders	"To my mind, it's a community education program, it's not a community data generating program, and it's learning by doing, and it's the communication of that learning through the rest of the community" – scientist, MSW
Demand*	Citizen science data is not integrated due to limited demand by scientists and decision-makers	"[W]hy would we use Waterwatch volunteer data when we've got [a professional organisation's] data that comes in at the same time every month [and] is really reliable?" – catchment manager, MSW

*This justification was only observed in the Mill Stream case.

8.7.1.2 Creating distance

Constructing boundaries between citizen science and expert communities was not just performed by professional scientists and decision-makers. Coordinators, too, were assessed as being involved in this type of boundary work as a means to improve program efficiency by delineating tasks, roles and responsibilities. In the Mill Stream case, the program's capacity building goals have decentralised control over the processes and outcomes of

monitoring activities. On the one hand, our interviews with some volunteers highlighted the benefits of this approach as they took on this responsibility to drive their data collection efforts and succeed in building new relationships, developing skills and addressing locally defined problems. On the other hand, we spoke with three additional volunteers who were uncertain about the credibility of their efforts and how it would be received by other stakeholders, as this representative quote illustrates:

> So, the concerns are that the water quality in [the creek] is decreasing. We would like to have some data to present to show this. I'm not sure a) whether our data is good enough and b) whether it's going to have any effect anyway, which presents a bigger problem of how we encourage landowners concerned about their water quality to do something about it (volunteer, MSW).

This inconsistent feedback from volunteer participants highlights the benefits and challenges of a localised and action-oriented approach. While volunteers were given additional responsibility relating to management of local issues, the way in which this was being implemented and managed also meant that their activity was in some cases occurring in a knowledge and policy vacuum. The approach can therefore limit their capacity to build knowledge and connection across the broader environmental landscape, thereby maintaining boundaries and excluding individuals from solving difficult-socio political challenges.

Another type of boundary maintenance enacted by coordinators was also revealed in the Regional Highlands case. This involved a concerted effort to distinguish the education goals of the program from the scientific goals. As the program facilitator in this case suggested, “you’ve got to be really careful that your education goals are not muddled with your data goals, because I think [if they are], you do them both a disservice in a way” (program facilitator, Regional Highlands). The perceived need to maximise the legitimacy of the program by improving the clarity of the program's objectives and adhering rigidly to the parameters set for accepted educational and data goals was a clear example of a boundary work. This strategy was overtly adopted by the coordinator for boundary maintenance and highlighted the key role played by coordinators in setting and maintaining predetermined boundaries for both the program, and those participating in it.

8.7.1.3 Extending boundaries

While there was evidence found in the Regional Highlands case of boundary maintenance by coordinators, there was also an important example within this same case study of how the extension of boundaries can profoundly shape how citizen science is received by expert communities. As described in the previous section, the program has renewed its aims to integrate its program's data into regional decision-making. All coordinators from this case commented on the fact that the success of this approach was largely attributed to the program facilitator who had the "strategic vision" and "leadership at the top" (coordinator, Regional Highlands) to make these changes. They each highlighted the same example whereby the program facilitator commissioned a local university to examine the quality of Regional Highlands Waterwatch data compared to a professional dataset. The report demonstrated equivalency between the two datasets, among other scientific benefits, and was assessed by some as being "fundamental" in securing additional funding (program facilitator, Regional Highlands). This example shows Regional Highlands Waterwatch was able to improve its credibility by extending its boundaries to include a reputable, external organisation that validated its activities.

8.7.2 Working at boundaries

8.7.2.1 Appealing to scientific authority

A consistent theme across both study case studies was a belief that sound science was essential for collaboration with expert communities or to advocate for environmental change. This sentiment was described succinctly by the program facilitator in the Regional Highlands case:

> We need to have a tight case if we're going to throw rocks at people. We do throw rocks at people; we just have to make it clear that we've got evidence to support it. I don't think anyone can argue with you then (coordinator, Regional Highlands).

This perspective that advocacy requires a "tight case" highlights the way volunteers view the role when working at boundaries by conforming to the rigorous scientific standards underpinning environmental decision-making. For example, a volunteer we

interviewed from Mill Stream Waterwatch similarly describes the importance of science for challenging industry to reduce their pollution impacts, commenting: "[I]f you show them the numbers and provide a solution, I think they'll be more cooperative and willing to help" (volunteer, Mill Stream Waterwatch).

Yet, several interviews with volunteers showed that even when armed with data supporting adverse environmental impacts, resolution of environmental problems was still found to be a difficult process. For example, an interview with a volunteer from Regional Highlands revealed an instance where the volunteer observed significant and frequent nitrate spikes and raised the issue with the local council. This volunteer was ultimately met with inaction over what the volunteer perceived to be an obvious pollution impact likely emerging from a recent housing development. The volunteer felt that the work was not being taken seriously by environmental agencies and was frustrated by the lack of feedback: "you think what's the bloody point of doing all this work if you're already not going to take any interest in what is obviously a problem" (volunteer, Regional Highlands). This example provides an important illustration of the potential of existing boundary constraints to minimise proactive action (regardless of scientific data) and disempower groups and individuals attempting to work across boundaries to achieve enhanced environmental responses.

8.7.2.2 Translation and timeliness

A key factor enabling closer alignment between Regional Highlands Waterwatch and expert communities was the presence of the program's previous scientific advisor. This individual, who now works to develop more environmental monitoring plans for the region, was foundational to redeveloping the Regional Highlands Waterwatch program with assistance from the program facilitator. This individual's deep understanding of the limitations and possibilities of citizen science data have been critical in championing the program and shifting viewpoints from within government departments. The scientific advisor is a self-described 'boundary spanner' and considers one of their main roles is to deliver maximum benefits across community and government:

> I see my primary role now, in regard to [Regional Highlands Waterwatch], is finding ways to maximise the value that Waterwatch data can provide to both government but also more broadly, I suppose, to community (scientist, RHW).

To achieve this goal, this scientist highlighted the importance of communicating the benefits and limitations of community data to catchment managers and policymakers. The scientific advisor insisted that citizen science data is not a panacea and is not suited to every catchment management issue. Furthermore, the scientific advisor emphasised the importance of timing as critical to the alignment of citizen science with decision-making:

> A policy maker is only interested in understanding monitoring data and what monitoring programs are out there, and their relative strengths and weaknesses at a very specific and narrow point within the policy development cycle. To try and engage with the policy maker outside that specific time is probably of low value, because they're just not thinking about it (scientist, RHW).

The boundary spanner was therefore essential to maximising perceptions of Regional Highlands Waterwatch being a credible, salient and legitimate form of environmental knowledge that can be used and applied by government scientists and other stakeholders.

In the Mill Stream case, the coordinators lacked a similar connection with people skilled in data analysis and interpretation, which reduced the likelihood that monitoring results will be seen and acted upon, as one coordinator described:

> I don't have someone who has a lot of time internally to make that link between the data and the research that's done by [other stakeholders]. And then the potential with this to be a way to make [citizen science] data more meaningfully used (coordinator, MSW).

8.7.2.3 The role of boundary objects

Regional Highlands Waterwatch releases an annual report, which has become the centrepiece of the program. This report which can be described as a 'boundary object', which compiles various indicators, including water quality parameters, macroinvertebrates, physical habitat descriptions and local knowledge contributions, to provide an annual snapshot of regional catchment condition. Almost all interviewees commented on the importance of this report in creating more productive relationships between Waterwatch and decision-making. For example, a catchment committee manager said, "It's the tangible

outcome. It's what we can flash and it's also important because it gives me data" (catchment manager, RHW). The multiple purposes of the report were also highlighted by a regional coordinator who considered it an essential feedback mechanism for volunteers:

> On the one hand, [the report] provides a catchment picture for catchment managers, but on the other hand, it provides a summary reporting on volunteer activities that's based around a reach-based approach. A volunteer may be proud that they're contributing to this overall picture, but also, they may only really be interested in their site. So, they can just turn to that page and they can see the reach with their sites, their photos, their anecdotes on that report card…We really make an effort to personalise it that way (coordinator, RHW).

Consistent feedback from volunteers indicated an appreciation of this report as a symbol of feedback for their efforts: "I think you see an outcome from your work is not just this kind of disembodied data just sitting in a data base" (volunteer, RHW). However, despite this view relating to the perceived value and translation of their efforts, they were generally unaware about how their data were being used across the region, as this representative quote by one volunteer describes:

> I'm not sure how data were applied. Various reports were prepared and given [but] I'm not sure then the application of those – whether it went through the decision-making process of government…that side of it, I don't know (volunteer, RHW).

In the Mill Stream case, a similar report acting as a boundary object was not a feature of the program despite most coordinators speaking of the importance of "telling a story" (coordinator, MSW). Developing material to summarise program data and outcomes, while not occurring, was nonetheless assessed by these coordinators as being critical to the future alignment of boundaries between the program and expert communities. These assessments reinforce the importance of boundary objects as tools for change.

8.7.3 Working through boundaries

8.7.3.1 Creating spaces for interaction and learning

In Mill Stream Waterwatch, rather than align activities with regional government priorities, coordinators directed attention to possibilities for knowledge outcomes at local levels. Reflecting the program's capacity building logic, a major focus was on building new and

reconfiguring existing relationships with catchment managers and other stakeholders. In particular, coordinators instigated projects that embed Mill Stream Waterwatch in the monitoring and reporting of short-term, investigative projects. For example, one group of volunteers were engaged to take part in regular monitoring of habitat refuges for a threatened fish species. Their involvement was critical in triggering emergency watering when the pools dried up during the summer period. One coordinator felt strongly that these types of projects were critical in efforts to shift narratives within the funding agency:

> [B]y getting involved in some of these other projects, we're able to shift that perspective…that perception that it's low quality data and therefore it doesn't have much use…I'm hoping we can change the narrative around it essentially and say, 'here's where it's being used very directly within these management processes', and just being able to show there's value within it (coordinator, MSW).

A scientist involved in this project testified to the benefits of type of involvement for management outcomes:

> I think that's a great example of a really measurable impact that the Waterwatch volunteers are having. It's because of their visits, their regular visits, that we are able to keep track of this really key habitat in the waterway, and know that we need to go out and deliver some emergency water (scientist, MSW).

Furthermore, this scientist reflected on the importance of short-term, management-oriented projects as delivering salient environmental knowledge for the management of water resources:

> In all the ways we use Waterwatch, the data fits the purpose, and I think that's where Waterwatch is at its best. When the data are not being squashed together to draw huge conclusions. It's not [for a] scientific study but it's guiding management outcomes, which is ultimately pretty powerful (scientist, MSW).

Thus, these projects have enabled volunteers, scientists and land managers to engage in and address an issue of mutual concern while giving both an opportunity to construct their boundaries in ways favourable to their own perspectives.

8.8 Discussion

The results revealed how the perceived credibility, salience and legitimacy of citizen science is related to ways boundaries are constructed, aligned and redrawn. Previous research has

tended to view the ability of citizen science to work across the boundaries of science, society and policy to be a function of a program's characteristics, design features or levels of volunteer participation (e.g. Shirk et al. 2012). While this research provided the field with useful insights, we show that a focus on boundary work provides additional understanding of the micro-level processes of collaboration in citizen science, including the macro socio-cultural conditions under which this work is realised.

The findings show how actors in professional roles *constructed boundaries* to maintain a position of authority and exclude citizen science to the periphery of waterway governance. For much of its history, both study cases appeared to have struggled to establish themselves as credible, salient and legitimate source of waterway knowledge. Eden (2010) suggests that when such practices are considered unscientific, they can lose access to resources gained by science, which undermines their capacity to influence policy debates. Similarly, our interviews with coordinators across both study cases revealed that negative perceptions of citizen science by expert communities have closed down opportunities for collaboration, innovation and dialogue. However, it appears instances of exclusion are not borne out of strategic efforts by scientists in response to a specific event or threat to credibility, as described by Gieryn (1983). Instead, we suggest our findings align with Kinchy and Kleinman (2003) that boundary work also takes place as part of ongoing routine or unconscious efforts by expert communities that reflect their field's "tacit rules."

The novelty of this research relates to understanding *how* citizen science programs have responded to historic and current marginalisation. We observed two distinct boundary work practices and strategies that were employed by coordinators to maximise credibility, salience and legitimacy. First, Regional Highlands Waterwatch has strategically *aligned boundaries* with government monitoring and policy frameworks. The processes of alignment involved the use of boundary objects (e.g. the annual catchment health report) and employing boundary spanners and advocates (e.g. the scientific advisor) that were foundational in shifting perspectives on the value of citizen science for environmental decision-making. We also observed in both case studies that aligning boundaries between citizen science and other stakeholders at a local level was dependent on appeals to scientific

authority to ensure the credibility of their data collection activities. However, this expectation that resolving environmental problems is solely aligned with having a sound scientific case minimised the complexity of waterway governance which is shaped by a range of contextual, socio-political and project specific factors (Kimura and Kinchy 2019).

Alternatively, Mill Stream Waterwatch coordinators were mainly focused on *reconfiguring boundaries* to "shift narratives" about the value of the program. They achieved these boundary configurations by bringing together catchment managers and volunteers to address short-term, manageable projects with clear aims and outcomes. The temporary nature of these projects provided a way to bypass the internal constraints that limit uptake of program data at higher levels. It has also meant that managers do not have to commit to building newly learned practices into their everyday work, but it can promote willingness to try new things and experiment (Langley et al. 2019).

