





Adaptive and transformative learning in environmental water management: Implementing the Crocodile River's Ecological Reserve in Kruger National Park, South Africa



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Dates:

Received: 13 Nov. 2020
 Accepted: 17 Feb. 2021
 Published: 20 Apr. 2021

Read online:



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Freshwater biodiversity loss in the Anthropocene escalates the need for successful environmental water management to sustain human benefitting ecosystem services. Of the world's river basins, one-third are now severely water depleted, rendering the quality and quantity of water to maintain or restore freshwater ecosystem integrity increasingly urgent. However, managing environmental water is intricate because of complexity and uncertainty in interacting social and biophysical system components, and trade-offs between costs and benefits of implementing environmental flows. Learning enabled adaptive management – embracing the uncertainty – is essential; however, practising adaptive management (worldwide) is challenging; single-, double- and triple-loop learning is required, along with social learning, to tackle complex problems. There is progressive realisation of environmental flows (Ecological Reserve) in the Crocodile River, South Africa, linked to the Kruger National Park, using Strategic Adaptive Management (SAM). In this research article, we reflected on adaptive (single- and double-loop) learning and transformative (triple-loop) learning capacity emergent in SAM between 2009 and 2019 whilst also considering social learning potentials. We found evidence of preconditions (e.g. transparency) for social learning within a burgeoning stakeholder 'community-of-practice', likely fostering capacities (e.g. information sharing) for sustained social learning. Adaptive and transformative learning is enabled by social learning, underpinned by ongoing nested feedbacks supporting assessment and reflection, which facilitates single-, double- and triple-loop learning. Champions exist and are vital for sustaining the adaptive management system. Executing adaptive and transformative learning aids in positive change across the range of ecological, social and economic outcomes that are essential for success in environmental water programmes, worldwide.

Conservation implications: Crocodile River Ecological Reserve implementation, associated with Kruger National Park, provided an important national precedent (lessons) for protecting the ecological integrity of river systems – obligatory under the *National Water Act* (Act No 36 of 1998). We demonstrated the importance of ongoing stakeholder learning for successful management of the Ecological Reserve.

Keywords: adaptive management; Ecological Reserve; environmental flows; feedbacks; Kruger National Park; single-, double-, triple-loop learning; social learning.

Introduction

The Anthropocene is characterised by ubiquitous loss of biodiversity at unprecedented rates and scales (Kingsford, Bino & Porter 2017a). Globally, this biodiversity loss is severest across the freshwater realm (Albert et al. 2021; Vorosmarty et al. 2010), which exhibits the highest species diversity per unit area (Pittock et al. 2015). Over the last half century, alteration to natural flows in rivers – from land-use change, water over-abstraction and building of dams – has contributed towards more than 80% reduction in the freshwater species population (Harwood et al. 2017; WWF 2020 – Freshwater Living Planet Index). Currently, one-third of the world's river basins are severely water depleted (Harwood et al. 2017), thereby, rendering the quality and quantity of water to

How to cite this article: McLoughlin, C.A., Riddell, E.S., Petersen, R.M. & Venter, J., 2021, 'Adaptive and transformative learning in environmental water management: Implementing the Crocodile River's Ecological Reserve in Kruger National Park, South Africa', *Koedoe* 63(1), a1663. <https://doi.org/10.4102/koedoe.v63i1.1663>

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maintain or restore freshwater ecological integrity (e.g. habitats) increasingly urgent (WWAP 2018). Setting allocations of water for the environment in environmental flow policy and programmes, and monitoring and evaluation of outcomes are now imperative for sustained delivery of human benefitting ecosystem services (e.g. drinking water, food) emanating from rivers (cf. Harwood et al. 2017; Nel & Roux 2018; Tickner et al. 2020; Webb et al. 2018).

Managing freshwater resources in complex, interacting social and biophysical systems (Anderson et al. 2019; Biggs et al. 2015; Cilliers 2008) – achieving diverse values and goals – is an arduous undertaking (Harwood et al. 2017; Pahl-Wostl et al. 2013) fraught with uncertainty (Biggs et al. 2015; Rogers et al. 2013). Uncertainty is exacerbated by poor water governance historically (Harwood et al. 2017; Pahl-Wostl et al. 2013) and impacts from climate change (Palmer et al. 2009; Pittock & Max Finlayson 2011). Moreover, escalating competition for limited water resources is fuelling growing conflict (Nel & Roux 2018; WWAP 2018) with implicit trade-offs between costs and benefits of environmental water, as evidenced in Australia's Murray-Darling Basin (Chen et al. 2020; Schoeman, Allan & Finlayson 2019; Thoms, Rose & Dyer 2020; Webb et al. 2018). Adaptive management is the foremost approach for effective and successful planning and delivery of environmental water (McLoughlin, Thoms & Parsons 2020; Nel & Roux 2018; Webb et al. 2018). Adaptive, learning-by-doing strategies assume that complex social-ecological systems are in a state of flux, and understanding is always imperfect (Biggs & Rogers 2003; Gunderson 2015; Rogers 2003). Management expects to face substantial uncertainty (Biggs et al. 2015; Stankey, Clark & Bormann 2005), and therefore, seeks to remain flexible in the achievement of goals (Anderson et al. 2019; McLoughlin et al. 2020).

Generically, adaptive management encompasses a series of actions characterised by feedback loops, with deliberate intent to achieve goals through the modification and refinement of hypotheses, objectives, outputs or outcomes and of management actions (Kingsford et al. 2017b). This iterative process is supported by strategic monitoring, with feedbacks and learning from the outcome of decisions (McLoughlin & Thoms 2015). Learning amongst all stakeholders is key to success (Pahl-Wostl 2009; Rogers, Roux & Biggs 2000; Roux et al. 2017), and to be effectual requires three modes: 'adjusting, improving existing routines' (single-loop learning), 'reframing, changing practice' (double-loop learning), and 'reviewing norms and values, and transforming governance' (triple-loop learning) (Fabricius & Cundill 2014; Pahl-Wostl 2009; Pahl-Wostl et al. 2011a). Single- and double-loop learning (adaptive), and triple-loop learning (transformative) help to drive the achievement of goals within uncertain contexts, and this is performed by aiding modification and improvement of policies, approaches and actions whilst also transforming governance (Pahl-Wostl et al. 2013; McLoughlin & Thoms 2015).

Sustaining the practice of adaptive management, with learning, is not without its challenges; limited evidence exists

for successful applications in natural resource management (cf. Nel & Roux 2018; Pahl-Wostl et al. 2011b; Rist, Campbell & Frost 2013; Stankey et al. 2005; Susskind, Camacho & Schenk 2012). Main barriers to learning in adaptive management practice include a deficit in trust and cooperation across institutions and organisations, and ingrained norms of action without reflection, which can impede learning (Kingsford et al. 2017b; Nel & Roux 2018; Pahl-Wostl et al. 2011a). Furthermore, often, there is insufficient stakeholder collaboration with shared learning, as shown in the Glen Canyon Dam (United States [US]) adaptive management project where adverse impacts on species and habitats eventuated despite planned interventions for protection (Garmestani & Allen 2015; Susskind et al. 2012). Indeed, successful learning in adaptive management relies on individuals, their perceptions, experiences, social relations and networks that function as the web binding the adaptive system together (Nel & Roux 2018; Pahl-Wostl 2009) in stakeholder participation and social learning processes (Ernst 2019; Reed et al. 2010). Social learning is an iterative learning and negotiation process rooted in a specific context, with communication comprising many feedback loops for adaptation to ongoing change (Ison & Watson 2007; Pahl-Wostl & Hare 2004). Active involvement of stakeholders and building of a sense of ownership during decision-making processes strengthen commitment, thus promoting consensus for achieving agreed outcomes (Pahl-Wostl 2009).

This research study demonstrates adaptive (single-loop and double-loop) learning and transformative (triple-loop) learning in practice, and importance of this learning for striving towards successful management of environmental water in water-stressed and contested river systems. We use a case study of the Crocodile River in the north-eastern part of South Africa, linked to the Kruger National Park (KNP), where implementation of environmental flows (Ecological Reserve) is being pioneered (Harwood et al. 2017; Jackson 2015; Riddell et al. 2014) using Strategic Adaptive Management (SAM) (McLoughlin et al. 2011a; Pollard, Du Toit & Biggs 2011; Roux & Foxcroft 2011). We reflect on adaptive and transformative learning capacity emergent in the Crocodile River SAM system, over a decade from 2009 to 2019. Learning capacity is interpreted through a lens of single-, double- and triple-loop learning assimilated within a heuristic SAM cycle framework (cf. McLoughlin & Thoms 2015), in conjunction with a stakeholder social learning assessment. The heuristic framework describes desirable (often theoretically based) feedbacks that drive adaptive and transformative learning, thus nurturing stakeholder social relations (cf. Anderson et al. 2019). It affords direction to the learning narrative presented. The authors argue that meaningful progress with Ecological Reserve delivery in the Crocodile River reflects trustworthy, cooperative and flexible management – moving through modes of single-, double- and triple-loop learning – enabling positive change and objectives achievement. 'Learning-by-doing' is supported by a rapid response system (RRS), where swift and reliable

feedbacks of information allow timely decisions on river flow operations for the adjustments when needed. This article underscores key learning experiences, which are applicable to environmental water management across South Africa and further abroad.

Conceptual pillars for adaptive and transformative learning

Single-, double- and triple-loop learning

Originating from the management theory (Hargrove 2002), triple-loop learning builds on the double-loop learning concept developed by Argyris and Schon (1978). This is by increasing the time scales for change by considering different management and governance levels that provide direction and stability in social contexts (Fabricius & Cundill 2014; Pahl-Wostl 2009). It differs from single-loop learning, which results in the incremental advances from action strategies without questioning underlying assumptions (Pahl-Wostl 2009). Single-loop learning involves a continuation of, with concurrent improvements to, established practices and routines in targeting the achievement of goals (McLoughlin & Thoms 2015; Pahl-Wostl 2009).