An unexpected finding was the role that coordinators play in creating distance between volunteers and expert communities. This finding challenges the traditional notion of program coordinators functioning primarily as neutral mediators at the science-policy-society interface. The findings showed how coordinators actively separated volunteers from expert communities by delineating roles, tasks and responsibilities and by creating distinctions between the scientific and educative dimensions of their program. While these demarcations may limit the interactions between volunteers and expert communities, they were also key strategies to improve program efficiency and maximise the credibility, salience and legitimacy of citizen science. Thus, we conclude that the way in which boundaries are divided or brought together can have both simultaneous positive and negative effects.

In highlighting these practices, we consolidate our findings of boundary work in citizen science into a conceptual model to illuminate the various ways boundaries shift and move, thereby, shaping the credibility, salience and legitimacy of citizen science as an important component of environmental management practice. (Figure 18). Our model is inspired by the framework development by Langley et al. (2019) and comprises three distinct, but interlacing, forms of boundary work found to be present in citizen science

through our analysis of the data drawn from the targeted case studies: (1) constructing boundaries, (2) aligning boundaries and, (3) reconfiguring boundaries. The model captures not only the forms of boundary work but also the strategies observed during the data collection process as used by key individuals in their boundary work practices.

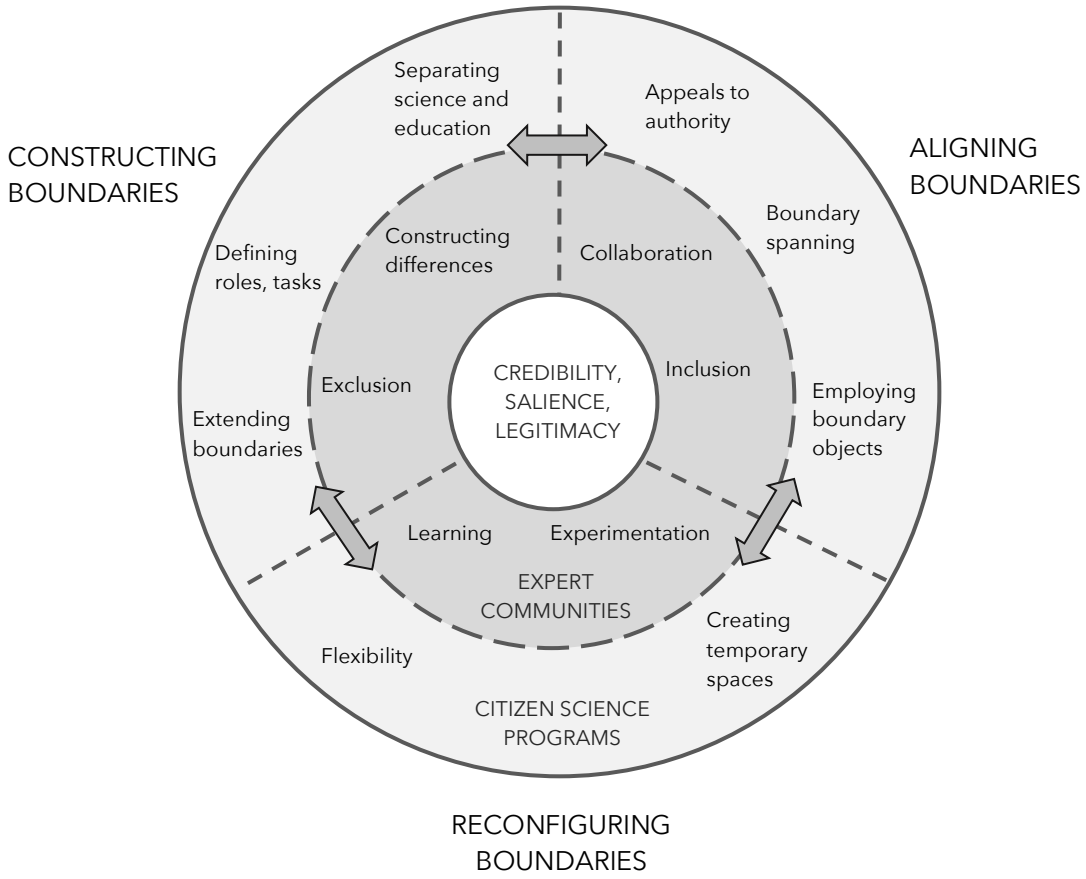

Figure 18. Three types of boundary work in citizen science and their purposes for peripheral and central actors

The comparative nature of this study revealed differences in socio-cultural contexts between the two cases that influenced the relative rigidity and permeability of boundaries between citizen science and expert communities. For example, differences in demand for citizen science data between the study cases influenced the willingness to accept and use citizen science data. In the Regional Highlands case, scientists and decision-makers have needed supplementary sources of water quality information due to a decline in professional

monitoring and research in the region. This need has opened up new possibilities for collaboration and thus highlights the interactive effects of different boundary work practices. Indeed, it is important to note that these different forms of boundary work are not mutually exclusive but may interact and influence each other. Take, for example, how Mill Stream Waterwatch coordinators sought to reconfigure boundaries to enable new forms of interaction. The purpose of this form of boundary work to shift narratives about the value of citizen science may have implications for reducing the extent to which the program is excluded from future decision-making through boundary construction.

On a practical level, this study has several insights for citizen science practice. First, the concept of boundary work is useful as a conceptual tool for programs to consider their relations within a wider domain of environmental governance. As such, volunteers, practitioners and scientists would benefit from reflecting on how they affect, or are affected by, their respective boundaries. Second, programs would find benefits in creating boundary objects, such as reports, maps, online material, which bridges community and institutional needs. Such 'boundary objects' are recognised to be critical in facilitating collaboration and, thus, mutual recognition of environmental issues. Finally, our study highlighted the importance of creating spaces for interaction and learning. Coordinators should actively encourage greater forms of interactions across boundaries to encourage experimentation, flexibility and innovation. Not only is it possible to facilitate greater learning across established boundaries, but a chance to challenge their very construction.

8.9 Conclusion

The primary objective of this paper was to examine how citizen science creates productive community-government relations by employing the concept of boundary work. This focus enabled analytical emphasis on the social and contextual elements that shape the community-government interface, rather than on factors such as program design, characteristics and quality and quantity of volunteer participation more commonly studied. We find that a longstanding contestation within environmental governance about the place of citizen science is largely driven by historical boundary work shaping distinctions between

professional and citizen science. Our findings are novel in that they expand on this literature by highlighting how programs and volunteers have responded to increase their legitimacy in the context of environmental governance. The type of boundary work enacted is dependent on an already constructed socio-political environment that influences the rigidity and porosity of boundaries between community and waterway governance. Understanding the way that boundary work shapes citizen science outcomes has implications for program design, whereby actors can approach dilemmas and challenges in their projects by recognising boundaries not as barriers, but spaces for negotiation and change.

9 Discussion

9.1 Introduction

In this thesis, I set out to examine, from a relational perspective, the opportunities and challenges associated with linking citizen science with the management of water resources. The decision to adopt this perspective was based on an identified need to extend citizen science research to include more focused attention on the social and organisational features that create productive, meaningful and lasting community-governance relations. In Chapter 2, a novel conceptual framework for relational analysis of citizen science practice was developed, based on insights gained from an interdisciplinary body of literature. The subsequent application of this framework in provided a new conceptual and methodological approach to advance citizen science both theoretically and practically. Before I reiterate and synthesise the key findings and implications of the approach, the first section of this discussion revisits the historical development of freshwater citizen science in Australia. Tracing this history is crucial not only to address a key objective in this thesis, that is to fill a gap in historical records, but also to set the right backdrop against which to examine and interpret the core research findings.

9.2 Freshwater citizen science in Australia: comparing the historical and contemporary practice

To fully grapple with how freshwater citizen science is shaping the water governance landscape in Australia, it is important to understand how we arrived at this point in the first

place. Neglecting this task risks 'policy amnesia,' in which past successes or failures in policy do not inform the creation or redesign of participatory approaches (Dovers 2000, p.3, see also May 1992). Prior to commencing this research, a documented history of freshwater citizen science in the Australian context was not readily available. Indeed, it was difficult to locate policy documents, reports or academic literature that provided more than fragmentary accounts of program evolution, geographical extent and characteristics. Filling this gap is therefore a key contribution of this thesis and provides an important foundation for improved policy learning and program development (Dovers 2000).

Public participation in freshwater monitoring programs has been a lasting feature in Australian natural resource management and, as such, it predates the more recent and global interest in citizen science. As described in Chapter 3 and Chapter 5, these efforts have been epitomised by the community-based water monitoring program, Waterwatch. Throughout its history, Waterwatch has advanced a core objective to engage volunteers in a combined process of place-based learning and action-oriented scientific inquiry (Carr 2002). As part of its broader development, Waterwatch has consistently endeavoured to improve its data quality standards to ensure the program has potential to contribute to catchment decision-making. Like most citizen science programs, this capacity to achieve both education and scientific benefits within a single program is a principal reason for its longstanding support and investment.

The national review of freshwater citizen science programs presented in Chapter 5 showed that most contemporary projects continue to advance these same core principles that characterised the original practice. Projects were found to be widespread across the country with most still enacted as a public engagement mechanism by local, regional and state governments. Their associations with government agencies reflected their expectations to inform catchment decision-making and advance education and engagement objectives throughout their respective regions. Additionally, programs partner and interact with an expanded network of schools, universities, local councils, private companies and non-government organisations. These informal networks remain one of the key benefits of citizen

science since they improve program stability through collaboration, knowledge uptake and additional sources of funding.

The national review was also the first-of-its-kind to investigate how Australian citizen science projects are contributing to the management of water resource by virtue of data uptake. This issue addressed the first research question in this thesis: *In what ways do freshwater citizen science projects in Australia contribute to the management of freshwater environments, and which factors enable or limit these contributions?* This investigation came almost two decades after Finlayson and Mitchell (1999) highlighted the potential of Waterwatch to assist researchers and government agencies in better understanding and managing freshwater environments. The analysis of verified reports of citizen science data uptake in water resource management showed that these data can be applied across various phases of a typical adaptive management cycle: for strategy development and planning, monitoring management actions and interventions and reporting on waterway and catchment condition. Additionally, data collected by volunteers were sometimes critical in triggering management actions and justifying applications by local monitoring groups for environmental funding. Providing this evidence that programs have been able to successfully contribute to management of water resources and support community objectives justifies program investment and validates the efforts of volunteers who are often motivated by a need to see tangible outcomes from their efforts (Carr 2002).

Despite highlighting several successful linkages between citizen science in decision-making contexts, the national review survey also showed that most programs experience significant barriers that constrain further integration. However, the identified barriers were not necessarily tied to scientific or technical dimensions of data collection activities. Indeed, based on reports by coordinators, the accuracy of volunteer data was not rated as a high-level concern. Additionally, most programs have in place quality assurance and quality control procedures to ensure the robustness of collected data. Rather, coordinators reported their main challenges as funding and financial constraints, difficulties connecting and coordinating with data end-users and a lack of interest by decision-makers in citizen science. As such, a key conclusion of Chapter 5 was a need for strategies and further research to

address these identified social, organisational and institutional factors that can limit citizen science from reaching its full potential in natural resource management and environmental policy.

The second phase of this thesis involved a comparative case study of two longstanding citizen science programs and was foundational in providing a more in-depth and contextual account of the issues highlighted in the national review survey. With respect to the historical development of the practice, the case study findings indicated that the place of Waterwatch within the wider governance landscape has remained largely consistent over the course of its development. In Chapter 8, interviews with coordinators from both study cases revealed that Waterwatch was just "doing the same thing, the same people" or has "kept going on and on and on." They also described how the program has long been viewed as an "edge-case" or a "fringe thing" and that these perceptions have limited possibilities for collaboration, cooperation and inclusion. Despite clearly improving the program's design and data quality, it appears both Waterwatch programs have continued to struggle with what Finlayson and Mitchell (1999, p.110) identified as the 'great scepticism and overt opposition from some research and government officials' that has historically challenged citizen science in Australia. While this opposition was found to be increasingly less overt in the Regional Highlands case due to recent success with integrating into regional policy and monitoring frameworks, a consistent trend identified from the research findings was that government agencies have generally been slow to accept Waterwatch as a viable source of environmental information over its near thirty-year history. This finding highlights the critical role of context, networks and boundaries in shaping perceptions of citizen science and influencing the potential of the program to be a partner in decision-making for waterway governance in Australia.

In tracing the history of freshwater citizen science in Australia, a comparison of the historical and contemporary practice suggests the capacity of citizen science to enhance key waterway governance objectives has been constrained more by inert social and institutional processes rather than inefficiencies in program design and characteristics. As the new phase of citizen science takes hold in Australia, there is critical need for reflection on past practices

and emerging visions. Without this reflection, new citizen science projects may fall into similar dilemmas faced by existing programs, particularly with respect to the risks of ending up in a similar state of inertia. Thus, based on these findings, the core challenge for new and existing programs is not only about improving what happens "inside" a given project but also engaging equally with what (and who) lies beyond these boundaries. This highlights the importance of understanding how people work together to convert the potential of citizen science into practice and the strategies that might make this possible—to which I now turn.

9.3 Citizen science for enhanced waterway governance: a relational perspective

The relational perspective adopted in this thesis takes as its starting point the associations and connections in citizen science that exist between people and phenomena of interest. In this section, I show that the framework proved useful in understanding:

(i) the structure of relationships within and outside citizen science projects, including the relationship between network characteristics and outcomes;

(ii) how actors navigate and experience their relationships, including the role of context (i.e. social, political, institutional factors) in enabling or constraining network connections; and

(iii) the way in which boundaries between citizen science and expert communities were constructed and coordinated to shape the credibility, salience and legitimacy of citizen science knowledge and practice. A summary of the findings across the two studies cases is presented in Table 17.

9.3.1 The role of structure

The first dimension of the relational framework was an investigation into structure, or the network characteristics and patterns of relations in a citizen science social network. This dimension of the framework was crucial in answering research question 2: *What role do social*

networks play in shaping citizen science practice and its knowledge outcomes, and how can the conceptual and methodological tools of social network analysis be applied to advance this understanding?

Table 17. Summarising the findings of the relational research framework across the study cases.

Relational dimension	Mill Stream Waterwatch	Regional Highlands Waterwatch
Structure *(the characteristics and patterns of relations in a citizen science social network)*	Favours decentralised network governance and encourages cross-boundary connections at a local level	Favours centralised network governance with cross-boundary connections across formal or institutional gradients
Meaning *(how actors navigate and experience relationships with others within a particular context)*	Enacted in a context that privileges inclusiveness, internal legitimacy and flexibility; volunteers create meaning through local action	Enacted in a context that privileges efficiency, external legitimacy and stability; volunteers create meaning through being part of a collective
Boundaries *(physical, social, conceptual distinctions enacted by boundary work practices)*	Efforts to improve credibility, salience and legitimacy primarily enacted through reconfiguring boundaries;	Efforts to improve credibility, salience and legitimacy primarily enacted through aligning boundaries

The importance of social structure in collaborative environmental management is well-known but is largely unexplored in citizen science literature. This insight led to a review of literature (Chapter 6), that revealed social networks were regularly discussed in citizen science as critical to important social processes, individual and program outcomes and social attributes, such as the development of trust and social capital. However, there was clearly a lack of systematic research on the internal and external connectivity of citizen science projects, including how social networks both enabled and constrained processes and outcomes. To address this shortfall, Chapter 6 provided background information on the key principles of a social network perspective and discussed several opportunities to guide future research. Specifically, research opportunities were presented on the links between social networks and knowledge uptake, social learning and the building community empowerment.

Following this review, Chapter 7 demonstrated the application of social network analysis in a comparative case study of two freshwater citizen science projects for one of these principles, the issue of linking knowledge with action. For understanding how knowledge is translated into action, social networks are considered a 'natural organising concept' since they highlight how knowledge can be distributed across diverse actors in collaborative governance arrangements (Henry and Vollan 2014, p.586). Furthermore, the way in which a given network forms an overall program network structure can profoundly shape how knowledge is shared and applied to a particular environmental problem. By investigating a series of whole-network characteristics, the social network analysis presented in Chapter 7 revealed important insights into the nature of collaboration and knowledge outcomes with the two cases. While both cases engaged in similar data collection activities (i.e. water quality monitoring), they had developed different network structures. These differences in network structures were found to correlate with the type and scale of each program's impacts on decision-making. As other researchers have demonstrated, the network structures were also found to have a 'dual-nature' (Diani 2003; Ernstson et al. 2008), which means that they facilitate some benefits while constraining others.

In the Mill Stream case, the development of a decentralised network structure that encouraged local network development (i.e. between volunteers and local stakeholders) has enabled greater attention and resolution of local waterway problems. There was a low density of connections among coordinators and between coordinators and decision-makers. These sparse network connections between the program and decision-makers within the funding agency can explain the few reported instances of data uptake in policymaking at a regional level. Decentralised governance networks have been identified as being a preferred approach for complex and uncertain policy contexts, whereby actors can understand and share information across different parts and scales of an environmental problem. Indeed, the local development of social networks in the urban environment in which Mill Stream Waterwatch operates can be considered a suitable way to address often local and acute environmental issues, such as pollution events or restoration activities. However, a

decentralised approach can pose difficulties in coordinating the entire network to achieve collective aims and thus require more attention to actors who bridge different subgroups.

By contrast, the Regional Highlands Waterwatch program was characterised by a core-periphery network structure, which served an important role in coordinating activities and facilitating knowledge uptake for regional policy. This capacity to link the program within policymaking areas can be explained by the presence of a tightly connected group of scientists who actively collaborate with the programs and apply its data. Yet, this same network structure was not efficient at addressing and solving local environmental concerns as local network structures were not a main feature of this network. Core-periphery networks with strong central leadership have been discussed as important in developing consensus on goals and values and can ease knowledge sharing (Newig et al. 2011). Yet, overly centralised networks can be vulnerable to collapse due to the strong reliance on one or few individuals. This is particular risk for the Regional Highlands case, where data sharing and collaborative ties were strongly centred around the main program facilitator.

In sum, the social network analysis of the two freshwater citizen science programs highlighted both programs were characterised by cross-scale and multifunctional relationships. Social network analysis as a mechanism to map these connections has proven valuable for making citizen science networks visible. While not all citizen science programs will involve such extensive network connections, the analysis still highlighted how network structures correlate with social and scientific outcomes. The type of social network analysis described in this thesis can serve as a tool to understand and strengthen citizen science networks by, for example, selecting appropriate network partners that match the type and scale of environmental objectives at hand. For citizen science to be part of transitions to more sustainable water futures (Bhaduri et al. 2016), an understanding of the nature and complexity of informal networks and relationships is part a reflexive and iterative approach to the planning and development of citizen science.

9.3.2 The role of meaning

The second dimension of the relational research framework was *meaning*, which referred to how actors in a citizen science network navigate and experience their relationships with others in a particular context. This dimension of the framework was also critical to answer research question 2, but through qualitative rather than quantitative methods.

The comparative case study approach adopted in this thesis also enabled a cross-contextual view of citizen science networks (Mason 2006), which means that the social network of each case was explained with reference to their situated context. These explanations revealed important differences in social, political and environmental contexts that strongly structure the relationships that underpin each program and shape how network tensions are managed or resolved. In Mill Stream Waterwatch, the program has structured relationships in a way that places greater importance on inclusiveness over efficiency, internal over external legitimacy, and flexibility over stability. Adopting these aspects to network governance are crucially important for the main functions of the network: to build local community leaders who take ownership of local waterways, to respond quickly to heterogeneous environmental problems and to engage volunteers and catchment managers in short-term, locally relevant monitoring projects.

By contrast, Regional Highlands Waterwatch has promoted a form of network governance that favours efficiency over inclusiveness, external over internal legitimacy and stability over flexibility. These dimensions of network governance reflected the largely rural focus of activities and often diffuse nature of environmental problems in this part of the country, such as drought and the impacts of fire, which are well-suited to a broadscale monitoring approach. Additionally, the continued functioning (or stability) of the program was dependent on Regional Highlands Waterwatch demonstrating its scientific value (or external legitimacy) to scientists and decision-makers who are increasingly using citizen science data. As a result, the program operates from a strong foundation of central and regional coordination that promotes high efficiency of activities.

Attention to meaning also highlighted that the ways in which volunteers in each case navigated their relationships differed in purpose and character. On the one hand, volunteers

from Mill Stream Waterwatch mostly participated as part of established community environmental groups, whereby the program supports these groups to direct their own actions toward locally relevant issues. While some groups have been successful in solving local problems, other volunteers have struggled, or seemingly lacked the necessary socio-political skills and connections, to generate social and environmental change. When issues were resolved, volunteers were assisted "from above" (Cornwell 2008), suggesting that responsiveness was contingent on active institutional support.

On the other hand, volunteers in the Regional Highlands case mostly worked alone, supported by their respective coordinator with whom they had a working relationship. Unlike volunteers from the Mill Stream case, they generally did not view their capacity to enact change through local action. Instead, volunteers were more inclined to "contribute to the whole" and assist scientists and decision-makers attend to the region's waterway problems. Despite volunteers often not knowing how their data were being used, this did not seem to be a major issue as the collective spirit of volunteers appeared to create a sense of community. That alone was often enough to satisfy their motivations to participate.

Considered together, the insights from the qualitative analysis reiterated and further validated the importance of networks and relationships, and the meanings attributed to them, for the planning and development of citizen science. The decision to incorporate "meaning" as a key relational dimension in citizen science responds to the recognised limitations of a purely structural perspective, as described in Chapter 3 and Chapter 7. A mixed method approach or, more specifically, the integration of quantitative and qualitative data collection and analysis techniques, has served to broaden the explanatory power of the social network analysis, contrast and validate quantitative results and capture the dynamic and multidimensional nature of citizen science networks from both an 'outsider' and 'insider' perspective' (Bolíbar 2015).

9.3.3 The role of boundaries

The final dimension of the relational framework was on *boundaries*, or the physical, social and conceptual distinctions between social groups and enacted through boundary work

practice. This dimension provided the basis to answer research question 3: *How do boundary work practices that create, maintain or breakdown boundaries between citizen science and expert communities shape the outcomes of citizen science knowledge and practice?* Boundary work is recognised as a useful theoretical concept to not only understand how fields of knowledge are constructed, defended or undermined, but also how the boundaries between knowledge and action can be aligned and practically coordinated (Wyborn 2015). As such, applying the concept to citizen science was viewed as having a dual purpose: (1) to understand how expert communities perceive citizen science in relation to their own practices and (2) to investigate the practices and strategies enacted by citizen science programs to challenge existing organisational boundaries and maximise their credibility, salience and legitimacy.

Using the framework developed by Langley et al. (2019), Chapter 8 described three distinct, but interlacing, forms of boundary work present in the two case studies that shape the credibility, salience and legitimacy of citizen knowledge and practice: (1) working for boundaries; (2) working at boundaries and (3) working through boundaries. The first form, working *for* boundaries, highlighted historical challenges of Waterwatch in demonstrating its scientific utility in waterway governance. To varying extents, both programs have been perceived as irrelevant to broader monitoring frameworks, lacking credibility for decision-making, or best placed as a community engagement mechanism. Historically, these conceptual distinctions have excluded Waterwatch from decision-making processes with expert communities, thus reinforcing a boundary between the program, volunteers and expert communities. The study suggested that a longstanding contestation within environmental governance about the appropriate role of citizen science is largely driven by this exclusionary form of boundary work.

The findings are novel since they highlight how programs and volunteers have responded to maximise their credibility, salience and legitimacy in the context of environmental governance. Coordinators from Regional Highlands Waterwatch were primarily focused on *working at boundaries* to enable uptake of the program according to government priorities and regional monitoring frameworks. The processes of alignment were assisted by use of boundary objects, employing boundary spanners, and conforming to

rigorous scientific standards set by the scientific and policy community. Alternatively, Mill Stream Waterwatch coordinators were largely focused on working *through* boundaries to shift narratives about the value of Waterwatch by bringing together catchment managers and volunteers to address short-term, manageable projects with clear aims and outcomes. The temporary nature of these projects provided a way to bypass the internal constraints that limit uptake of Waterwatch at regional policy-making levels. It also meant that managers did not have to commit to building newly learned practices into their everyday work. Instead, these types of engagement can promote willingness to try new things and experiment, which may eventually alter the rigidity of boundaries between citizen science and expert communities.

A surprising finding was the role that coordinators play in not only bridging the divide between volunteers and expert communities but also creating distance between these domains. This finding lies in contrast to a traditional notion of program coordinators functioning primarily as neutral mediators at the science-policy-society interface. In this study, coordinators actively separated volunteers from expert communities by delineating roles, tasks and responsibilities and by creating distinctions between the scientific and educative dimensions of their program. These boundary constructions served an important role in improving program efficiency and maximising the credibility, salience and legitimacy of citizen science.

The main contribution of this relational dimension is enabling an understanding of the micro-level processes of collaboration in citizen science, including the macro socio-cultural conditions under which this work is realised. A focus on boundary work shifts the analytical emphasis towards the social and contextual factors that shape contributions at the community-government interface, rather than on factors such as program design, characteristics and quality and quantity of volunteer participation. However, the type of boundary work enacted is dependent on an already constructed socio-political environment that influences the rigidity and porosity of boundaries between community and waterway governance. Understanding the way that boundary shapes citizen science outcomes has implications for program design, whereby actors can approach dilemmas and challenges in

their projects by recognising boundaries not as barriers, but spaces for negotiation and change. This notion of "spaces" between research, policy and practice, as opposed to "gaps" that need to be filled, is a useful concept that enables a pathway to reconceptualise the role of citizen science in environmental governance.

9.4 Rethinking citizen science as "hybrid spaces"

The findings and theory presented in this thesis contribute to an understanding of citizen science as a practice strongly shaped by its relational dimensions and its broader social and political context. First, the case studies illustrated that citizen science can comprise a diverse network of actors from different organisations and backgrounds. Second, the way in which these actors formed overall network structures generated different types of tensions that programs must navigate and manage to reconcile potentially conflicting needs and expectations among different actors. Third, boundary management in citizen science is a multidimensional process that involves strategic and routine efforts to divide or align the boundaries between citizen science programs and expert communities. Finally, the way in which these boundaries shift and move have implications for the perceived credibility, salience and legitimacy of citizen science knowledge and practice.

Considered together, these findings highlight that management and policy-oriented citizen science is a practice that, at its core, facilitates cooperation and interactions between individuals from different social worlds. In many ways, citizen science reflects a type of "boundary organisation"—a theoretical concept developed by Guston (1999) to understand collaborative processes involved in creating productive knowledge-action relationships between science and policy. In acknowledging this similarity, the following section engages in a process of theorising (Phase 4 of this thesis) to reconceptualise the nature of citizen science practice. Towards this end, I argue that citizen science is, indeed, a type of boundary organisation that occupies a "hybrid space" between research, policy and practice. In what follows, I elaborate on the key characteristics of hybrid spaces borrowing from Guston's (1999) criteria for what makes a boundary organisation and Parker and Crona's (2012) notion of a "landscape of tensions."