In comparison, double-loop learning refers to a change in the actual frame of reference and includes a re-visitation of initial underlying assumptions of any action (Fabricius & Cundill 2014; Pahl-Wostl 2009). Social learning processes (see below) – trust, cooperation and buy-in between stakeholders, for example – are vital in double-loop learning (Pahl-Wostl 2009; Pahl-Wostl et al. 2011a). The reframing process commonly occurs within stakeholder networks characterising the resource governance regime, and improvements are achieved by experimenting with innovative approaches. Stakeholders involved in double-loop learning normally explore reframing in the context of structural constraints of governance systems, such as regulatory frameworks (Pahl-Wostl 2009).

Triple-loop learning refers to a change in the structural constraints. It includes transformation of the factors that determine the frame of reference of issues and a transformation of the entire governance regime itself (Pahl-Wostl 2009). This style of transformation necessitates an acknowledgement that paradigms and structural constraints inhibit effective reframing of resource governance and management practices. Thus, triple-loop learning implies a paradigm shift, as well as changes in the norms and values underlying the processes of governance (Pahl-Wostl 2009; Pahl-Wostl et al. 2011a).

Social learning

Social learning assists natural resource practitioners to deal with complex situations by building a shared understanding amongst stakeholders, cooperation and trust (Cundill et al. 2011; Daniel & Walker 1996). Acquiring of new information and experiences, via participation and social interactions, can

lead to changes in the perception of individuals (Reed et al. 2010). However, such change should go beyond individuals and include relational (e.g. improved sense of community), cognitive (e.g. change of perspectives) and technical (e.g. communication skills) dimensions (Muro & Jeffrey 2012).

There are two prominent constructs to social learning in natural resource management (cf. Pahl-Wostl et al. 2007; Pahl-Wostl, Mostert & Tabara 2008). Firstly, processing of factual information involves a problem task or content management about a specific problem. Secondly, engagement in social exchange emphasises social relations, which are inextricably connected to management problems, because managers must consider whose problems to solve and how to frame them. Integration of the 'social' and 'content' components is facilitated via 'relational practices', for example, quality of interaction, shared ownership of tasks, transparency for mutual testing of options and contradiction, and suitable opportunities for reflexive sessions (McLoughlin et al. 2020) in problem-solving activities. Thus, natural resource management is not only composed of technical qualities, for example, improvement in the condition of ecosystems, but relational qualities too, for example, improved capacity of stakeholders to solve conflicts by achieving consensus through cooperation.

A number of key criteria have been found to influence social learning dynamics in a group of stakeholders practising adaptive resource management; these criteria are summarised and described in Table 1 across three categories. The first category includes a set of preconditions for social learning to take place (cf. Mostert et al. 2007). The second category relates to the emergence of a stakeholder 'community-of-practice' (sensu Wenger 1998), as a vital mechanism driving social learning. Evolution of a community of practice depends on a number of criteria, as displayed in Table 1 (cf. Iaquinto, Ison & Faggian 2011; Pahl-Wostl et al. 2008). The third category relates to key capacities, which enable social learning to occur (cf. Cundill et al. 2011; Pahl-Wostl et al. 2007; Pahl-Wostl & Hare 2004), and often these capacities emerge from within a community of practice.

Generally, a context of trust, network building, shared understanding and conflict resolution shape stakeholder's social learning (Ernst 2019), emergent within processes of single-, double- and triple-loop learning (Pahl-Wostl 2009). Success results from ongoing learning and negotiation through communication within trusted networks, perspective sharing and development of adaptive group strategies (Huxham & Vangen 2000; Pahl-Wostl & Hare 2004). Notably, 'reframing' required during double- into triple-loop learning would be difficult to achieve without social learning (Fabricius & Cundill 2014; Pahl-Wostl et al. 2011a). Active involvement of stakeholders and building of a sense of ownership during decision-making processes strengthen commitment, thus promoting consensus for achieving agreed outcomes in natural resource management (Pahl-Wostl 2009).

TABLE 1: Key criteria expected to influence social learning in a group of stakeholders practicing adaptive resource management, spread across three categories – ‘pre-conditions for social learning’, ‘community-of-practice’ and ‘capacities for social learning’.

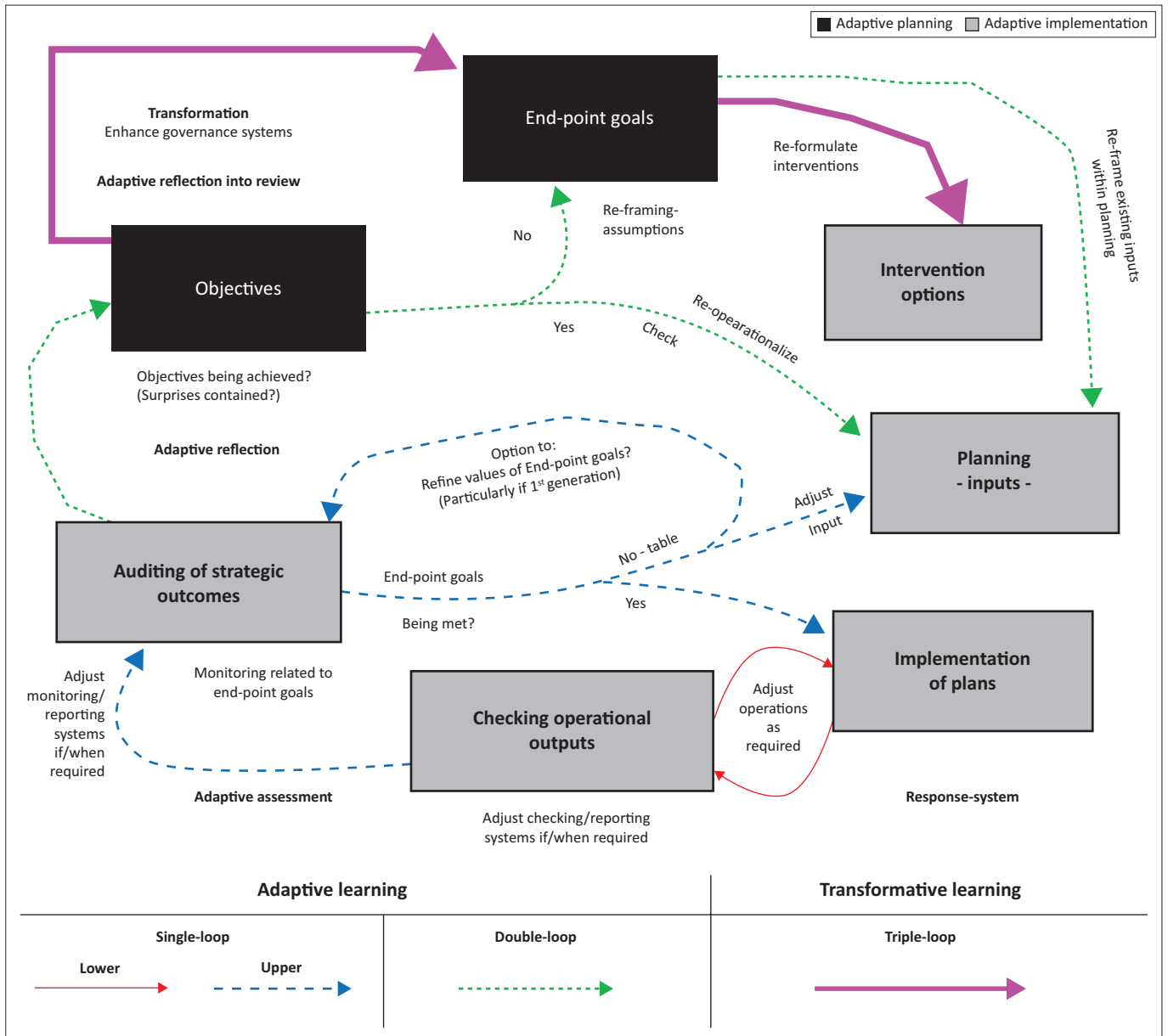
Category	Key criteria	Description of key criteria	References
Preconditions for social learning	Role of stakeholder involvement	Clarity on the purpose for stakeholders to become involved in the management initiative, whereby different stakeholders do become involved.	Mostert et al. (2007)
	Institutional setup	Strong institutions with legal authority over the area under management, cognisant of system scale and relationships amongst key authorities. Interactions amongst diverse stakeholders, recognising types, number and quality of meetings.	
	Representativeness	Inclusion of all relevant stakeholders. Organisations have adequate member representation. Large group discussions may require special meeting formats.	
	Type of facilitation	Facilitator is neutral, and thus, there is no bias in stakeholder collaboration processes. Facilitator invokes trust within the social learning process, allowing differences of opinion to be overcome.	
	Transparency of the approach	Programme legitimacy is established, and this is by development of ongoing feedbacks with joint planning and setting of clear ground rules.	
	Framing of problems	Different stakeholder perspectives are accounted for. The identification of various problem perceptions increases ownership of the many issues, and solutions agreed upon. Quality of communication is not too complex and is conducive to problem solving.	
	Resources	Stakeholder commitment is important, promoted if each stakeholder can say how they want to be involved. Stakeholder time or finances play a role.	
Community-of-practice (CoP) criteria	Joint enterprise	Joint enterprise built by bringing different stakeholder groups together, with shared roles, responsibilities and practices. Stakeholders address clear-cut issues.	Pahl-Wostl et al. (2008); Iaquinto et al. (2011)
	Stakeholder interaction	Mutual respectful engagement between stakeholders, wherein they interact and learn from each other.	
	Capability of practice	Shared repertoire of resources is developed, for example, lessons learned, rules of thumb and standards. Stakeholders accumulate a shared knowledge.	
	Identity of the stakeholder group	Shared practices amongst stakeholders, with tangible product outcomes, generates group identity, including a history and shared knowledge that is different to individuals within the network.	
	Limitations of the group	Stakeholders have the capacity to identify their pertinent limitations, and are willing to make improvements if and where needed to solve complex problems.	
	Recognition of coordinator	The stakeholder coordinator is well networked and accepted within these networks.	
	Management support	High-level management support exists, at pertinent levels within the stakeholder process.	
Capacities for social learning	Awareness	Stakeholders have an awareness of each other's goals and perspectives and are willing to overcome any differences.	Cundill et al. (2011); Pahl-Wostl et al. (2007); Pahl-Wostl and Hare (2004)
	Shared problems	Stakeholders have a common interest and vision.	
	Interdependence	Stakeholders understand that they are interdependent and recognise value of sharing information. They have respect for one another and listen to each other's point of view.	
	Cooperation	Stakeholders are learning how to work together and engage in collaborative decision-making processes.	
	Understanding complexity	Stakeholders have a good understanding of the managed system's complexity.	
	Trust	Stakeholders perceive the decision-making process to be open and fair.	
	Informal interactions	There is an informal network of participants, who conduct regular meetings. Rules and arrangements of the network are not formally imposed. There is increased potential for self-organisation, innovation and creative thinking if networks are autonomous and familiar.	
	Communication	There is good communication between stakeholders. Stakeholders are informed about issues, and their views and opinions are listened to.	
	Collective actions	There is engagement in collective decision-making within a process of learning, for example, whilst developing new management strategies.	
	Joint problem-solving	Stakeholders jointly identify and agree on solutions to any problems and reflect on assumptions concerning the system dynamics.	
	Exchange of ideas	Stakeholders willing to exchange ideas and are open to new ways of doing things. An initiative is viewed by all involved as a new learning opportunity.	
	Sharing information	Stakeholders perceive the value in sharing of information, and they respect one another with a willingness to listen to each other's point of view.	

Heuristic strategic adaptive management cycle framework

The SAM cycle framework (McLoughlin & Thoms 2015) is designed primarily to complement the SAM (Roux & Foxcroft 2011) variant of adaptive resource management. Each SAM cycle has two phases: an adaptive planning and an adaptive implementation phase (Figure 1). The adaptive planning phase (represented in the black boxes in Figure 1) is focused on developing objectives, culminating in the explicit, measurable end-point goals of the SAM cycle. End-point goals are the thresholds of potential concern (TPCs), and they recognise the natural variability of selected response indicators by incorporating upper and/or lower levels (thresholds) of acceptable change (McLoughlin et al. 2011b). Thresholds of potential concern are viewed as hypotheses of

acceptable change, and open to challenge and refinement forming an inductive approach to adaptive management (Biggs & Rogers 2003; Rogers & Biggs 1999). The adaptive implementation phase includes five components (represented in the grey boxes in Figure 1). These are concerned with processes of selecting the best intervention options to meet goals, determining inputs for planning (associated with meeting goals), operationalising inputs via implementation of the plans, checking adequacy of plan implementation by response to operational outputs, assessing suitability of the operational outputs by auditing strategic outcomes (against TPCs) and testing achievement of the broader objectives within the adaptive management system.

The learning component in the heuristic SAM cycle framework is structured as an essential nested and ongoing



Source: Adapted from McLoughlin, C. A. & Thoms, M.C., 2015, 'Integrative learning for practicing adaptive resource management', *Ecology and Society* 20(1), 34

FIGURE 1: The adaptive phases and components of the heuristic strategic adaptive management (SAM) cycle framework. The SAM cycle has no distinct evaluation step – rather, an ongoing and overlapping feedback system, which drives assessment and reflection facilitating adaptive (single- and double-loop) learning and transformative (triple-loop) learning.

process, rather than a distinct step (Figure 1). There are two learning potentials recognised – adaptive and transformative learning – facilitated by the SAM cycle adaptive feedback system (McLoughlin & Thoms 2015). Adaptive learning includes single- and double-loop learning. Two types of single-loop learning – lower and upper – allow for, respectively, more immediate responses to check operational outputs (thin, solid arrows in Figure 1), and adaptive assessments to audit strategic outcomes against explicit and measurable end-point goals (hashed arrows in Figure 1). Adaptive feedbacks for single-loop learning are mandatory because this is the actual doing, where progress is made within adaptive management (Fabricius & Cundill 2014). Double-loop learning (dotted arrows in Figure 1) is about reframing problems and solutions, which is facilitated by adaptive reflection to test achievement of the agreed

objectives, considering the occurrence of any surprises. The skill lies in achieving a balance between the use of single-loop and double-loop learning (Fabricius & Cundill 2014). Reviewing values and objectives along with transformation of governance arrangements (Folke et al. 2005) is triple-loop learning (thick, solid arrows in Figure 1). Transformative (triple-loop) learning is important because if governance remains too rigid, this impedes the reframing potentials of double-loop learning (Pahl-Wostl 2009). Time scales for these feedbacks might include daily or weekly (single loop, lower), 1–3 years (single loop, upper), 4–6 years (double loop) and 8–10 years (triple loop).

The main objective of this research study was to explore the role of adaptive (single-loop and double-loop) learning and transformative (triple-loop) learning in Crocodile River

management, related to the reasonable success with Ecological Reserve delivery in KNP, over a decade since 2009. We deployed the heuristic SAM cycle framework as a tool for guiding our learning investigation, integrating adaptive and transformative learning processes into the SAM system (Roux & Foxcroft 2011). Another objective was to include a stakeholder social learning assessment, because this learning is integral whilst progressing through the modes of single-, double- and triple-loop learning (Ernst 2019; Pahl-Wostl 2009). We used a quantitative assessment based on stakeholder responses (from interviews) to statements, concerning the key criteria for social learning taken from the literature (see Table 1). Assessment results offered valuable insights into 'potentials' for social learning amongst the Crocodile River stakeholders, although the authors concede that there were no definitive answers – further social learning research is needed. Still, improved understanding on social learning potentials helped to support the Ecological Reserve related learning narrative presented in this article. With this learning narrative, the final objective of this study was to offer lessons from the accompanying experiences for Ecological Reserve delivery in other catchments and water management areas of South Africa.

Methods

Study area

The Crocodile River is one of three river systems of the Inkomati Water Management Area (IWMA) located in the north-eastern region of South Africa (Figure 2). The water management area has a catchment size of 28 757 km², of which the Crocodile River Catchment is 10 400 km². Rainfall

is strongly influenced by topography, varying from over 1200 mm per annum in the west over the Drakensberg Escarpment to as low as 400 mm per annum over the lowland plains in the east. Natural mean annual runoff in the IWMA is estimated at 3188 million m³ per annum, whilst present-day conditions yield 2058 million m³ per annum (Bailey & Pitman 2016). The Crocodile River flows eastward and confluences with the Komati River just before entering Mozambique, when it becomes the Incomati River flowing into the Indian Ocean (Figure 2). Consumptive water uses associated with the Crocodile River include industry, irrigated agriculture, domestic water supply and plantation forestry. The non-consumptive water uses are the specified minimum flow requirement to Mozambique and the South African Ecological Reserve, which is critical for maintaining biodiversity values of the KNP (see Rountree & Rogers 2004; Russell 1997; Van Coller, Rogers & Heritage 2000).

The Crocodile River is important ecologically as it forms the southern boundary of KNP (Figure 2), a world-renowned protected area whose river landscapes contribute markedly to aquatic and terrestrial biodiversity (Rountree & Rogers 2004; Russell 1997; Van Coller et al. 2000). The KNP has a well-developed history of SAM (Pollard & Du Toit 2007; Roux & Foxcroft 2011): There are river-related TPCs (e.g. Todd & Thirion 2011), which are explicit and measurable end points (operational and biodiversity) of an Objectives Hierarchy (see Biggs et al. 2011a; McLoughlin et al. 2011b) linked to KNP's vision for maintaining biodiversity in all its natural facets and fluxes (Rogers & Bestbier 1997). The TPCs are indicators that assist management to respond to biodiversity change resulting from human-induced pressures within the catchment, predominantly upstream and outside the protected area (Biggs & Rogers 2003; Kingsford et al. 2017b). The majority of the Crocodile River catchment is dominated by unregulated river reaches, but the main stem is regulated by the Kwena Dam in the upper catchment (Figure 2). The dam has a gross storage capacity of 158 million m³, and the primary use is to supplement water supplies for irrigated agriculture in the middle and lower reaches (DWA 2010). There are smaller dams, weirs and water supply schemes throughout the catchment, which transfer water to towns, and these alter river flow and water quality, and also increase sedimentation rates. Management interventions are designed to maintain or return TPC indicators towards more natural ranges, necessitating cooperation and integration of management activities between different catchment institutions (Kingsford et al. 2017b).

Crocodile River Operations Committee

The *National Water Act* (Act No. 36 of 1998) supports stakeholder-centred, adaptive and sustainable use and protection of freshwater-linked ecosystems (O'Keeffe & Rogers 2003; Roux & Nel 2013). At the level of the water management area, the Minister of Human Settlements, Water and Sanitation promotes management of freshwater resources by assigning powers and duties to catchment management agencies (CMAs) (section 73[4] of the *National*

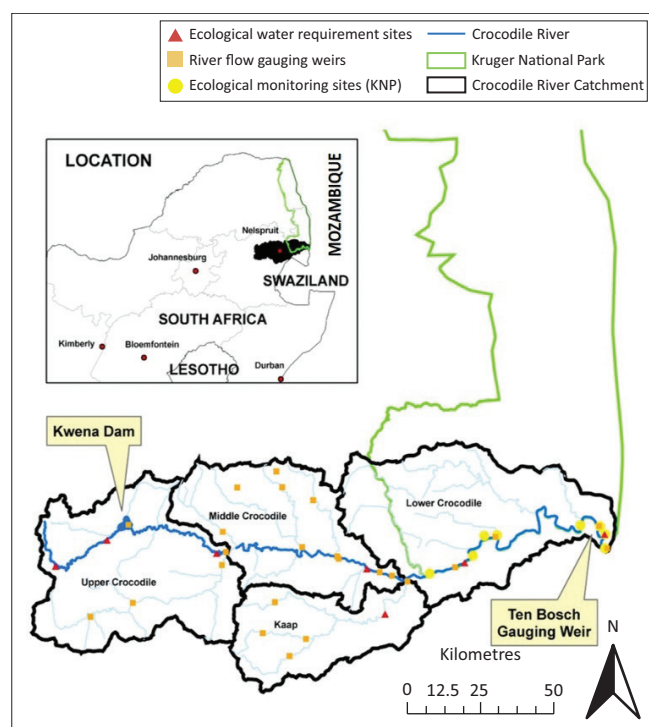


FIGURE 2: The Crocodile River Catchment and its position in relation to the Kruger National Park (KNP). Ecological Water Requirement (EWR) sites, river flow gauging weirs, ecological monitoring sites in KNP and the Kwena Dam are indicated.