9.4.1 Characteristics of hybrid spaces

The concept of hybrid spaces builds on the influential work of Guston (1999) who developed a theory of "boundary organisations" to describe an organisational structure that facilitates collaborative processes between researchers and policymakers while maintaining a stable boundary between science and politics. Guston (1999) describes three characteristics of boundary organisations: (1) they involve the participation of actors from different social world, often including professional mediators; (2) they exist between two distinct social worlds, e.g. science and politics, with distinct lines of responsibility and accountability to each; and, (3) they provide a space that supports the creation and use of boundary objects. Boundary organisation theory has since been applied in various settings as a useful empirical label to describe the mediation of cultural differences and multiple accountabilities in knowledge-action relationships that are essential to promote more effective use of environmental knowledge in policymaking.

Several authors have since elaborated on boundary organisation theory (Miller 2001; Parker and Crona 2012; Wehrens et al. 2013; for a review see Gustafsson and Lidskog 2018). A particularly relevant refinement for citizen science is the landscape of tensions model put forth by Parker and Crona (2012). In their study on university-based boundary organisations, the authors demonstrated, through in-depth qualitative research, the incommensurate demands and knowledge requirements placed on the boundary organisations that shape their internal processes and capacity to facilitate productive interactions. Parker and Crona (2012) suggest that it is more appropriate to consider these organisational mechanisms as occupying a hybrid space to acknowledge the processual and dynamic nature of such organisations as they work to negotiate among tensions, rather than stabilise, the boundaries between research, policy and practice (Gustassfon and Lidskog 2018; Parker and Crona 2012).

Drawing on this literature, I assess the extent to which each case functions as a hybrid space and describe how this reconceptualisation of citizen science can benefit the creation and realisation of useable citizen science knowledge and facilitate interactions among stakeholders.

Central to this reconceptualisation is the exploration of the key characteristics of boundary organisations—actors, attributes and boundary objects—and how they relate to the insights gained during exploration of the case studies that have been a central component of this research.

Actors

The first characteristic of boundary organisations is that they involve actors from different social worlds. In Guston's (1999) original theory, constituents of boundary organisations involve those from research and policy communities, with professional facilitators mediating their interactions. However, citizen science is different in this regard. The findings in this thesis show that citizen science brings together a diverse network of people from diverse backgrounds and organisations from the social worlds of both science, policy *and* society. Figure 19 (below) illustrates how the networks from different social worlds are connected within the hybrid space of citizen science. These actors are mediated by program coordinators who provide each group the necessary resources, training and advice, facilitate collaboration and adapt the program to suit to diverse stakeholder needs. Both study cases certainly satisfy this first criterion when the role of citizens as active producers and consumers of environmental information is considered (Bäckstrand 2003).

Accountabilities

The second characteristic of boundary organisations is that they operate at the interface between science and policy and have distinct lines of accountability to each. The relational perspective adopted in this thesis has highlighted that the citizen science-policy interface is characterised by complex knowledge relations between diverse actors holding different roles, capacities and potentially conflicting values. This was found consistently in both the case studies explored in this thesis with the data highlighting lines of accountability between volunteer participants and funding agencies. This finding aligns with other work in STS and environmental governance literature that conceives the science-policy interface not as a "gap" to be filled, but as a "space for negotiation" that accommodates different knowledges,

experiences and worldviews, and negotiates the tensions among them. Such a space needs careful planning since it is a key site that profoundly shapes how environmental knowledge is perceived and understood.

Boundary objects

Guston's (1999) final criterion of boundary organisations is the creation and use of boundary objects. Boundary objects, such as maps, databases and reports, are recognised to enable the spanning boundaries between different social worlds to shape understanding of mutually recognised problems. A good example of a boundary object described in this thesis was the annual report created by Regional Highlands Waterwatch that served as a source of data for policymakers but also as an important communication tool for volunteers. The boundary object served as an important outcome of the project that enabled productive relations to be formed between volunteers and expert communities. The issue of boundary objects in citizen science has received limited research attention, but serves as an important avenue for the future development of projects aiming to influence policy processes.

The application of these characteristics of hybrid spaces, when placed within the context of the insights gained over the course of this research study, highlights the importance of the development of a clear definition of the notion of hybrid spaces. Consequently, I pose the following definition of hybrid spaces as it relates to citizen science:

> *Networked environments or "spaces" where diverse actors contribute to an ongoing, dynamic process of negotiating tensions, manage multiple accountabilities and create and use boundary objects, thereby facilitating new ways of working, different ways of knowing and the transformation of societal relations.*

This conceptualisation of citizen science as a hybrid space, and the scope of the environment and relevant actors and their interconnections, is graphically represented in Figure 19.

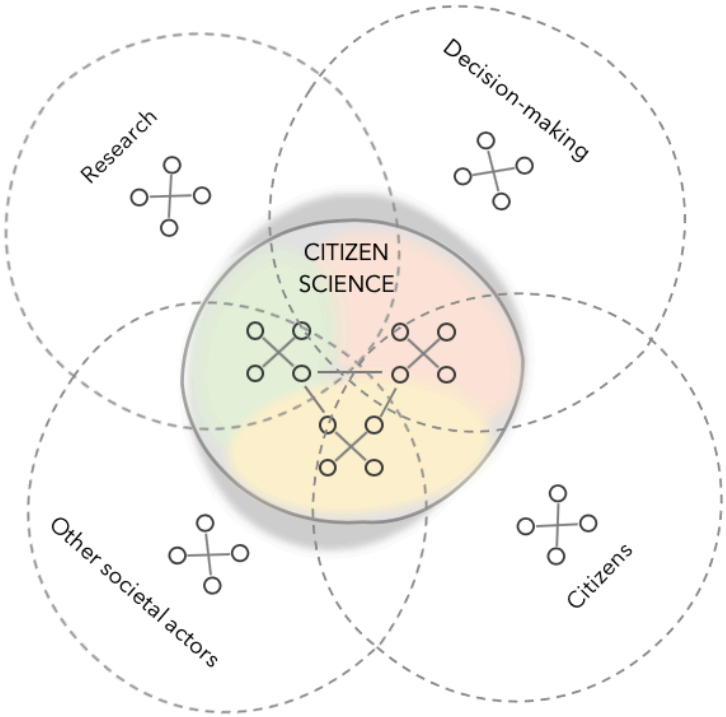

Figure 19. Citizen science as a hybrid space. Each symbol ( ) represents 'an amalgamation of norms, discourses and knowledges' (Miller 2001, p.485). The management of different demands and tensions is illustrated by the coloured spheres blurring together.

9.4.2 Summary and implications

In academic literature, citizen science is consistently discussed as an important mechanism operating at the interface between science, society and policy. However, this position between these social worlds is often only realised in theory. In practice, as the preceding chapters have shown, citizen science can be perceived more as a marginal participatory approach that is largely disconnected from mainstream arenas of environmental decision-making. This peripheral position in the wider governance landscape is particularly problematic for projects aiming for impacts on policy and on-ground management actions. As such, there is a critical need for mechanisms and strategies that can assist in reorienting the practice to more effectively link community-based knowledge with action. This section has attempted to bring to light the similarities of citizen science with boundary organisations which occupy a hybrid space between research, policy and practice.

The main benefit of conceiving citizen science as a hybrid space lies in the ability to create a common point of reference between actors to develop mutual understandings (Gustafsson and Lidskog 2018). Citizen science projects require careful planning to overcome the barriers to achieving greater acceptance and use of the practice. This does not just include improvements to project design, but also to strategies that facilitate productive discussion between projects, volunteers and expert communities (Kimura and Kinchy 2019). The concept of hybrid space acknowledges the blurring of relations between citizens and experts, and the intersection of professional and participatory science. It provides an opportunity to guide discussions through effective strategies, such as the creation and use of boundary objects, to facilitate more meaningful collaboration between citizen science and expert communities for improved uptake and acceptance of useable knowledge. Further empirical analysis and refinement of the hybrid space concept for citizen science will be needed following this initial theoretical development.

10 Conclusion

10.1 Introduction

The main research question that this thesis aimed to answer was: *How does citizen science create productive, meaningful and lasting connections between science, society and policy for the sustainable management of water resources?* In working toward, and achieving, this goal I began this thesis by suggesting a need for deeper insight into the issues and opportunities associated with linking citizen science with the management of water resources. I sought to extend research possibilities to better understand how citizen science contributes to water resource management, but also how social and organisational factors shape and define the practice. From a methodological standpoint, this thesis benefited from its multi-phase mixed methods research design, which was built on a range of theoretical concepts, data collection methods and analysis techniques. This multifaceted approach enriched the inquiry and enabled novel, empirically derived understandings of citizen science. In particular, I have demonstrated that not only is citizen science a crucial mechanism to realise collective environmental objectives, but also I have presented a perspective that illuminates how achieving these objectives depends on the interplay between knowledge, networks and boundaries of citizen participation in science.

In concluding, it is important to stress that the insights gained from this thesis strongly relate to management and policy-oriented citizen science projects. Additionally, the study cases that informed the core interpretations were based on more mature forms of citizen science, which comprised large numbers of volunteers and sites monitored when compared

to other projects. I am therefore cautious about generalising my findings. For instance, the interpretations may not necessarily be relevant to smaller, newer initiatives or those projects that engage in traditional research-oriented approaches. Nevertheless, I remain confident that many of the discoveries in this thesis, particularly with respect to the role of relationship building and strategies to enable knowledge outcomes, will be of great value for projects in diverse social, organisational and environmental contexts.

With this caveat in mind, what is the broader significance of this thesis and what does it suggest for the future development of citizen science in governance contexts? This thesis is written at a time when public participation in scientific research has reached unprecedented levels of popularity across the world. This growth has resulted in substantial scholarship, with most research attention directed towards improving the scientific dimensions of the practice. Such efforts reflect the increasing expectations of citizen science to, for example, augment research possibilities and overcome shortfalls in government monitoring networks. This thesis provides a counterweight to the prominence of these expectations by addressing some lesser explored aspects of citizen participation in science. In particular, what this thesis shows is that the core challenge for the practice is less to do with issues of data quality, technology developments or other design features, but more a question of building the necessary relationships and political will to establish better connections between science, policy and practice.

None of this is meant to imply that bringing together volunteers, coordinators, scientists and decision-makers to realise collective aims is an easy or straightforward process. Indeed, in the global quest for sustainability, realising effective public participation in natural resource management is a challenging endeavour. Nevertheless, if citizen science is to promote innovation at the science-society-policy interface, then understanding how people and organisations work together at both an individual and network-level will be crucial to enable its full potential. The findings from this thesis suggest that by attending to networks and boundaries, programs can improve the acceptance and uptake of citizen science environmental governance, overcome inert government relationships and, ultimately, prevent project failure.

To assist in this process, this thesis has highlighted a set of strategies and practices that can be implemented to maximise the potential of citizen science in environmental governance (see section 10.3). These strategies are aimed at overcoming enduring challenges associated with negative perceptions by expert communities regarding the credibility, salience and legitimacy of citizen science knowledge and practice. The recommendations provided in this thesis avoid repeating scientific and technical advice, which has been discussed in-detail by several researchers. As this history of freshwater citizen science in Australia shows, general improvements to programmatic and technical dimensions are not necessarily linked to improved uptake in natural resource management or social transformation in communities. Instead, the practices and strategies that may have more bearing the uptake of citizen science in policymaking are those that alter attitudes, shift governance cultures and mediate different perspectives across social worlds.

Overall, this thesis demonstrates that the effectiveness of citizen science is not merely a product of its scientific practices, but also of its embeddedness in a wider social and political context. The way in which actors interact in broad social networks, how they navigate and experience their relationships and the practices that enable programs to cross and coordinate boundaries profoundly shape its processes and outcomes. From a theoretical perspective, these insights contribute to a body of literature that examines the role of participatory knowledge production in environmental governance. Additionally, conceiving management and policy-oriented citizen science projects as "hybrid spaces" more accurately reflects to the constructed, emergent and relational characteristics of the practice. For the practitioner, these theoretical insights can be adapted to open up opportunities to reconfigure relationships or bring them into new alignments to encourage more cooperative and facilitative interactions.

The following sections in this conclusion summarise the theoretical contributions and practical applications of this thesis. Following this, I discuss some limitations of the research design and methodology and present four opportunities for further research. In closing, I end with some final comments regarding the future of citizen science, both globally and in

Australia, as the practice gains increasing recognition as an important mechanism to promote sustainable social and environmental development.

10.2 Theoretical contributions

From a theoretical perspective, this thesis has made a number of contributions. The first main contribution was providing a more nuanced perspective regarding the contributions of citizen science to the management of water resources by virtue of data uptake. Recently, Newman et al. (2016) called for greater clarity on what is meant by "impacts on decision-making." In this thesis, this clarity was achieved in Chapter 5 by categorising instances of data uptake according to its influence within a typical adaptive management cycle. I found that data uptake for strategy and planning was less common than assessments of management actions or reporting on resource condition. Delivering impacts for strategy and planning tends to occur at larger geographic scales than for those impacts on monitoring management actions at a more local level. Thus, the findings suggest that the capacity to influence policy and on-ground management outcomes is not uniform. Instead, the type of contribution on decision-making will require different information needs, a need to engage with relevant actors and the collection of data at suitable spatio-temporal scales.

A second contribution relates to an empirical understanding of how actors participating in, or interacting with, citizen science projects are embedded in a social network structure. Previous research has tended to view the contributions of citizen science to research and policy as being dependent on a specific set of factors, including methodological design, data quality and levels of volunteer participation (Shirk et al. 2012). The insights gained from the social network analysis showed that citizen science projects conducting similar activities, such as water quality monitoring, can create divergent network structure that influence collaborative potential and their capacity to achieve knowledge outcomes. This insight thus adds further clarity on discussions regarding the factors that enable or limit the contributions of citizen science to environmental decision-making. This highlights the need to attend to the networks and relationships the enable and constrain these efforts.