Water Act). The Inkomati–Usuthu CMA was established in 2004 to manage the freshwater resources of the IWMA, but later including the Usuthu-to-Mhlathuze Water Management Area. A responsibility of CMAs is to develop a catchment management strategy (see DWAF 2007 for a full treatise), and in 2010, the Inkomati–Usuthu CMA drafted its first such strategy in collaboration with all stakeholders (ICMA 2010). It incorporates SAM principles, including development of a vision, mission and objectives (Jackson 2015; Rogers & Luton 2011).

Set up by the Inkomati–Usuthu CMA, the Crocodile River Operations Committee (CROCOC) is an institutional arrangement, which oversees management of the freshwater resources linked to the Crocodile River (Harwood et al. 2017; Jackson 2015), and serves as a technical subcommittee to the broader Crocodile River Forum. The CROCOC stakeholders include the Inkomati–Usuthu CMA, Department of Water and Sanitation, Crocodile River Major Irrigation Board (CRMIB) and, more recently, those in the tributaries, KNP, Mbombela Municipality, Nkomazi Municipality, Ehlanzeni District Municipality, Komati Basin Water Authority, and consultants or research-related personnel. The CROCOC was initially set up to meet every 2 months, with ad hoc meetings if and when required, and the committee plays an active role in integrated planning and operations of the Crocodile River system. This includes provision of important decision-making advice about implementation of the Ecological Reserve using this as one of its performance metrics, along with meeting international flow requirements and maintaining an assurance of supply to consumptive uses.

The Crocodile River Ecological Reserve

Under the *National Water Act*, the Ecological Reserve is defined as the quantity and quality of water required in freshwater resources to protect the ecological functions on which humans depend (O’Keeffe & Rogers 2003). For river systems, it is the recommended flow regime and water quality expected to maintain a specific agreed river ecological category, rather than reinstating pristine conditions (DWAF 1997). Ecological categories are derived via an eco-classification procedure (see Kleynhans & Louw 2007) and range from A (natural) to F (highly impacted), representing an order with decreasing levels of protection for (or increasing levels of risk to) freshwater aquatic species and habitats (Kleynhans & Louw 2007). The intention is to create a balance between the environmental, economic and social benefits emanating from river resources. Once agreed by catchment stakeholders, the ecological category (included in an overall Management Class; Pollard et al. 2011a) is used to plan for the environmental water requirement of Ecological Reserves in different river systems.

In 2010, the Crocodile River’s comprehensive Ecological Reserve determination study was undertaken (DWA 2010). There have been concerted efforts since then to implement and manage the low-flow requirements of the river’s Ecological Reserve (maintaining Ecological Category ‘C’),

mainly during the critical dry winter and spring months (April–November). Implementation of the low-flow Ecological Reserve (hereafter, ‘Ecological Reserve’) is aided by flow gauging stations located along the river (Figure 2), which enable remotely accessible collection of near real-time river flow data. Furthermore, sophisticated hydrological models (e.g. Water Resource Modelling Platform, DWAF 2008) are deployed, with several Ecological Water Requirement sites (Figure 2) used to determine flow requirements for the ‘C’ Ecological Category river. Biophysical monitoring is performed at demarcated sites (Figure 2) along the KNP sections of the Crocodile River (and upstream to the headwaters; Roux et al. 2018). Notably, KNP TPCs intend to prioritise biodiversity monitoring along these demarcated sites, and TPC auditing enables appropriateness of the managed Ecological Reserve to be assessed (McLoughlin et al. 2011b). There is no management plan for the high-flow or flooding requirements of the river, as specified in the Ecological Reserve determination study (DWA 2010). However, larger flooding events are not affected by the Kwena Dam, which is located high up in the catchment (Figure 2).

Social learning assessment

Potential for social learning within the CROCOC was assessed based on stakeholder values, experiences and perceptions concerning the forum. A total of 12 stakeholders were purposefully sampled from a cross-section of sectors represented in the CROCOC forum: Inkomati–Usuthu CMA (3), Crocodile River Major Irrigation Board (2), South African National Parks (3), Silulumanzi – Mbombela Local Municipality water supplier (1), Komati Basin Water Authority (1) and IWR Water Resources (2).

After obtaining ethics approval and informed consent from all participants, in-depth, semi-structured interviews were conducted with stakeholders in 2013. Each stakeholder was interviewed individually where the dialogue about the managed system was initiated. Discussions focused on key criteria taken from the literature (Table 1), which, for this study, were grouped into three relevant categories, as displayed in Table 1: ‘preconditions for social learning’, ‘community-of-practice’ and ‘key capacities for social learning’ often evolving from within a community of practice. On conclusion of each discussion session per social learning criterion (per category), the stakeholder was asked to indicate how much they agreed (or not) with a statement related to that criterion (Online Appendix 1), based on his or her experiences within the forum. For example, ‘There is mutual engagement between the various stakeholders, and this is ongoing’. Quantitative data were collected by employing a Likert-scale scoring system ranging from 1 to 10, where 1 = ‘strongly disagree’, 5 = ‘neutral’ and 10 = ‘agree completely’. Mean scores were calculated per criterion across the three categories and presented graphically in bar charts. Qualitative data were also collected during the 2013 stakeholder interviews; however, these data were not used for the purposes of this research study and its objectives, although valuable for future study (see Discussion).

Single-, double- and triple-loop learning

In order to centre our narrative on adaptive and transformative learning capacity, initially, we selected key Ecological Reserve-related elements (e.g. TPCs, ecological monitoring and hydrological modelling) from Crocodile River management, which existed at the beginning of the period 2009–2019 (Online Appendix 2). We then assigned the selected elements to applicable components of the SAM cycle framework (McLoughlin & Thoms 2015; Figure 1). Adaptive Planning: Summary objectives of the KNP Water in the Landscape Objectives Hierarchy (see McLoughlin et al. 2011b) includes maintaining the 'C' Ecological Category river. The objectives culminate in the TPCs (Online Appendix 2; see McLoughlin et al. 2011b). Adaptive Implementation: Current management interventions and planning inputs to apply the Ecological Reserve, including operational and strategic monitoring, governance arrangements, actions to deliver the Ecological Reserve, monitoring of ecological conditions, checking operational outputs and auditing of strategic outcomes or TPCs (Online Appendix 2).

The Ecological Reserve-related elements selected (Online Appendix 2) are by no means an exhaustive set. For instance, water quality is excluded, yet recognised and used as an important ecosystem driver, and examples of monitoring (related to biodiversity objectives or TPCs) stem from the KNP river reaches, although monitoring occurs upstream (outside) of the protected area (Roux et al. 2018). Moreover, social and economic objectives of the broader Crocodile River SAM system (Jackson 2015; Rogers & Luton 2011) are important and recognised, but not taken further in this study (achieving these objectives entails comparable and concurrent learning processes). Nonetheless, we consider the selected elements to be sufficient for presenting a succinct but informative learning narrative.

We then identified key experiences from within the Crocodile River SAM system (related to Ecological Reserve management) over the period 2009–2019 and categorised these into observations of change according to the SAM cycle framework: single-loop, double-loop and triple-loop learning (Figure 1). We sourced information from journal articles, research or technical reports (e.g. Water Research Commission), internal South African National Parks documents or reports (and discussions with staff) and, importantly, from our personal experiences with the SAM system. The adaptive and transformative learning capacity narrative was then constructed around these observations (examples) – representing key learning experiences (single-, double- and triple-loop learning) – and also outcomes from the social learning assessment. Notably, any adaptive management system is an ongoing evolutionary process (Allan & Stankey 2009); hence, the narrative of this study makes reference to promising future single-, double- and triple-loop learning processes, where appropriate.

Ethical considerations

Ethics approval for the study was obtained from the Human Research Ethics Committee, Ethics Office, Research

Development & Integrity Research Division of the University of New England, Armidale, NSW, Australia – HE13-240.

Results

Social learning assessment

Preconditions for social learning

By 2013, there were promising preconditions for social learning within the CROCOC stakeholder group, given that all seven criteria had an average score > 6 (Figure 3a) (numbers in brackets below link to Figure 3; see Table 1 for criterion

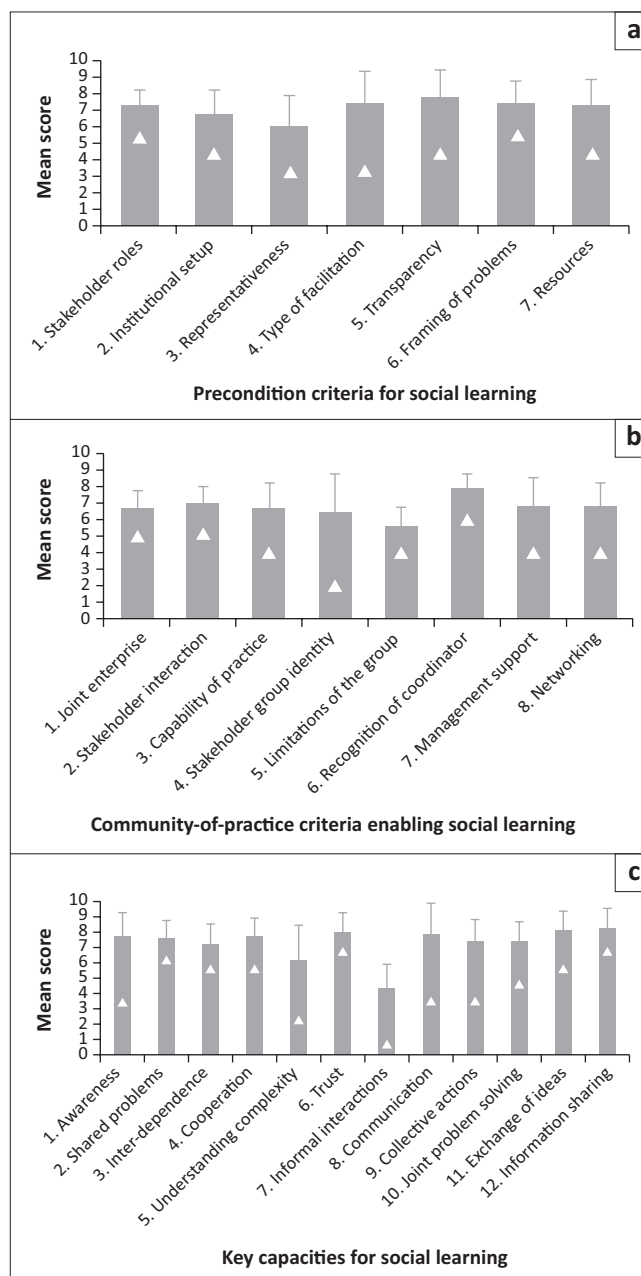


FIGURE 3: Scores (mean) indicating how much stakeholders agreed (or not) with a statement related to each key criterion influencing social learning potentials within the Crocodile River Operations Committee, across three categories: (a) 'preconditions for social learning', (b) 'community-of-practice' and (c) 'capacities for social learning'. The mean scores range from 1 to 10, where 1 = 'strongly disagree', 5 = 'neutral' and 10 = 'Agree completely' (standard error bars indicated; white triangles represent minimum-value scores obtained; number placed beside each key criterion link to numbers in brackets within the text; see Table 1 for criterion descriptions).

descriptions). This included five criteria rated 7.5 and higher: 'Role of stakeholder involvement' (1), 'Type of facilitation' (4), 'Transparency of the approach' (5), 'Framing of problems' (6) and 'Resources' (7). Transparency is vital for promoting social learning amongst stakeholders and was scored the highest by the CROCOC. This suggests a high legitimacy of the work undertaken by the stakeholder group, which is achieved by developing a system of ongoing feedbacks with joint planning and setting of clear ground rules. However, the criterion 'Representativeness' (3) has the lowest average score though > 5 , suggesting that relatively, increased effort is needed to include pertinent stakeholders in the forum in order to increase organisational representation.

Community-of-practice

There is evidence for an emerging CROCOC 'community-of-practice', as all eight criteria received an average score > 6 (Figure 3b) (numbers in brackets below link to Figure 3; see Table 1 for criterion descriptions). Of specific interest is 'Recognition of coordinator' (6), which has the highest average score at 8.83. Social learning requires a coordinator who is well networked and accepted within the stakeholder group. The Inkomati-Usuthu CMA has played a key role in this regard, setting up and harmonising interactions of the CROCOC stakeholders, and acting as a neutral and trusted coordinator that is championing the management process. Other relatively high scoring criteria include 'Stakeholder interaction' (2), 'Management support' (7) and 'Networking' (8). Although rated > 5 , the lowest scoring criterion includes 'Limitations of the group' (5), suggesting that stakeholders require a greater ability to identify their limitations in order to improve their actions over time.

Capacity for social learning

The CROCOC stakeholders have been building their capacity for social learning since prior to 2013, given that 11 criteria have an average score of ≥ 6 (Figure 3c) (numbers in brackets below link to Figure 3; see Table 1 for criterion descriptions). Notably, five criteria scored ≥ 8 , including 'Cooperation' (4), 'Trust' (6), 'Communication' (8), 'Exchange of ideas' (11) and 'Information sharing' (12). This suggests that stakeholders are informed about issues, and their views and opinions are listened to. Stakeholders are learning how to work together with group communication likely strong, and they generally view initiatives as a learning process. Furthermore, stakeholders realise the value of sharing information, exchanging of ideas and being open to new ways of doing things. Respect for one another is also being built up as stakeholders seem to be willing to listen to each other's point of view, and processes are perceived to be open and fair. This situation promotes collaboration when key decisions must be made. The lowest scoring criterion includes 'Informal interactions' (7), with an average score of 4.8 (minimum score 1.5), suggesting that emphasis is placed on the more formal interactions. Thus, the forum should be looking into ways of promoting informal arrangements, because this is where social learning is often nurtured. The second lowest scoring criterion includes 'Understanding complexity' (5), although > 6 , suggesting that relatively more

could be performed to increase stakeholder's conceptualisation of the social and biophysical components, importantly the complex interactions between these components. This is to help with consensus in decision-making and collaborative solving of complex problems that arise.

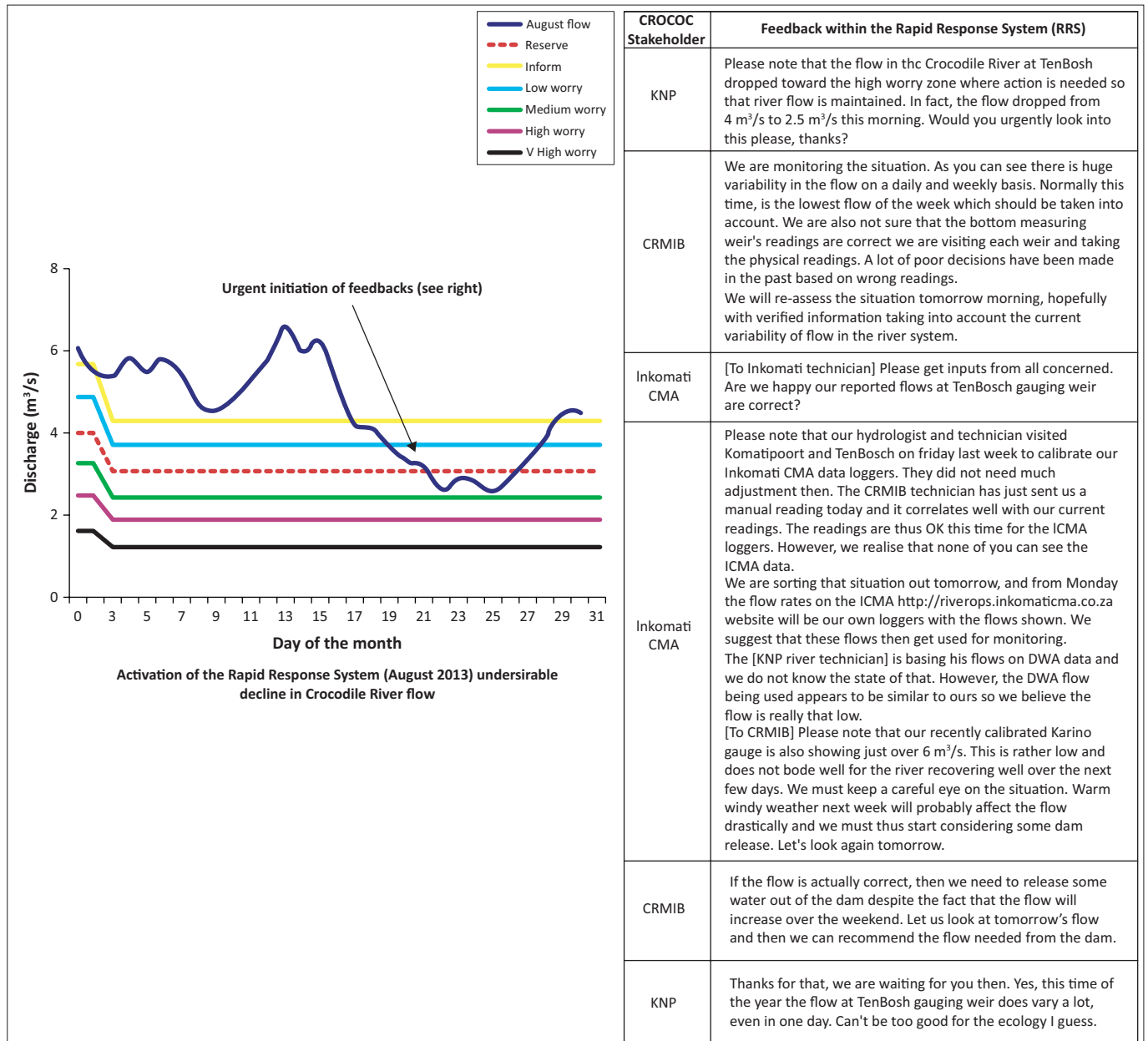
Single-, double- and triple-loop learning

Lower-grade single-loop learning (rapid response system)

The RRS (Figure 4; Online Appendix 2) drives this learning in the Crocodile River SAM system. It is facilitated by rapid (daily or weekly) email or telephone messaging amongst the CROCOC stakeholders, and more recently, through visual communication tools using social media platforms, such as WhatsApp™ (e.g. for real-time gauge verification and incident reporting). The RRS was designed to include different 'worry-levels' relative to the low-flow requirements of the Ecological Reserve (benchmarks are calculated each week). There is an increased urgency if and when the different 'worry-levels' are breached (Figure 4), as measured at the TenBosch Gauging Weir (Figure 2). Stakeholders work together to determine triggers for the deteriorating river flows, thereby coming up with mitigation actions. For example, river flows may be augmented via dam releases and/or water restrictions imposed on irrigation. Importantly, feedbacks are executed as soon as possible so that actions can ideally be executed prior to the river flow declining unacceptably.

In reality, river flow sometimes falls into the 'Medium' and even 'High', worry levels, often explained by unprecedented weather conditions, such as unusually high temperatures and/or evaporation rates. One of the early associated learnings was realisation of the KNP staff that meeting daily requirements downstream becomes increasingly challenging during critical low-flow periods. Simply, it is because the nature of water abstractions increase as one moves downstream, compounded by energy tariffs from the national electricity utility, Electricity Supply Commission (ESKOM). This means that irrigators seek to optimise for access to water and energy, with a '3-day average rule' being accepted. Notably during the year 2017, this factor prompted CROCOC stakeholders to engage with ESKOM in order to negotiate a workable solution but, unfortunately, to no avail.