A third contribution relates to an understanding of the micro-level processes of collaboration in citizen science, including the macro socio-cultural conditions under which this work is realised. The close examination of boundary work in citizen science showed how expert communities have historically distanced themselves from citizen science. My findings suggested boundary construction has been historically based on perceptions that the practice lacks credibility, salience and legitimacy for environmental decision-making. This thesis provided important insights into how citizen science, as a marginal knowledge practice, has worked to overcome the barriers that limited its broader influence in environmental decision-making. However, the boundary work enacted by these programs depended on the relative rigidity and permeability of the barriers attempting to be overcome, which are influenced by differences in historically contingent socio-political contexts. Exploring the processes by which citizen science was able to overcome pre-defined boundaries therefore helps researchers and practitioners understand not only how citizen science is mobilised and taken up in policymaking but also how its transforms social relations.

Fourth, and relatedly, I show how coordinators do not just work to bridge the divide between volunteers and expert communities but also actively construct it. This finding is surprising, since a traditional notion of program coordinators concerns their primary function as neutral mediators at the science-policy-society interface. However, in this study, coordinators either consciously or subconsciously separated the activities of volunteers from expert communities by delineating roles, tasks and responsibilities and by creating distinctions between the scientific and educative dimensions of their program. While these efforts were not uniform across both study cases, boundary constructions nonetheless served an important role in improving program efficiency and maximising the credibility, salience and legitimacy of citizen science. For practitioners, realising that they can make boundaries more or less permeable may encourage reflexivity in their own role, but also more confidence in their capacity to enact change in their communities.

The final main theoretical contribution in this thesis relates to a broader reconceptualisation of citizen science as a hybrid space, informed by boundary organisation

theory and subsequent elaborations (e.g. Parker and Crona 2012). This reconceptualisation is built on the awareness that the boundary between citizen science and expert communities are not fixed and stable but constructed through social practice. In view of citizen science as a hybrid space, the practice attempts to not only translate its knowledge across boundaries but also actively attempts to hybridise the community-expert boundary to promote the legitimacy in environmental governance. This hybridisation is achieved by aligning professional and lay knowledge practices through the use of boundary objects, or by creating new spaces for interaction and learning. The main benefit of this reconceptualisation is creating a common point of reference for facilitating interactions between volunteers, coordinators, scientists and decision-making. Within this space, participants can develop shared understanding, negotiate tensions, create and use boundary objects and, ultimately, improve uptake and acceptance of useable community-based knowledge.

10.3 Practical implications

In addition to theoretical and conceptual insights, the findings from this thesis provide several practical recommendations that programs could implement to improve the overall effectiveness of citizen science waterway governance. These recommendations cover the relational and organisational features of the practice that extend beyond scientific, technical and programmatic recommendations that have already been discussed extensively in citizen science literature (e.g. Hecker et al. 2018a).

As citizen science continues to grow in popularity in Australia and globally, it is important for programs to develop a vision for the future of the practice. This vision should be co-developed in an ongoing, adaptive process with multiple stakeholders, as has been recommended by other researchers. I extend this recommendation to suggest that this vision does not need to remain fixed. As was found in the Mill Stream case, a culture of innovation that engaged with stakeholders in short-term, 'experimental' projects was highly valuable in showcasing the benefits of Waterwatch for translating monitoring efforts into concrete action. Furthermore, citizen science is often misunderstood as solely a public engagement

mechanism, which can limit the data uptake for policy or natural resource management decisions. Thus, being clear about the scientific and educative differences in a given project may reduce confusion about the role and objectives of citizen science, as was achieved in the Regional Highlands case. Consequent to these insights, the following recommendation is proposed:

> **Recommendation 1:** That strategic and policy planning for citizen science development overtly recognise that freshwater citizen science is an ongoing, adaptive process. This recognition will enable the development of a clear and long-term programmatic vision supported by strategies that promote a culture of innovation, experimentation, rigour and locally relevant knowledge.

As this thesis has argued, citizen science is about relationship building, political will and attitudes. Building effective, lasting and genuine informal networks and informal relations by encouraging a networking mindset will be key to creating effective programs. Adopting this reflexive approach enables volunteers and coordinators to consider not only their immediate network partners but the network as a whole. Furthermore, volunteers in this study greatly benefited from regular meetings and events. These informal fora provide an opportunity for volunteers to meet with and learn from others. Coordinators are also encouraged to provide in these meetings opportunities to link with discipline experts, land managers and policymakers to improve the capacity for social and institutional learning. To realise these benefits, I make the following recommendation:

> **Recommendation 2:** That the use of social networks and the importance of relational factors be integrated into program development and planning. This incorporation will support the shift of the implementation mindset to one in which existing processes of integration, learning, engagement and reflection are recognised as integral to building a shared understanding of the potential of citizen science for freshwater monitoring.

Related to the above recommendation, a networking mindset should extend to considering how to mobilise key individuals who mediate, bridge and translate across the boundary between citizen science and expert communities. The findings from the Regional

Highlands case revealed the importance of the involvement of a scientist who connected the program with policymaking by promoting the program and communicating its opportunities and limitations. This individual, who is an example of a "boundary spanner," played a key role in shifting a culture of governance that is more receptive to the role of citizen science in understanding and management catchment issues. Thus, the role of spanning boundaries between volunteers and expert communities is not just a role for program coordinators, but also for scientists, participatory advocates and other community leaders. In realising this opportunity, I make the following recommendation:

> **Recommendation 3:** That citizen science programs identify and actively recruit, as part of their program development processes, individuals who can act as knowledge brokers, community leaders and policy entrepreneurs. This recognition and acknowledgement will support the acceleration of change and will actively address governance inertia.

Boundary objects are more than just a communication tool for a particular audience. As described in Chapter 8, boundary objects, such as maps, databases, and reports, can be interpreted differently by actors located on different sides of a given boundary but comprise a structure that is recognisable across these boundaries, what Star and Greiesemer (1989) call 'interpretative flexibility.' In this thesis, a catchment health report as a boundary object enacted by Regional Highlands Waterwatch was a key source of data, a communication tool and a symbol, which was able to meet the objectives of both community and government officials. It furthermore provided a mechanism to incorporate local knowledge contributions that could complement the scientific results of data collection efforts. Continued development and refinement boundary objects to bridge social worlds should therefore be part of future efforts at building more productive relationships between science, policy and citizen science practice. This includes evaluating the practices and outcomes surrounding the use of the boundary objects, rather than just focusing on the objects itself (Levina 2005). In highlighting this potential, I recommend:

Recommendation 4: That citizen science programs be supported to identify, create and use boundary objects as integral to building a stronger policy-program interface. These objects include annual reports, online spatial information systems and even local waterways that provide a common focus for different actors organise and negotiate their perspectives. The application of these objects should be evaluated regularly to assess their effectiveness.

Finally, from a historical perspective, freshwater citizen science in Australia was underpinned by principles of Participatory Action Research, whereby knowledge production is inextricably linked to action (Kidd and Kral 2005). As we have seen, newer citizen science initiatives tend to take a 'knowledge-oriented' rather than 'action-oriented' approach, which privileges a fact-finding mission to understand a particular phenomenon. The capacity to link knowledge with action is less likely in knowledge-oriented projects and should thus be celebrated and fostered in programs like Waterwatch who have historically enabled these community-directed efforts. However, a particular challenge for volunteers in this study was a lack of awareness and skills in realising their goals to improve environmental condition outside of their ability to scientifically monitoring water environments. Who should they speak to? What data do they need? Who can help? Programs will benefit from addressing these questions in projects where volunteers are assisted to direct their own environmental efforts. The following recommendation is directed at this issue:

Recommendation 5: That opportunities be provided to build volunteer skills in understanding the nature of policy frameworks and their own role in shaping and supporting policy development. Strategies to achieve this include workshops discussing locally relevant policies, best practices for local conservation action, leadership and data analysis strategies. Additionally, it is recommended that these extra scientific criteria be built into program evaluations.

10.4 Limitations

In this section, I acknowledge and discuss some limitations of the research design and methodology. Given the novelty of the application of social network analysis to citizen

science, I emphasise limitations associated with conducting and implementing this research approach in an effort to improve the quality of future efforts.

The first limitation relates to the lower than expected response rate from volunteers in each study case. The main reason for this was due to the ethical constraints placed on this research that limited direct contact with volunteers to request their participation. While protecting the anonymity of research participants is a critical issue in social network analysis (Borgatti et al. 2013), low response rates can create an inaccurate representation of a social network. Misrepresentations are a particular problem if central actors are missing from the analysis. Fortunately, most central actors (e.g. coordinators, scientists and key government decision-makers) who interacted with the study cases were accounted for in each case. Nevertheless, obtaining a more satisfactory response rate for volunteers would have enabled sophisticated analytical techniques, such as assessing individual network characteristics, degree and betweenness centrality, and their role in actor-level outcomes. In addressing this limitation, a decision was made to only include whole-network measures that were relatively robust to missing data.

The second limitation relates to the cross-sectional approach of the social network analysis conducted in this thesis. This meant that the studied networks were viewed at a single point in time and assumed to be stable, which fails to capture the dynamic and evolving nature of social networks that characterises citizen science. Moreover, in cross-sectional social network analysis, causal relationships are difficult to establish (Barnes et al. 2016). This limitation is common across many social network studies, but comparative approaches and the use of mixed methods can strengthen causal inferences. In a best-case scenario, collecting network data at multiple points in time is the most effective way to uncover and establish causal mechanisms. Such studies have the potential to capture how social networks change over time, and how these changes influence network function and outcomes. Longitudinal studies on the role of social networks in collaborative environmental governance arrangements are rare but should be strongly considered in future research.

The final limitation relates to the implications of social network analysis and capacity to translate the findings into practical action. An initial proposal that was not realised in the final the project design was to provide network visualisations to interviewees to assist in a sense-making process as they responded to interview questions. Through this approach, participants would have been able to view their program's network and comment on its structure and function and how it may be strengthened. For instance, network visualisation may reinforce participants' intuitive understanding of the program's network or highlight apparent deficiencies in network connections to stimulate conversations on possible remedial strategies. Despite the advantage of this approach, not presenting the network visualisations to interview participants did not have a major effect on the findings presented. In fact, there was some advantages, such as using interview data to validate the structural analysis of these networks.

10.5 Opportunities for further research

This conclusion also provides an opportunity to highlight some remaining questions for citizen science as it relates to natural resource management and policymaking. These opportunities are discussed in light of both limitations presented above and emergent findings in this thesis. Presented below, the research opportunities are aimed at improving the capacity of citizen science to enhance key waterway governance objectives for future social and environmental sustainability.

1. *Expanding the application of social network analysis to citizen science.* Social network analysis has proven to be useful tool to understand the structural and relational characteristics of citizen science networks. These insights are particularly valuable for projects that involve the participation of multiple actors who hold different roles, responsibilities and capacities to exert influence. Such demonstrations of this methodology are still limited, with only one other study applying the analysis to citizen science (Richter et al. 2018). This thesis provided insight into the role of social networks in linking citizen science knowledge with decision-making. However, there is additional potential to explore how networks shape learning opportunities,

behaviour change and community empowerment, as addressed in Chapter 6. There are many exciting possibilities for future studies. These would benefit from continuing to adopt a mixed methods approach, developing longitudinal studies, conducting cross-case comparisons of different project types (i.e. contributory, collaborative and co-created forms of citizen science), studying the interactions between organisations as well as individuals and exploring ego networks and narrative networks. Critical to such studies will be the implementation strategies to ensure a satisfactory response rate.

2. *Investigating contestation and collaboration in policy-oriented citizen science.* Not all citizen science projects will aim to develop 'productive' relationships with government agencies. In some cases, citizen science can enable the public to challenge the very authority of science or adopt scientific inquiry as means to advocate for environmental justice issues (Ottinger 2017). While most citizen science projects, as is the case in this thesis, will work with rather than against government agencies, the differences in project orientation raise several important questions. How do these different orientations interact, conflict or complement each other? Can instrumental and transformative goals exist in the same project? What strategies are needed for government agencies to improve the perceived legitimacy of social movement-based citizen science? Addressing these questions will require empirical work and could be informed by initial explorations conducted by Ottinger (2017) and Kinchy et al. (2014).

3. *Crafting citizen science through the creation and use of boundary objects.* Boundary objects have been discussed in this thesis as a crucial, yet largely unexplored, feature of citizen science. A growing body of literature has examined the development and function of boundary objective in collaborative environmental arrangements, including diverse artefacts such as models (White et al. 2010), ecological indicators (Turnhout 2009), and even entire watersheds (Cohen 2012). These objects—whether concrete or abstract—are capable of connecting and spanning different social worlds

aiding individuals in sharing and creating new knowledge, thereby laying the foundation for effective communication, collaboration and cooperation. Thus, I note significant potential to explore, characterise and enact different forms of boundary objects in citizen science to reconcile knowledges and values between citizens and experts.

4. *Investigating freshwater citizen science and sustainability in the global context.* This research has captured only a subset of the diversity of freshwater citizen science as it is practised in the Australian context. While the programs under study are relatively typical, there are other versions of the practice that similarly hold significant potential for improved scientific research and may enable transitions towards social and environmental sustainability. Of particular note are those projects operating in developing countries, which have been described in detail by Buytaert et al. (2014). A consolidation of research efforts in both developing and developed countries—situated in a global context and directed at transitions towards freshwater sustainability (Gleick 2018)—would greatly benefit the practice.

10.6 Final comments

In the years I have been following the development of citizen science, I have seen the practice expand across different research fields and embraced by universities, government departments and community-based organisations. In Australia, this growth has been paralleled by rising professionalisation of the practice as evidenced by, for instance, the emergence of the Australian Citizen Science Association and its state chapters. These organisations promote citizen science at a local and national level, deliver conferences and networking opportunities and facilitate its broader acceptance and uptake in universities and government policy. While these developments are certainly aimed at genuine efforts to develop equitable science governance and substantive improvements to research and decision-making, I end this thesis with some final comments and a word of caution for new and existing practices.