Recommendations for management of the Ecological Reserve and actual RRS operations emanate from bimonthly meetings of the CROCOC. A monthly management log (see McLoughlin et al. 2011b) provides valuable feedback on actions and measures undertaken (e.g. percentage of river flows per 'worry-level'), used to decide on successes and/or failures enabling adaptations and improvements to the RRS. For example, daily hydrological data received at the TenBosch Gauging Weir became increasingly unreliable, indeed, because of lack of maintenance on its data loggers, a situation compromising trust relations built up. Although working cooperatively, stakeholders agreed to purchase and install dependable data loggers and upkeep them regularly, thereby reducing river gauge measurement uncertainties, which occasionally lead to shortfalls in the various short-term allocations (even under restrictions)



CROCOC, Crocodile River Operations Committee; KNP, Kruger National Park; CRMIB, Crocodile River Major Irrigation Board; CMA, catchment management agency.

FIGURE 4: Example of the deployment of the Rapid Response System, within strategic adaptive management of the Crocodile River Ecological Reserve.

during times of water stress. A largely self-reliant community of practice was nurtured across disparate sectors, that is, without the need for relying on government interventions. The above-mentioned example fosters confidence in river flow monitoring and is important for meaningful engagement within the RRS approach to Ecological Reserve compliance.

Upper-grade single-loop learning (adaptive assessment)

This learning is driven by adaptive assessment linked to the TPCs and associated monitoring processes in the Crocodile River SAM system (see McLoughlin et al. 2011b). Post monitoring, TPC audit reports (e.g. fish TPCs) are completed using data and information collected at Crocodile River sites along the KNP boundary. The TPC process is a 'red-flag' concept and may call into question the appropriateness

of river flows in line with achieving amongst others the KNP ecological objectives. Ultimately, TPC auditing informs management about risks of losing the 'C' Ecological Category river, thus supporting longer term decisions associated with operational adjustments to Ecological Reserve implementation. For example, the risk of deteriorating fish assemblages (i.e. exceedance of fish TPCs) contributed towards a decision to alter the frequency of RRS benchmark calculations (Ecological Reserve, using data from TenBosch Gauging Weir; Figure 2) from an original 3-month interval to a weekly calculation. The higher temporal resolution in the calculation allows for judicious stakeholder responses to undesirable river flows in the Crocodile River. The RRS Ecological Reserve benchmark has undergone further refinement in recent years following the gazetting of the Ecological Reserve to allow for a

compliance certainty band around the targeted flows. The benchmark currently allows for a 70% assurance (maintenance flows), with some variation for drought (up to 90% assurance), including the absolute limit of the 99% assurance rule. This in itself was cross-institutional learning, applying a less rigid (dynamic) and cumbersome (reduced worry level triggers) compliance reporting system, to meet the institutional needs of Inkomati-Usuthu CMA. Notably, this operating rule now includes compliance with the international flow obligations towards the Republic of Mozambique (Figure 2). Over time, such refinement to the Ecological Reserve benchmark allows for increased flexibility in the approach to achieving the Crocodile River's flow targets.

Ongoing management decisions are needed in conjunction with progressive implementation of the Ecological Reserve in the Crocodile River, particularly if or when TPCs become exceeded, or deemed to be close to exceedance. For instance, the volume of water released from Kwena dam is altered relative to the different RRS 'worry-levels' to avoid undesirable declines in the river's flow regime. Importantly, to foster upper-grade single-loop learning CROCOC stakeholders must keep perusing the summary statistics emanating from the RRS (see McLoughlin et al. 2011b), because its purpose was to enhance stakeholder feedbacks and actions related to delivery of the Ecological Reserve, that is, meeting the calculated benchmarks each week.

Double-loop learning (adaptive reflection)

Two key types of feedback and adaptive reflection opportunity arise from within the Crocodile River SAM system, and these facilitate the 'reframing' of complex management problems. Firstly, assumptions (hypotheses and/or models) associated with prevailing TPCs can and should be altered based on any newly acquired information and understanding. For example, although based on robust research, there was much subjectivity involved in application of the original geomorphic TPCs developed for the KNP mixed alluvial-bedrock controlled rivers (see Rogers & Bestbier 1997; Rountree & Rogers 2004), particularly by non-geomorphologists. Furthermore, the focus was on a 'gradual, incremental change' over time in the macro-morphology of the river channel, but this proved to be unrealistic for red-flagging problems before these arise. New strategies suggested monitoring to be carried out only in the critical in-stream habitat, that is, within the most sensitive sites where suspect sedimentation build-up can be detected quickly. Using aerial imagery, the TPC process includes assessing change in the active channel width (instream habitat availability) and functioning of exposed bedrock habitats important for biota (McLoughlin et al. 2011b). The new TPCs are cost-effective and logistically more feasible to implement, which are measured against actual Ecological Categories of the managed Ecological Reserve. Further double-loop learning examples related to TPCs exist, for instance, dominant understanding – about biotic indicator responses

to unnatural sedimentation in mixed alluvial-bedrock controlled rivers – was questioned (e.g. *Breonadia salicina* TPCs; see Mackenzie, Van Coller & Rogers 1999; McLoughlin et al. 2011b for a full treatise). All such change, concurrent with experience and knowledge progression, help to test (realistically and efficiently) and adapt the low-flow Ecological Reserve being implemented.

Secondly, 'reframing' of planning inputs in the Crocodile River SAM system occurs when TPC monitoring protocols are reflected upon, often as a consequence of scarce resources (people, time and costs). For example, the Ecological Water Resource Monitoring Framework (EWRMF; Kleynhans et al. 2009) was modified into a pragmatic approach for testing effectiveness of the Ecological Reserve river flows. Four levels of monitoring intensity were envisaged: Frequent but cheaper or feasible monitoring occurs earlier on prior to higher level and increasingly more costly or intensive monitoring, which is applied based on relevant TPC exceedances. Ultimately, this sequence of monitoring aids in more efficient management decision-making about how, where and when to intervene, or not. Owing to the logistical burden and ease of sampling encountered, the EWRMF was never implemented in its original form; however, its underlying principles helped to tailor a new approach currently in use. One of the sites, 50 km upstream of the TenBosch Gauging Weir, is now used for full ecological benchmarking where the full suite of aquatic variables and habitat types are sampled over a 100-m stretch of the Crocodile River. Replication is achieved at five additional sites solely by macro-invertebrate sampling using the SASS-5 method (Dickens & Graham 2002). This approach, although in its infancy and despite there are problems associated with pseudo-replication, is showing promise. It more explicitly determines the drivers of change in the aquatic environment (Bain & Stevenson 1999; Kleynhans & Louw 2009) and dynamics of the response indicators of change to be measured (Clarke & Warwick 2001; Jewitt et al. 1998; Weeks et al. 1996), which promotes decision-making.

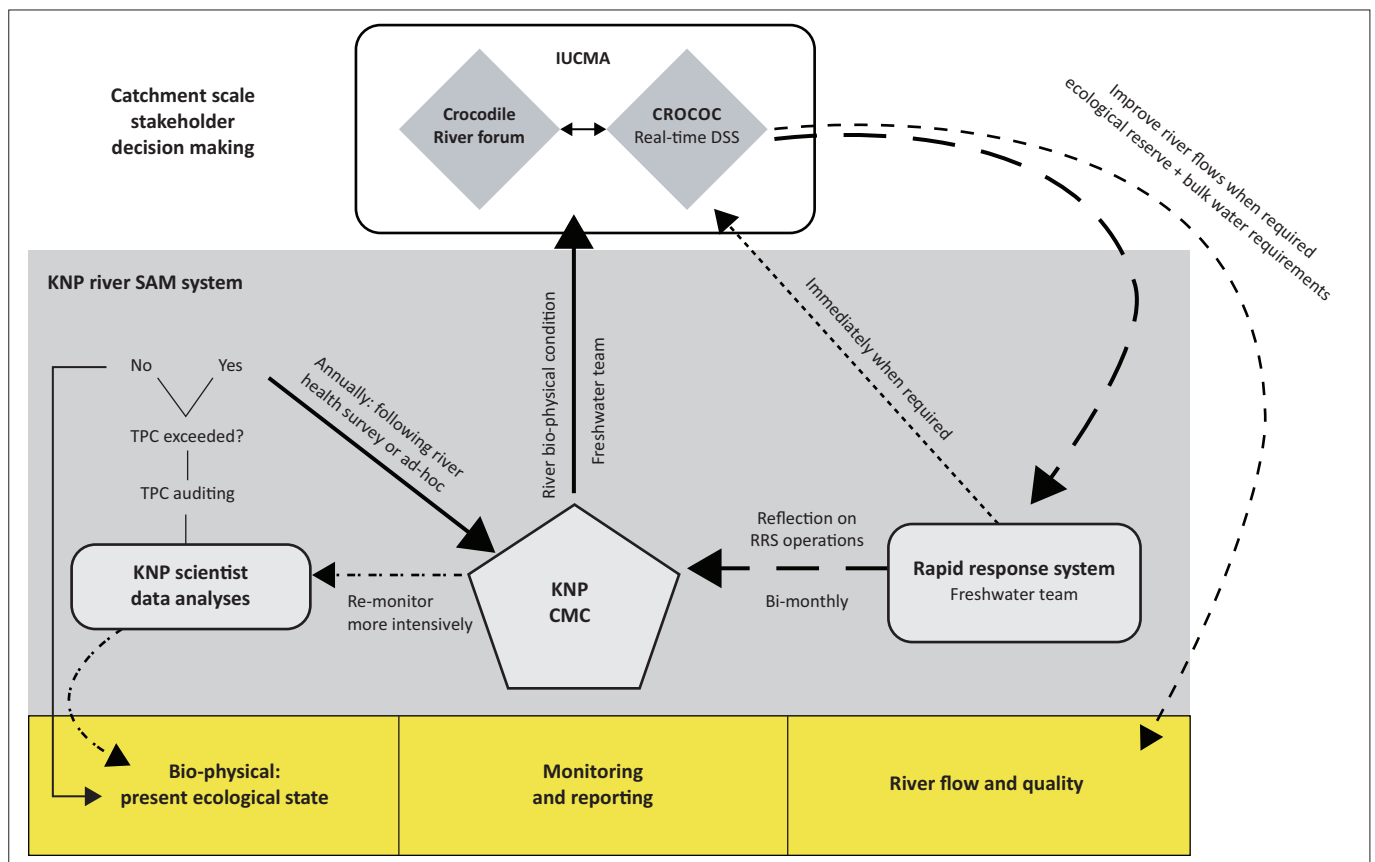
Future 'reframing' exercises might include reconsideration of the modelling techniques employed for successful delivery of Ecological Reserve, specifically during the critical dry season period (August–September) when the system is most vulnerable to low flows and a high relative water demand from irrigation. Experimentation with the timing of Kwena Dam water releases is another option, for instance, in conjunction with the international flow requirements into Mozambique; however, irrigation farmers most likely will need to coordinate their irrigation activities using water more efficiently. Meanwhile, new endeavours are emerging in close cooperation with the irrigation sector to improve the assurance of water supply to both consumptive uses and the Ecological Reserve, with the 7–10 day lag being realised at the lower end of the river system in response to Kwena Dam water releases. Notably, during the severity of the 2015–2016 drought, the CRMIB disaggregated the river along the boundary of the KNP into three irrigation reaches, with