This thesis has maintained a view that citizen science is a promising approach to transform the way society understands and manages natural resources. There are, of course, many ways to "do" citizen science and not all projects will be suitable for such purposes (Bonney et al. 2016). However, most newly created projects tend to reflect a particularly narrow vision of what citizen science *is* but, more importantly, what it can *be*. The growing enthusiasm for the practice has resulted in the privileging of projects that advance scientific objectives rather than by making direct links to environmental improvements. There is a risk, therefore, that the extra scientific benefits of citizen science are neglected in these newer projects amid the growing enthusiasm for increased data access, new technologies and volunteer-assisted scientific discovery. I believe there needs to be more critical reflection about why we do citizen science and how it builds active, connected and informed communities leading to ultimate improvements in environmental quality.

Citizen science is by no means a panacea to the growing water crisis. However, it is a crucial part of sustainable knowledge production and policy processes. When appropriately organised, administered and managed, the practice holds significant potential to improve understanding and management of water resources, build stronger societal connections and create genuine opportunities for social transformation. As we enter a new era of valuing community involvement in scientific inquiry, this thesis has underscored the importance of attending to the social, as well as the scientific, dimensions of the practice.

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Appendices

Appendix A National Review Survey

Thank you for participating in the citizen science and community-based water monitoring National Review Survey.

We are inviting coordinators and program leaders of all community-based water monitoring programs and freshwater citizen science projects in Australia to ask about their views and experience working with their program. If you are not serving in this position, please pass this survey onto the appropriate person, and/or check the appropriate box in Q2.

This study is a key step in building an understanding of the nature and extent of community-based water monitoring programs in Australia and fill a critical knowledge gap about the impact of citizen science programs on waterway decision-making.

The research findings from this study will be used to inform the planning and development of citizen science and community-based monitoring programs in order to maximise their purpose and potential in natural resource management.

The survey is broken down into three sections. First, we want to get to know some general features of your program. Second, we hope to get a clearer picture about your program's impact and influence on waterway management and policy. Lastly, we want to know which organisations you are connected to, in what ways, and how these impact on your program's ability to achieve its goals

We estimate that completing the survey may take 20-25 minutes.

General questions

1. What is the name of your community group or citizen science program that undertakes data collection in freshwater or estuarine environments? Please be as specific as possible e.g. Waterwatch Victoria – Corangamite region.
2. Are you a program leader or coordinator?
   - Yes
   - No

[If Yes, continue to Question 3. If No, finish survey with comment "Sorry, we are only surveying program leaders and coordinators for this study. Thanks for participating."]

3. How long have you been in this position?
    - 10 years or more
    - Between 5 and 10 years
    - 1-5 years
    - Less than a year
4. Which organisation or institution do you currently work for?
    - Federal Government
    - State Government (environmental department)
    - State Government (education department)
    - University
    - Education institution
    - Regional NRM board or Catchment Management Authority
    - Government organisation
    - Non-government organisation
    - Local government
    - Water utility
    - Community group
    - Not applicable (no organisation)
    - Other, please specify.

Program characteristics and operation

5. For how many years has your program been collecting monitoring data?
    - More than 20 years
    - 10-15 years
    - 5-10 years
    - 1-5 years
    - Less than one year
6. What are the main priorities of your program? Please check all that apply.
    - To educate and engage the community

- To obtain data useful to inform management decisions and policy
- To address a lack of monitoring / waterway data
- To create long-term data sets on a particular waterway
- To investigate the outcome of a restoration or other management efforts
- To monitor a perceived environmental threat (e.g. pollution, impacts of a development)
- To investigate an environmental crisis
- To answer a research question
- Other, please describe.

7. What is the number of active volunteers in your program? (A volunteer is defined as active if they have participated in your program i.e. collected data in the past year)
8. Please identify the type(s) of water environments monitored by your program. Please check all that apply.
    - Lake/Pond/Reservoir
    - Wetlands
    - Rivers/Streams
    - Estuaries
    - Other, please specify.
9. What is the geographical focus of your program?
    - Local waterway or single catchment
    - Multiple catchments
    - Regional
    - State
    - National
    - International
    - Other, please describe.
10. Please identify the biological, chemical or physical indicators collected by your program? Please check all that apply.
    - pH
    - Dissolved oxygen (DO)
    - Electrical conductivity

- Turbidity
- Temperature
- Nutrients
- Physical habitat descriptions (e.g. riparian cover, sediment particle size, flow)
- Macroinvertebrates
- Frogs
- Algae
- Other species, please specify.
- Not listed here, please specify.

11. In the year 2017, how many sites were monitored by your program?
12. Approximately, how frequently are sites monitored by volunteers? If some indicators are sampled at different frequencies, please indicate in the space provided.
    - Once per week
    - Once per fortnight
    - Once per month
    - Once per season
    - Autumn and spring
    - Other, please specify.
13. Approximately, what is age composition of active volunteers? (Answer must equal 100%)
    - Under 18 ____
    - 18-25 ____
    - 25-55 ____
    - 55+ ____
    - Don't know ____
14. Considering your volunteers, what stage of the scientific/monitoring process are they given responsibility? Please check all that apply.
    - Developing research questions
    - Collecting data
    - Selecting sites for monitoring

- Managing data (e.g. upload to database)
- Analysing data
- Disseminating monitoring results

15. Are your methods based on:
    - state, national or international waterway monitoring methods/protocols?
    - a method protocol established by your organisation?
    - Not sure
16. Does your program implement the following:
    - Volunteer training?
        i. Yes
        ii. No

[If Yes, answer Question 16a, if No go to Questions 17]

16. a) How often per year is this implemented?

    iii. Once per month
    iv. Once per season (e.g. Autumn and Spring)
    v. Once per year
    vi. Other, please specify

    - Quality assurance and quality control procedures?
        i. Yes
        ii. No

[If Yes, answer Question 15b, if No go to Questions 16]

16. b How often per year are these implemented?

    iii. Once per month
    iv. Once per season (e.g. Autumn and Spring)
    v. Once per year
    vi. Other, please specify

17. How is data stored and managed by your program]?
    - Hard copy (paper)
    - Internet database

- Online mapping software (e.g. Google Earth)
- Atlas of Living Australia
- Spreadsheet or database (personal)
- Spreadsheet or database (institutional)
- Other, please specify.

Contribution to catchment management

The following questions consider your community-based water monitoring program's contribution to catchment management and policy in Australia.

18. Has data collected by your program been used in catchment decision-making?
    - Yes
    - No
    - Not sure

[If Yes, go to Question 19 and 20, if No go to Question 21]

19. Please identify the type(s) of contribution your program's data has made to catchment decision-making? Please check all that apply.
    - Baseline monitoring information
    - Environmental impact assessment
    - Investigating management action e.g. response to restoration activity
    - Water quality compliance
    - Education programs
    - Spatial products (maps)
    - Advocacy
    - State of environment reporting
    - Index of Stream Condition
    - Index of Estuary Condition
    - Other, please describe.
20. Could you provide references or web links that illustrate the uses of citizen science data by your organisation/project?
    - Yes, I can provide references below

- Yes, but can you follow up with me at a later date
- No

[If "Yes, I can provide references below", add space for references to be added]

21. How much influence do you feel your program has in catchment management decision-making and/or policy development?
    - Extensive
    - Some
    - Little
    - None
    - Unsure
22. How would you characterise how your program's data is viewed by decision-makers?
    - Very receptively
    - Somewhat receptively
    - Neutral
    - Somewhat sceptically
    - Very sceptically
23. Do you or your program experience barriers to achieving data uptake in decision-making processes?
    - Yes
    - No

[If Yes, go to Question 24, If no, go to 25.]

24. What are the main barriers to achieving data uptake by decision-makers? Please choose the top three.
    - Connecting and coordinating with data end users (i.e. decision-makers)
    - Data quality issues:
        - Frequency of sampling
        - Location of sampling
        - Accuracy of data collection methods
    - Retaining consistent data records

- Inefficient data storage/management
- Data not "fit for purpose"
- Funding and financial constraints
- Lack of interest by decision-makers in volunteer-collected data
- Other, please describe.

25. Please take this opportunity to mention any other issues or comments in relation to the use of volunteer data for catchment management decision-making processes.
26. For the volunteers within your program, how would you rate the importance they place on providing data for catchment decision-making in their region?
    - Use scale 1 (very important) & 5 (not important)
27. Are volunteers provided opportunities within your organisation to participate in catchment management decision-making processes?
    - Yes
    - No
    - Unsure
28. To the best of your knowledge, have any of your volunteers become actively involved in catchment management decision-making processes as a result of their participation by…
    - Contacting decision-maker directly to voice support or concern for management action or policy decision
        - Yes
        - No
        - Unsure
    - Attending public meetings related to a resource management issue
        - Yes
        - No
        - Unsure
    - Writing a letter that referenced their monitoring results to support or refute a policy decision
        - Yes
        - No
        - Unsure
    - Other contributions? Please describe.

Program interactions and partnerships

The following questions attempt to elicit information on the types of interactions and partnerships between your community-based water monitoring program and other entities involved in environmental protection.
For the purpose of this study, an ***interaction*** can be defined as a 'one-off' or ongoing exchange of ideas or advice, training, collaboration on projects, sharing data and resources or receiving funding whereas a ***partnership*** involves the above interactions but includes a signed formal agreement between two organisations.

29. In the past year, has your program interacted with the following entities? Please check all that apply.
    - ○ Federal or state environmental management department
    - ○ Local council
    - ○ Non-government organisation (NGO)
    - ○ NRM board or Catchment Management Authority (CMA)
    - ○ Other community or citizen science group
    - ○ TAFE or University
    - ○ Museum, zoo
    - ○ Primary or secondary school
    - ○ No interactions

[For each checked item, answer Question 30, 31, 32 and 33. If "No interactions" go to Question 34.]

30. What is the nature of your interaction with [insert checked organisation/entity]?
    - ○ Exchange of ideas or advice
    - ○ Training
    - ○ Collaboration on projects
    - ○ Sharing data and resources
    - ○ Receiving funding
    - ○ Other, please describe.
31. How is your program valued by [insert checked organisation/entity]?
    - ○ Highly valued

- Somewhat valued
- Neutral
- Somewhat unvalued
- Not valued at all

32. Is this interaction with [insert checked organisation/entity] apart of a formal partnership i.e. a contractual agreement or memorandum of understanding?
    - Yes
    - No
    - Unsure
33. How important are interactions with [insert checked organisation/entity] a necessary part of achieving your program's goals?
    - Very important
    - Somewhat important
    - Neutral
    - Somewhat unimportant
    - Not important at all
34. From your perspective, what do you think the value placed by your volunteers on partnerships and interactions as part of the monitoring process?
    - Highly valued
    - Somewhat valued
    - Neutral
    - Somewhat unvalued
    - Not valued at all
35. Please describe any new partnerships will be sought in the next year.
36. Do professionals (e.g. scientists) influence its planning and development?
    - Yes
    - No

[If Yes, go to Question 37. If no, go to Question 38]

37. What is the nature of this influence? Please check all that apply.
    - Developing research questions
    - Choosing sites for monitoring

- Volunteer training and education
- Informal advice
- Quality assurance and control
- Sharing monitoring data
- Data analysis and interpretation
- Communication of monitoring results
- Other, please describe.

38. Do you have any other comments about program partnerships and interactions?

Appendix B Social network mapping survey

Connections in Community-based Monitoring Networks

What is this research about?

The field of citizen science is increasingly valued for its dual benefits to environmental monitoring and community education and engagement. However, these benefits are often dependent on the interactions and relationships among various individuals and organisations. Therefore, the goal of this survey is to map and analyse these interactions in community-based water monitoring networks to understand how the patterns of social connections influence collaboration and data sharing. An example is shown below. An analysis of this network will provide critical insights that will help volunteers, community groups and government agencies better understand how community-based monitoring networks operate and how they might be strengthened to achieve positive social and environmental outcomes.

What will I be asked to do?

Should you agree to participate, you are invited to take part in a short questionnaire about your experience with community-based water monitoring and the people with whom you interact in its planning, implementation and data sharing. You will be asked to recall and identify these individuals and specify the purpose and strength of this relationship. The survey is short and will take approximately 10-15 minutes of your time.

Will your identity be protected?

We take participant confidentiality seriously and adhere to best ethical practice in social network research. The following strategies have been put in place to protect the identity of individuals and organisations:

- We will immediately assign your responses with a unique ID code such that your personal identity, the individuals you identify, and the identity of your group or organisation will remain confidential;
- Any publicly available analyses of these data will not show any individual by name or identify a specific monitoring group or organisation (as per example above);
- Survey data will be collected across three community-based water monitoring networks in Australia, which provides an additional layer of anonymity to research findings.

Do I have to take part?

Your participation in this research is voluntary and you are free at any time to withdraw your participation. There are no consequences for withdrawing from this research. You may also choose not to respond to all questions in the survey, just answer the questions you are comfortable with. Completing this survey indicates your consent to participate in this research

Will I hear about the results of this project?
Yes. The information you share will be used for PhD research with data and findings used in the preparation of a thesis, research papers for publication, conference papers and presentations, and industry-based stories for general publication. We will also provide all participants with specific, personalised feedback, including information they might use to improve their personal networks or that might be useful to satisfy the goals and motivations of their organisation.

Where can I get further information?
If you require further information, or require support regarding your participation in this project, please contact Patrick Bonney. Phone XXXX, or email p.bonney@federation.edu.au.