alternating abstractions to ensure continuity of flow, albeit very low towards the Komati River confluence. This, in turn, allowed the KNP staff to broaden their understanding of environmental water allocation issues in a previously contested section of river. Furthermore, there was cooperation in initiating research, for example, related to the unaccounted-for water transmission losses in the river, and a socio-economic review of drought impacts on neighbouring communities dependent on commercial agriculture. Such ongoing activities enable (conscious) change, which is vital for harmonious implementation of the Ecological Reserve in the Crocodile River.

Triple-loop learning (review and transformation)

Triple-loop learning is about changing norms and values whilst transforming existing governance arrangements, and we identify four key experiences in Crocodile River SAM. Firstly, there is the development and instigation of the RRS and its communication and feedback arrangements, uniquely involving stakeholders collaboratively (Figure 4). Secondly, there are attempts to broaden the stakeholder networking system, that is, expanding participation and representation in both the CROCOC (with local municipalities and irrigation boards situated along the Crocodile River tributaries) and the more widely constituted Crocodile River Forum (especially connecting with key

sectors in broader freshwater management, for example, mining). Thirdly, stakeholder roles and tasks have been identified and agreed upon, which increases the efficiency and effectiveness of Ecological Reserve management (Appendix 3). Importantly, such a change in the process of dividing up resources and responsibilities requires (and builds) trust and cooperation between different stakeholders. For instance, there is an informal understanding between the Inkomati-Usuthu CMA, KNP, CRMIB and other stakeholders of the CROCOC where KNP monitors river flows against the Ecological Reserve benchmarks and reports on ecological outcomes (McLoughlin et al. 2011a, Petersen et al. 2019) (Figure 5). Fourthly, flexible networking between CROCOC stakeholders is encouraged. For example, an informal fieldtrip was commenced by stakeholders at the Kwená Dam, who then visited a sugar cane farm (irrigation pump station) and a KNP river reach (ecological monitoring site). The fieldtrip allowed fruitful discussions amongst stakeholders in a relaxed atmosphere, for instance, on ecological monitoring methods, water extraction needs and other key aspects of Crocodile River management. Furthermore, during the year 2015 in the early part of the severe drought, a smaller informal working group was established to explore various low-flow abstraction options for implementation. More recently, there has been concerted collaborative research with a recently established local



CMC, Conservation Management Committee; CROCOC, Crocodile River Operations Committee; IUCMA, Inkomati-Usuthu Catchment Management Agency; KNP, Kruger National Park; RRS, Rapid Response System; SAM, Strategic adaptive management; TPC, threshold of potential concern.

FIGURE 5: Governance, information, and feedback arrangements and agreed responsibilities in managing the Crocodile River Ecological Reserve between Kruger National Park, Inkomati-Usuthu Catchment Management Agency and stakeholders of the Crocodile River Operations Committee (e.g. Crocodile River Major Irrigation Board).

university on river aquatic connectivity issues, and also problems concerning exotic aquatic species. Participation and collaboration in such informal activities help to foster key social learning potentials in adaptive management of the river system (cf. Pahl-Wostl 2009).

Future triple-loop learning in Crocodile River SAM should include a review of values and high-level objectives. There are key questions to ask, for example, if the Ecological Reserve is being implemented as planned, then what undue impacts, if any, will this have on sugar cane farming outside of KNP, and therefore, on the region's economic outcomes? Resolving such issues will require innovative thinking; for example, the irrigation farmers are finding ways to use water more efficiently. In addition, the decision made to maintain the 'C' Ecological Category river should be reviewed from time to time, and perhaps, also the broader KNP biodiversity objectives based on stakeholder values. By and large, the balance between social, economic and ecological objectives of the managed river system needs to come up for reflection, as knowledge advances along with values change.

Discussion

The Crocodile River SAM system linked to the KNP is setting an important precedent for implementation of Ecological Reserve in South Africa via learning in adaptive management. In order to explain this reasonable success with the Ecological Reserve, the authors weigh three factors heavily in this regard. Firstly, there is evidence of preconditions (e.g. transparency) for social learning, as sensed by the stakeholders themselves; thus, there is valid potential for this learning. The CROCOC forum has had a trusted and recognised coordinator and is itself a developing 'community-of-practice' exhibiting fruitful stakeholder interactions, a situation likely fostering capacities (e.g. information sharing) for sustained social learning. Secondly, capacity for adaptive and transformative learning is underpinned by ongoing and overlapping feedbacks supporting adaptive assessment and reflection (Biggs et al. 2011b), which help to lubricate the cogs of single-, double- and triple-loop learning. At this point in the evolution of the adaptive management system, we do not suggest that these feedbacks and ensuing learnings are part of any rigorous predetermined systematic plan. They likely occur as opportune 'real world happenings' (cf. Biggs et al. 2017), for instance, key motivated or informed staff, funding timing, stakeholder attributes and responses to crises, and outside research interests or collaborations. Thirdly, champions exist and are the glue that binds the adaptive management system together without which it is more likely to falter (McLoughlin & Thoms 2015; Nel & Roux 2018). They are enlightened individuals within relevant agencies who are motivated and adaptable, with a grasp of complexity and a desire to learn and integrate knowledge (Roux, Murray & Hill 2010; Stirzaker, Roux & Biggs 2011). We now turn to discussing the learning experiences (lessons) emanating from the Crocodile River SAM system.

Lower-grade single-loop learning (rapid response system)

A large part of this learning occurs because of operations of the RRS in the Crocodile River SAM, which gets feedbacks working as quickly as possible ideally before river flows decline to unacceptable levels (Figure 4). These feedbacks are vital because uncertainties exist; for instance, the hydrological models are built on imperfect data and assumptions; therefore, errors will always exist when predicting river flow behaviour. Typically, lower-grade single-loop learning improves understanding on the quantity and timing of the Kwena Dam water releases for implementing the Ecological Reserve in conjunction with irrigation and water restrictions imposed. Whilst this article is framed around Ecological Reserve implementation, there is a concomitant process undertaken by the commercial irrigation sector, who themselves proactively monitor river flows at their specific target points, implement restrictions or strategies where necessary, and/or request releases from Kwena Dam. Critically, RRS-related understanding is growing whilst Ecological Reserve flows are actually being implemented, and this 'learning-by-doing' is likely the key factor promoting ability to make timely decisions on river flow operations and the adjustments when needed.

In the authors' view, success of the RRS would not be possible without champions – people who initiate and facilitate significant stakeholder interactions via more informal interactions and operational feedbacks, often using pragmatic communication mechanisms (e.g. via WhatsApp™). The champion role has been taken up by the River Systems Planning and Operations Manager of the Inkomati-Usuthu CMA and the KNP freshwater team, and more recently the CRMIB themselves who value the Ecological Reserve as a sustainability metric. By streamlining operations of the RRS and the now quarterly CROCOC meetings, these champions are arguably the most important catalyst building social learning potentials (e.g. exchange of ideas, trust, cooperation) in Crocodile River SAM. This point is significant, given typical (formal) structural constraints imposed on Ecological Reserve practitioners and stakeholders at the catchment-scale in South Africa, from national water policy (see Pollard & Du Toit 2011a). Overall, the RRS is an operational conduit illustrating how progressive and adaptive implementation of the Ecological Reserve can be realised in South African rivers.

Upper-grade single-loop learning (adaptive assessment)

The TPC-related auditing process (cf. McLoughlin et al. 2011b) is the prominent instigator of feedbacks for this learning in Crocodile River SAM; its intention is to support stakeholders in making purposeful decisions related to implementation of Ecological Reserve. The process involves collating TPC audit reports via the TPC maintenance system where TPCs are tabled if or when they are exceeded, or close to being exceeded (see Biggs & Rogers 2003). The TPCs are

measurable end points ultimately alerting stakeholders to risk of the 'C' Ecological Category river being lost. If so, increased effort is directed towards technicalities (e.g. RRS procedures) for getting expected Ecological Reserves delivered. To this end, the reporting of the Ecological Reserve 'worry levels' has to be amended from time to time, as mentioned previously. This is to account for new compliance targets, including international flow obligations (the triple-loop related change, see below), and that in itself is an adaptive process.

Attention often skews towards the Ecological Reserve operations (RRS), that is, at the expense of the upper-grade single-loop learning feedbacks. However, implementing the Ecological Reserve is not an end in itself but a recommended flow regime (hypothesis) to maintain the 'C' Ecological Category river based on the best available knowledge. This is then one constructive critique of Crocodile River SAM, because monitoring outcomes are needed to test the generally precautionary estimates of required flows – against the real Ecological Categories which result – thus, enhancing understanding of the relationship between river flow patterns and ecological conditions (McLoughlin et al. 2011a). A greater appreciation of such feedbacks and outcomes can be strengthened by improved group understanding of system complexity (vis-à-vis low-relative score – Figure 3c), in particular appreciation of the range of interwoven interests, influences and needs. Such a favourable outcome can be achieved if stakeholders co-construct conceptual 'systemic' diagrams of the managed system (cf. Biggs et al. 2008; Pollard, Biggs & Du Toit 2014) and/or with mental model analyses (see Adams et al. 2018; Biggs et al. 2011c). Importantly, learning processes in Crocodile River SAM need to accommodate changing circumstances across water-use sectors, and factor any change into future medium to long-term river operations and decision-making.