Section 1/3

1. To begin, please enter your name. Please provide your first and last name. However, you may use your first name and last initial if preferred. *

Please write your answer here:

***Please note that names are only collected in order to understand the general patterns of connections across community-based water monitoring networks. We will not publish any identifying information of individuals or organisations in research outputs.

2. What group or organisation are you affiliated with?

Please write your answer here:

What is your role within this group or organisation?

Please choose only one of the following:

- Volunteer
- Coordinator / Program leader
- Catchment manager
- Policy-maker
- Scientist
- Other

3. How long have you been part of this group or organisation? Please choose only one of the following:
   - Less than one year
   - 1-4 years
   - 5-9 years
   - 10-14 years
   - 15 years or more
   -

Section 2/3

Please read:

In community-based water monitoring networks, various people 'interact' for numerous and wide-ranging reasons. Individuals in these networks may include volunteers, program coordinators, catchment managers, policy-makers and members of the scientific community, among others.

In this study, an 'interaction' might involve the following:

- Sharing community-based water monitoring data
- Collaborating on projects
- Exchanging ideas or providing advice on the selection, planning and/or outcomes of projects
- Acquiring resources e.g. funding or other tangible resources
- Seeking support or requesting management actions as a result of monitoring activities

4. Consider your relationships, please list the names of up to ten people with whom you 'interact' about community-based water monitoring activities? See above for our definition of 'interaction'.

Where possible, please use full names. However, you may also use the person's first name and last initial if preferred (e.g. John S.)

If you can't recall a particular person, please refer to their organisation and position (e.g. catchment manager, scientist, volunteer).

Please write your answer(s) here:

- Person 1
- Person 2
- Person 3
- Person 4
- Person 5
- Person 6
- Person 7
- Person 8
- Person 9
- Person 10

***Please note that names are only collected in order to understand the general patterns of connections across community-based water monitoring networks. We will not publish any identifying information of individuals or organisations in research outputs.

5. If known, what organisation or group is this person affiliated?

Please write your answer(s) here:

- Person 1
- Person 2
- Person 3
- Person 4
- Person 5
- Person 6
- Person 7
- Person 8
- Person 9
- Person 10

6. How would describe this person?

Please choose the appropriate response for each item:

Person	Friend	Family member	Colleague	Professional acquittance	Fellow volunteer
Person 1					
Person 2					
Person 3					
Person 4					
Person 5					
Person 6					
Person 7					
Person 8					
Person 9					
Person 10					

7. What is the nature of your interaction with each person?

Please check all that apply.

Person	Sharing data	Collaborating on projects / Coordinating activities	Exchanging ideas / Providing advice	Acquiring resources	Seeking support / Requesting action
Person 1					
Person 2					
Person 3					
Person 4					
Person 5					
Person 6					
Person 7					
Person 8					
Person 9					
Person 10					

8. Overall, how would you rate the strength of your relationship with this person?

Please choose the appropriate response for each item:

Person	Very Strong	Strong	Weak	Very Weak
Person 1				
Person 2				
Person 3				
Person 4				
Person 5				
Person 6				
Person 7				
Person 8				
Person 9				
Person 10				

9. How frequently do you interact with this person?

Please choose the appropriate response for each item:

Person	Not often (1-3 times per year)	Sometimes (1-3 times per month)	Regularly (1-3 times per week or more)
Person 1			
Person 2			
Person 3			
Person 4			
Person 5			
Person 6			
Person 7			
Person 8			
Person 9			
Person 10			

Section 3/3

10. How valuable is community-based water monitoring for:

a. Understanding waterway issues?
   - Very valuable
   - Valuable
   - Average value
   - Limited value
   - Not valuable at all
   - Unsure

b. Community education?
   - Very valuable
   - Valuable
   - Average value
   - Limited value
   - Not valuable at all
   - Unsure

c. Enabling public participation in waterway decision-making?
   - Very valuable
   - Valuable
   - Average value
   - Limited value

- Not valuable at all
- Unsure

11. How satisfied are you with the level of collaboration that exists in community-based water monitoring networks?
    Please choose only one of the following:

- Very satisfied
- Somewhat satisfied
- Neither satisfied nor unsatisfied
- Somewhat unsatisfied
- Not satisfied at all
- Unsure

12. Are you interested in participating in a follow-up interview to expand on your experience with community-based water monitoring programs?

Please choose only one of the following:

- Yes
- No

13. If there are other comments you would like to make about this study or in relation to community-based water monitoring and catchment management, please do so in the space provided below.

Please write your answer here:

Survey complete!

Thanks so much for completing this survey. We are grateful for your time and contributions that will provide insights to help volunteers, community groups and government agencies better work together to achieve positive outcomes for Australian waterways.

Please be aware that this research adheres to strict ethical guidelines and that you and your group or organisation's confidentiality will be maintained. If you have any questions or comments, please do not hesitate to contact Patrick Bonney on 0432 673 054 or p.bonney@federation.edu.au. Otherwise, please read the Plain Language Information Statement that was sent to you via email. Thanks again!

Appendix C Interview schedule

Interview schedule

1. What are your roles and responsibilities in relation to this program?

2. What initially motivated your involvement?

3. What environmental/water-based issues are of concern to you in your region?

4. Please tell me about your most rewarding experience with Waterwatch? What is your most frustrating experience?

5. Please tell me about your overall experiences collaborating with different members in the Waterwatch network.
   Prompts:
   - With volunteers/coordinators/local government/state government/other stakeholders
   - Who do you have the most contact with?
   - Purpose/importance of interactions?
   - Positive/negative aspects?

6. How would you describe the flow of data through the Waterwatch network? What barriers or enablers exist?

7. What actions could be taken to increase the level of collaboration in your monitoring network? What resources could be provided? Impacts of funding?

8. What is your vision for an ideal community-based monitoring program in your region?

Appendix D Code structure

1. Environmental issues
    a. Development
    b. Restoration
    c. Species
    d. Water quality/pollution
    e. Other

2. External value
    a. Aspects of data
    b. Data uptake
    c. Environmental outcomes
    d. External challenges i.e. data quality
    e. Scale of issue/application

3. Internal value
    a. Capacity building
    b. Civic engagement
    c. Personal development/learning
    d. Place attachment
    e. Social connection
    f. Internal challenges

4. Internal/External interactions and tensions
    a. Inclusion/Exclusion

5. Network functioning
    a. Coordination
    b. Future vision
    c. Historical context
    d. Motivations
    e. Power
    f. Relationship barriers
    g. Relationship enablers
    h. Socio-political influences

6. Social processes
    a. Advice
    b. Collaboration
    c. Data sharing
    d. Requesting action
    e. Resources funding
    f. Social learning
    g. Trust

7. Social structure
    a. Bonding
    b. Bridging
    c. Linking

8. Technology

Appendix E Approval and final report for Human Research Ethics Committee

Approval with Comment

Human Research Ethics Committee

Principal Researcher:	Dr Angela Murphy	
Other/Student Researcher/s:	Mr Patrick Bonney Assoc. Prof Claudia Baldwin	Dr Birgita Hansen
School/Section:	**Centre for eResearch and Digital Innovation**	
Project Number:	**A18-006**	
Project Title:	**Citizens as monitors: Crowdsourcing for waterway management and policy development.**	
For the period:	23/02/2018 **to** 01/11/2019	

Quote the Project No: A18-006 in all correspondence regarding this application.

- **Comment** : The Interview Schedule in draft form as submitted is approved as is but if there are changes made the schedule will need to be re-submitted for approval.

Approval has been granted to undertake this project in accordance with the proposal submitted for the period listed above.

Please note: It is the responsibility of the Principal Researcher to ensure the Ethics Office is contacted immediately regarding any proposed change or any serious or unexpected adverse effect on participants during the life of this project.

In Addition: Maintaining Ethics Approval is contingent upon adherence to all Standard Conditions of Approval as listed on the final page of this notification

COMPLIANCE REPORTING DATES TO HREC:

Annual project report:

23 February 2019

Final project report:

1 December 2019

The combined annual/final report template is available at:

http://federation.edu.au/research-and-innovation/research-support/ethics/human-ethics/human-ethics3

Fiona Koop

Ethics Officer

23 February 2018

Annual/Final Project Report

Human Research Ethics Committee

Please indicate the type of report	☐ Annual Report (**Omit 3b & 5b**) ☒ Final Report
Project No:	A18-006
Project Name:	Citizen Science: Knowledge, Networks and the Boundaries of Participation.
Principal Researcher:	Dr. Angela Murphy
Other Researchers:	Patrick Bonney, Dr. Birgita Hansen, Assoc. Prof. Claudia Baldwin
Date of Original Approval:	23rd February 2018
School / Section:	Centre for eResearch and Digital Innovation
Phone:	0432 673 054
Email:	p.bonney@federation.edu.au

Please note: For HDR candidates, this Ethics annual report is a separate requirement, in addition to your HDR Candidature annual report, which is submitted mid-year to research.degrees@federation.edu.au.

1) Please indicate the current status of the project:		
1a) Yet to start		☐
1b) Continuing		
1c) Data collection completed		☐
1d) Abandoned / Withdrawn:		☒
		☐
1e) If the approval was subject to certain conditions, have these conditions been met? (If not, please give details in the comments box below)	☒ Yes	☐ No
Comments:		

1f) Data Analysis	☐ Not yet commenced	☐ Proceeding	☒ Complete	☐ None

1g) Have ethical problems been encountered in any of the following areas:		
Study Design		
Recruitment of Subjects	☐ Yes	☒ No
Finance		
Facilities, Equipment	☐ Yes	☒ No
(If yes, please give details in the comments box below)		
	☐ Yes	☒ No
	☐ Yes	☒ No
Comments:		

2a) Have amendments been made to the originally approved project?	
☐ No	☒ Yes
2b) If yes, was HREC approval granted for these changes?	
☐ Yes	**Provide detail:** ☒ Yes **Application for Amendment to an Existing Project** ☐ Yes **Change of Personnel** ☐ Yes **Extension Request**
☐ No	**If you have made changes, but not had HREC approval, provide detail as to why this has not yet occurred:**
2c) Do you need to submit any amendments now?	
☒ No	☐ Yes **Application for Amendment to an Existing Project** ☐ Yes **Change of Personnel** ☐ Yes **Extension Request** *** NB: If 'Yes', download & submit the appropriate request to the HREC for approval:** **Please note: Extensions will not be granted retrospectively. Apply well prior to the project end date, to ensure continuity of HRE approval.**

3a) Please indicate where you are storing the data collected during the course of this project: (Australian code for the Responsible conduct of Research Ch 2.2.2, 2.5 – 2.7)
As outlined in the original ethics application, storage of all data and information is contained in a locked cabinet, in a locked room located in the Centre for eResearch and Digital Innovation (the office location for the student and principal researchers on this application). Data collected via the online surveys and audio recordings are stored on a password protect FedUni computer/laptop and on a password protected web-based database.
3b) Final Reports: Advise when & how stored data will be destroyed (Australian code for the Responsible conduct of Research Ch 2.1.1)
All data will be disposed of by the principal researcher through the process of negotiation with the data disposal officer, at Federation University. The data will be disposed after 5 years. However, electronic data from this research may be retained for longer, as needed.

4) Have there been any events that might have had an adverse effect on the research participants OR unforeseen events that might affect continued ethical acceptability of the project?	
☒ No	☐ Yes *** NB: If 'yes', please provide details in the comments box below:**
Comments:	

5a) Please provide a short summary of results of the project so far (no attachments please):
Data collection for this study is now complete. A total of 168 surveys and 40 interviews were for this PhD research were conducted with a range of participatns including volunteers, program co ordinators and scientists. Analysis of both the qualitative and quantitative data for participants enabled the answering of the research questions that had been developed for the study and provided significant insights into the role of social networks in shaping practice and the ways in which boundary work both enabled and constrained involvement in waterway governance. The evidence from the data collected was analysed against an framework of relational practice involving structure, meaning and boundaries and clear recommendations supporting the embedding of network analysis and boundary work were provided for future work in this area.
5b) Final Reports: Provide details about how the aims of the project, as stated in the application for approval, were achieved (or not achieved). (Australian code for the Responsible conduct of Research 4.4.1)
Two studies were completed for this PhD research. The first study aimed to review the current state of community-based water monitoring projects across Australia through survey research of program coordinators. Results show that programs are operating nationwide, with variable size, multifaceted objectives and methods of data collection. Contributions to catchment management were found for less than half of programs with significant social, institutional and technical barriers currently limiting data uptake. Study two aimed to measure the nature and impact of social networks within two operating water monitoring programs. This data collection was achieved

through the use of survey instruments and interviews. Results show that there are a range of social networks in place and that these have been having a notable impact on how program delivery occurs, how professional boundaries are maintained and the ways in which they act as barriers and enablers to effective and integrated input into the governance process.

The above aims were achieved through the data collected from a range of participants, as identified in the original application to ethics. For the study 168 surveys were completed and 40 in-depth, semi-structured interviews were conducted. Analysis of both the qualitative and quantitative data revealed support for the aims of the research, and the specific research questions associated with this study. The study clear evidence that social networks and the nature of the way monitoring groups work within professional boundary structures influence the nature of service delivery and the capacity of monitoring groups to achieve diverse outcomes and influence policy making. They also shaped the type of governance structures in place across groups.

This research informed the development of a conceptual relational framework outlining the types of factors that needed to be examined and understood in order to maximise outcomes at the policy and practice level. There are broad implications from the research findings for the field of freshwater monitoring and governance, which have been documented in the PhD thesis and will be made public through the mechanism of four diverse publications. The thesis itself is expected to be lodged for examination in August 2020.

6) Publications: Provide details of research dissemination outcomes for the previous year resulting from this project: eg: Community seminars; Conference attendance; Government reports and/or research publications

Bonney, P., A. Murphy, B. Hansen and C. Baldwin (2018). Citizen science in Australia's waterways: Investigating Linkages with Catchment decision-making. *58th Annual Australian Freshwater Sciences Society Conference*, Adelaide, Australia. 23-28 September 2018.

Bonney, P., A. Murphy, B. Hansen, and C. Baldwin. 2020. Citizen science in Australia's waterways: Investigating linkages with catchment decision-making. *Australasian Journal of Environmental Management* 27(2):200–223.

7) The HREC welcomes any feedback on:

- **Difficulties experienced with carrying out the research project; or**
- **Appropriate suggestions which might lead to improvements in ethical clearance and monitoring of research.**

8) Signatures			
Principal Researcher:	Print name: Dr. Angela Murphy	**Date:**	20/8/2020
Other/Student Researchers:	Print name: Dr. Birgita Hansen	**Date:**	20/8/2020
	Print name: Patrick Bonney	**Date:**	20/8/2020
	Print name: Assoc. Prof Claudia Baldwin	**Date:**	20/8/2020

Submit to the Ethics Officer, Mt Helen campus, by the due date:
research.ethics@federation.edu.au

Appendix F Documented cases of data use by freshwater and estuarine community-based monitoring and citizen science programs in Australia

Data use category	Program name	Documented case of data use
Strategy and planning	Upper Murrumbidgee Waterwatch[i]	A grant obtained by an ACT council in 2016 for restoration works on the Cooma Creek contained a combination of Platypus data obtained during Waterwatch's Platypus Month and the results on Cooma Creek from the CHIP report. Within the ACT Government's Environment Division, the Biodiversity, Research and Monitoring Program, the Conservation Effectiveness Monitoring Program as well as the draft ACT Integrated Water Monitoring Plan have all included Waterwatch water quality monitoring data.
	Waterwatch – Melbourne Water[i]	Frog Census data uptake in Melbourne Water waterway planning processes. Platypus management plan used community data through an eDNA approach.
	Waterwatch – Manningham City Council	Data produced by the program have been used to shape water policy, such as 'A Cleaner Yarra River and Port Phillip Bay Action Plan' 'Manningham Water Cycle Management Plan 2014' and 'Generation 2030'.
	EstuaryWatch – Corangamite	Data sharing arrangement of a 10-year community data set with a consultancy and water utility to assist with future management of Gellibrand River.
Monitoring and implementation	Frogwatch ACT and region	Use of frog species richness and occurrence data over 13 years to investigate the effects of urbanisation on patterns of frog species. Program shows urban areas have lower occurrence of frog species but there is not an accelerating decline. Management report and research paper produced.
	Waterwatch Natural Resources SA Murray-Darling Basin	Waterwatch data used to evaluate the effectiveness of water allocation planning and implementation of a low flows return program.
	Waterwatch – Melbourne Water[ii]	Community data used to assess the effectiveness of three water sensitive urban design measures in SE Melbourne. Waterwatch data used in conjunction with professional datasets. Drought refuge monitoring by Landcare groups to track condition of important refuge pools over summer period for the protection of the Yarra Pygmy Perch. As pools dropped below critical levels, triggered emergency watering through trucking in 28,000L of water. Lower Werribee river data from volunteers used to investigate the effect of environmental flows. Data influenced management actions to reduce public health risks.

	EstuaryWatch – West Gippsland	Use of estuary mouth condition monitoring and physico-chemical data to assist with estuary closure management for Powlett River Estuary.
	EstuaryWatch – Corangamite	EstuaryWatch data used to provide an understanding of salinity variability in the lower Barwon River to identify modifications needed to the Reedy Lake outlet channel and culvert to improve the ability to flush the wetland with tidal water from Lake Connewarre. Use of estuary mouth condition monitoring and physico-chemical data to assist with estuary closure management for Painkalac Creek. EstuaryWatch volunteers monitored pre and post works of the installation of lateral groynes. Data shows the works are delivering the desired outcomes.
	Waterwatch - Corangamite	The Environment Protection Authority (EPA) Victoria did regular water quality monitoring and liaised with the community recognising the value of having skilled water testers ready to mobilise in the event of high rainfall and river flow. The baseline data from community monitors was invaluable in determining if the waterway had been impacted and how quickly it recovered.
	Waterwatch – Goulburn Broken	In 2016, Waterwatch undertook an intensive program of water quality monitoring in the Murray River upstream and downstream of the Barmah Forest to record the potential impact of management activities from the Barmah Forest floodplain. In 2014, Waterwatch assisted a university and research centre with the collection of data and samples from the Lower Goulburn River.
	WA Indigenous Ranger Program	Paper documenting management of freshwater systems through indigenous ranger program: “Collaborative research partnerships inform monitoring and management of aquatic ecosystems by Indigenous rangers”
	Bellingen Riverwatch – Our Rivers, Our Future	Data used in project titled ‘Our Rivers, Our Future’ focusing on filling monitoring gaps and support recovery actions for a threatened turtle species.
	Program A (program chose to maintain anonymity)	On-farm water monitoring in collaboration with a farming association in an effort to develop systems to decrease silt and nutrient loads. Bore monitoring to understand groundwater recharge times. Stormwater monitoring with a council to understand impacts of industrial stormwater.
	NSW Waterwatch	The adopt-a-SQID program encouraged community involvement in stormwater management and ownership of local constructed stormwater treatment devices (SQIDs) in Lake Macquarie to evaluate their effectiveness.

	Queensland Murray-Darling Committee	Identification of banned pesticides being used in parts of a catchment, resulting in changed practices by a user organisation with the pesticide not being detected again. Identification of turbidity and electrical conductivity readings above normal levels in a stream impacted by tailings from a quarry operation. Parameters returned to normal since the impacting organisation made changes to their practices. A local government was advised that nutrient readings in a stream downstream of an urban area were high in some rainfall/runoff events. The community monitoring data was analysed alongside urban water treatment plant operations data and the cause of the high nutrient runoff events was ascertained. The local government is now budgeting to upgrade facilities and operational processes to address the problem.
Reporting and evaluation	Upper Murrumbidgee Waterwatch[i]	Contributing data to annual report card (since 2014) providing a score of catchment health using water quality, macroinvertebrate and riparian condition data titled the Catchment Health Indicator Program (CHIP). For example, the 2016-17 CHIP report is based on 1,861 water quality surveys, 199 water bug surveys, and 210 riparian condition surveys collected by over 200 volunteers from four catchment groups. The Capital Metro project used Waterwatch data to help establish a historic baseline along the project alignment
	Mary River Catchment Waterwatch Program	Numerous Waterwatch reports are produced for the Mary River Catchment Coordinating Committee using a report card system.
	Waterwatch – North Central	Annual River Health Snapshot Report 2016 provides a baseline assessment of river health with results used to track progress against Native Fish Recovery Plans objectives. Contributed data for the third Index of Stream Condition report (2013)
	Merri Creek Management Committee Waterwatch Program	Organisational report providing a summary of water quality in the Merri and Darebin Catchment 2017
	Waterwatch – Goulburn Broken	Catchment condition reports produced in some sub catchment in the Goulburn Broken region. Contributed data for the third Index of Stream Condition report (2013)
	Waterwatch – North East	Waterwatch staff produce an annual report on the data collected by Waterwatch monitors with at least 11 points of data are collected for the 12-month period. This data is compared to the State Environmental Protection Policy Guidelines for Waters of Victoria. Contributed data for the third Index of Stream Condition report (2013)

	Waterwatch – Corangamite	Waterwatch data is used in the EPA's Report Card developed in 2013 as part of the Yarra & Bay Plan to report on the health of Port Phillip Bay and its associated catchments using water quality indicators. Contributed data for the third Index of Stream Condition report (2013)
	Waterwatch – Manningham City Council	In 20013/14, 25 volunteers monitored 20 sites across Manningham's seven catchments. The Waterwatch data was sent to Council and the results are tabled in the Waterwatch Healthy Waterways Water Quality Report.
	Bellingen Riverwatch	Dissolved oxygen, phosphates and temperature data across the Bellinger River, Never Never River, Rosewood site and Kalang River reported on project website
	Waterwatch – Wimmera region	Numerous Catchment Management Authority reports available documenting catchment condition in region.
	Queensland Murray Darling Committee	Report documenting Waterwatch macroinvertebrate data used for assessment of river health condition and trend

i The Upper Murrumbidgee Waterwatch program involves a network of four separate catchment groups (Ginninderra Catchment Group, Southern ACT Catchment Group, Molonglo Catchment Group and Cooma Waterwatch). Each program has a dedicated staff member coordinating monitoring activities in their respective region.

ii The Melbourne Water Waterwatch program covers the greater Melbourne region and has five dedicated coordinators (four of whom took part in this study) each coordinating water quality monitoring activities in separate regions.

Appendix G Summary of citizen science research emphasising the role and importance social networks and relational processes and concepts

Reference	Social process	Individual (I) or program (P) outcome	Social attribute; trust (T), social capital (SC)
(Appels et al. 2017)			(SC) Built 'sense of comradery' and new opportunities to discuss issues with others
(Becker et al. 2005)	Data from CS project facilitated cooperation and information exchange at multiple government levels		(SC) Program helped build social capital
(Bell et al. 2008)		(P) Participants placed high value on social interaction; relationships key to program stability and recruitment	
(Bremer et al. 2019)			(SC) (T) CS project had high impact on social capital through dense network formation, high attendance at meetings and improved 'trust and openness'
(Cappa et al. 2016)		(I) Participant motivation in technology-mediated CS is positively influenced by face-to-face interactions	
(Carballo-Cárdenas and Tobi 2016)		(I) Motivations of participants driven in part by desire to socialise with others	
(Chase and Levine 2018)		(I) Exposure to other volunteers strengthened pro-environmental attitudes	
(Church et al. 2018)	Volunteers shared project information with wider community; potential for behaviour change through social diffusion		
(Conrad 2006)			(SC) Community-based monitoring project has led to the creation of both social capital and social liability
(Cosquer et al. 2012)		(I) Individual learning associated with social interaction	
(Fernandez-Gimenez et al. 2008)	Collaborative monitoring acts as partnership building exercise, allowing for information sharing, social learning	(P) 'Deliberative, transparent and collaborative process[es]' were found to improve application of monitoring results	(T) Trust building, respect and understanding among stakeholders viewed as outcomes of collaborative monitoring initiatives

(Forrester et al. 2017)		(P) Shows citizen science as an effective mechanism to create support for conservation in the wider community through information diffusion to wider social networks	
(Gharesifard and Wehn 2016)	Sharing of CS data creates sense of belonging and promotes learning but depends on trust-related factors		
(Haywood et al. 2016)			(SC) Participation in rigorous citizen science promoted greater connections with community; Collective action linked to, among other factors, communication of results to personal acquaintances and elected officials
(He et al. 2019)		(I) Participant connections and recruitment of family members are more likely to sustain participation	
(Hollow et al. 2015)		(P) CS koala monitoring project provided opportunities for policymakers to engage in dialogue with interested people in early stages of policy development	
(Jalbert et al. 2014)	CS water monitoring programs operated in either centralised or decentralised networks, which had differential impacts of various social processes e.g. resourcing		
(Johnson et al. 2014)		(I) Promoted development of environmental opinion leaders who developed 'sense of self-efficacy'	
(Koss and Kingsley 2010)		(I) Participant sense of satisfaction linked to their socialisation with others	
(Martin and Greig 2019)		(I) Willingness to share experiences with their social networks drive volunteers' motivations to participate	
(McGreavy et al. 2016)	Program built new networks that enhanced information		

	flow, learning, and mutual understanding		
(Nerbonne and Nelson 2004)	Volunteer macroinvertebrate monitoring programs operating centralised state programs have access to greater resources than in networked states	(P) Data sharing and production of reports occurs more readily in programs with greater levels of state support	
(Nerbonne and Nelson 2008)		(P) Data use correlated with a 'group's feeling of connection'	(SC) Project provided opportunities to build social capital among actors
(Overdevest et al. 2004)		(P) (I) Networks served to enable individual political participation and promote program resilience, stability	(SC) Studied programs resulted in denser social networks generating social capital in communities
(Pollock and Whitelaw 2005)		(P) Programs were most successful when 'locally appropriate and adaptive, led by strong coordination and based on collaborative partnerships, provided meaningful opportunities to participants, established information delivery mechanisms and worked toward sustainability.'	(SC) Community-based monitoring cultivated the social capital needed to support local sustainability
(Richter et al. 2018)		(P) (I) Used social network analysis to show the role of coordination and social relations between individuals are vital for engagement of volunteers and program longevity	
(Sayer et al. 2015)	Social networks among stakeholders working at different hierarchical levels were critical for social learning and communicating results		
(Stepenuck and Genskow 2018a)		(P) Favourable support at policy levels and multi-stakeholder engagement improved uptake of citizen science data	
(Storey et al. 2016)	Volunteers communicated project information with other community members		(SC) Volunteers developed new relationships with council members and confidence to discuss issues with experts
(Thomsen 2003)		(P) Sustainability outcomes in community-based research facilitated in part by social interaction and social learning	

(Thornton and Leahy 2012)			(T) Trust in CS data by local community members drive by interpersonal trust and familiarity
(Van Brussel and Huyse 2019)			(SC) Project successful in building social capital through improved knowledge and broad outreach
(Van Rijsoort and Jinfeng 2005)	Project changed perceptions among stakeholders through social learning		(SC) (T) Participatory monitoring improved trust and built social capital among stakeholders
(Villaseñor et al. 2016)		(P) Data uptake in decision-making more common for 'collaborative-learning' monitoring approaches	