Overall, single-loop learning (lower- and upper-grade) is the basis for double-loop (reframing; changing practice) into triple-loop (reviewing; transforming governance) learning in the Crocodile River SAM (McLoughlin & Thoms 2015). Notably, in order to avoid the trap of 'learning for the sake of learning' (Fabricius & Cundill 2014), there must not be a disproportionate amount of time spent on double- and/or triple-loop learning (e.g. Biggs et al. 2011b; Pollard et al. 2011a; Varady et al. 2013), that is, at the expense of the 'actual doing' (single-loop learning). Hence, within environmental water programmes, finding an appropriate balance between modes of single-, double- and triple-loop learning is encouraged (McLoughlin & Thoms 2015).

Double-loop learning (adaptive reflection)

Adaptive reflection-related feedbacks in Crocodile River SAM foster a more deliberate and lengthy evaluation (cf. Biggs et al. 2011b) concerning the Ecological Reserve, which is linked to biodiversity objectives and the explicit measurable end-points or TPCs. Construction of TPCs uses existing knowledge (formal scientific and local/tacit), however,

incomplete this is (Biggs et al. 2011a; McLoughlin et al. 2011b) based on stakeholder values. Following principles of requisite simplicity (see Stirzaker et al. 2010) – necessitated when managing in complex and uncertain contexts – means that within the inductive approach to TPC development, stakeholders never attempt to finalise indicators and their associated thresholds. Hence TPCs are often developed as 'first generation' TPCs (Biggs et al. 2011a), and open to challenge and refinement as new knowledge becomes available and/or stakeholder values change. For example, the reframed KNP geomorphic TPCs (McLoughlin et al. 2011b) are cost effective, feasible and relevant to low-flow Ecological Reserve implementation and ongoing management (though still to be deployed). Generally, reframing should not occur too often; otherwise change at the expense of the 'actual doing' may well overwhelm management (Fabricius & Cundill 2014).

Another double-loop learning experience was facilitated when adaptive reflection processes led CROCOC stakeholders to identify and then acknowledge an approximate 10% inaccuracy in the Ecological Reserve benchmark calculated each week (S. Mallory [IWR Water Resources Pty (Ltd)] pers. comm., 13 August 2013). Effective communication and the build-up of trust amongst stakeholders enabled new thinking to emerge, and this translated into a decision to allow the Ecological Reserve to fluctuate within an 'envelope of acceptability' – rather than an exact amount – defined by the 'Low-worry' to 'Medium-worry' RRS levels (Figure 4). Still, if gauged river flow ever breaches the 'Medium-worry' level, then management urgency is definitely stepped up. Such change in practice – emanating from this more informal stakeholder network – is important, although in direct contrast to more rigid top-down constraints imposed by legislation on CMAs and stakeholders (e.g. expecting exact or legally defensible compliances with gazetted Ecological Reserves), making Ecological Reserves difficult to achieve in practice (Pollard & Du Toit 2011a). It is within these informal stakeholder networks (Figure 4) where innovation and learnings are supported, albeit under the necessary stabilising context of the formal water policy (cf. Pahl-Wostl 2015).

Overall, broadening social learning potential in the CROCOC forum (e.g. awareness of interdependence, information sharing and joint problem solving) helps to foster the reframing requirements of double-loop learning, which is important for resolving complex management problems. Here, the stakeholder network proceeds to deal with specific problems and is open to experimentation involving different approaches (Pahl-Wostl 2009). Such innovation and flexible management are crucial factors for progressive implementation of the Ecological Reserve in the Crocodile River.

Triple-loop learning (review and transformation)

Triple-loop learning encompasses a review of values, norms and governance arrangements associated with Ecological Reserve management; it is transformative change over longer

time frames. A key example is the Crocodile River's RRS, with already a decade of deployment and further refinement. The RRS reinvigorated (practical) ways for negotiations to occur in a highly contested and water-stressed catchment situation with a history of Ecological Reserve noncompliance (Pollard & Du Toit 2011b; Pollard et al. 2011b; Riddell & Jewitt 2010; Riddell et al. 2014). With collaborative decision-making when river flow declines below different 'worry-levels' (Figure 4), stakeholders are building trust as they cooperate and together explore best options and solutions for management. This was clearly demonstrated during the peak of the severe 2015–2016 drought. Crocodile River flows recorded at the TenBosch Gauging Weir were consistently higher than that was observed previously during the previous significant droughts of 1991–1992 and 1982–1983, despite lower catchment rainfall and higher temperatures occurring in the 2015–2016 period (Smit & Bond 2020). Furthermore, partnerships and interdependent roles have been entrusted to, and between, different stakeholders, for example, the monitoring and ecosystem reporting role of the KNP (Figure 5) and the dam and water restriction operations of the CRMIB. These kinds of innovation, and also cooperation, are vital for effectual Ecological Reserve implementation.

The degree of 'agency' – extent to which stakeholders as a group act independently, making free choices (cf. Pahl-Wostl 2015) – is pivotal for adaptive management of environmental water. Agency supports progression of transformative (i.e. double into triple loop) learning and innovation (Pahl-Wostl 2009) amongst practitioners and stakeholders, in conjunction with top-down (national) influences. Indeed, there is now significant national government interest in Crocodile River SAM, with nascent bottom-up learnings expected to help step up countrywide Ecological Reserve applications (E.S. Riddell [South African National Parks] pers. comm., 18 December 2019). Besides, national-level transformative change will certainly influence SAM of the Crocodile River, for example, a review of and amendment to the *National Water Act* itself including any legislated water resource protection mechanisms. In addition, recent review of the KNP's vision and mission (www.sanparks.org/assets/docs/conservation/park_man/knp/draft-plan.pdf), reflecting a change in values, demands holistic transformation of governance arrangements, for instance, refocusing management on the entire freshwater resource base, especially the current priority values of equity and redress (Pollard & Du Toit 2011b). In the future, a conscious review is required of all constraints and opportunities associated with the Crocodile River's gazetted Ecological Reserve. Altogether, these bottom-up and top-down processes impact the effectiveness of environmental flow planning and implementation, and hence, they are significant in shaping the delivery of Ecological Reserve in South African rivers.

Achieving progress with the Crocodile River Ecological Reserve

With emergent social learning – progressing through modes of single-, double- and triple-loop learning – since 2009 and a

decade of managing the Crocodile River, growing capacity for adaptive and transformative learning helps stakeholders to deliver the Ecological Reserve. Importantly, this learning has been concurrent and in combination with meaningful change happening in the Crocodile River system between 2009 and 2019 (see Table 2). Learning is by no means absolute; it is ongoing and evolving. After the 2013 interviews, the authors have witnessed further potential for CROCOC social learning. For example, group problem solving particularly concerning the low-flow river abstraction problems and early warning solutions implemented, applicable not only to the irrigation sector but also to the municipal sector now. Stakeholders generally communicate well, exchange ideas and share information, which assists them to deal with joint problems. Cooperation is growing within a dynamic environment of increasing trust and shared understanding, demonstrated via stakeholder consensus being reached to avoid, at all costs, river flows dipping into the very high (now extreme) RRS 'worry level'. Social learning-related advantages were evident during the severe drought crisis of 2015–2016. Future analysis of the qualitative data also collected during the 2013 interviews will be highly beneficial in understanding CROCOC social learning processes. Furthermore, eliciting stakeholder mental models (cf. Biggs et al. 2008; Lynam et al. 2012) can make explicit the implicit assumptions individuals hold and how they understand a managed system (Adams et al. 2018; Moon & Adams 2016). Besides, mental model analyses offer insights into how single-, double- and triple-loop learning transpires and proceeds over time (cf. Biggs et al. 2011c).

Learning experiences from the KNP-linked Crocodile River SAM system thus far have helped to tailor Ecological Reserve implementation in other perennial rivers traversing KNP (e.g. Olifants River; Biggs et al. 2017; Table 2) via translation of the social learning processes. Such experiences (and lessons) are applicable to environmental water programmes throughout South Africa and, the authors believe, further abroad too. As climate change uncertainties manifest, particularly frequency and intensity of droughts and floods, increased resilience with stakeholder collaboration, learning and ability to adapt and change will become increasingly important for sustainable management and use of rivers, worldwide.

Conclusion

Management of environmental water requires ongoing adaptive and transformative learning. Capacity for this learning is built progressively over time through quality stakeholder interactions wherein emergent social learning promotes opportune iterations of single-, double- and triple-loop learning (Fabricius & Cundill 2014; Pahl-Wostl 2009). For effective and successful delivery of the Ecological Reserve in South African rivers, CMAs and stakeholders need to engage within processes of continuing social learning. These processes must entail the generation of trust, cooperation, shared understanding and consensus building because this fosters continual rethinking and negotiation of options to solve

TABLE 2: Timeline of change events (2009–2019) associated with the Crocodile River SAM system, concurrent with Crocodile River Operations Committee stakeholder learning (single-, double- and triple-loop) whilst implementing the Ecological Reserve in the Kruger National Park.

Year	Outcome	Initiative	Lessons learned or shared
2009	Establishment of Operating Rules and DSS study, and creation of coordination and advisory committee.	Development of a Real-Time Decision Support System (DSS) for the Crocodile East River System, commenced 2008. Terms of Reference for Crocodile River Operations Committee (CROCOC).	Mutual recognition of shared interests in sustainable but productive use of the water resource. Recognition by all for a decision-making system at all levels (operations to policy).
	Historical assessment of reserve compliance in Crocodile River.	KNP-IUCMA co-operation on Ecological Water Requirement (EWR) implementation.	Inkomati-Usuthu Catchment Management Agency (IUCMA) embraces SAM as management philosophy, because of capacity, it recognises the need for collaborative support to implement EWR.
	Development and application of Crocodile River thresholds of potential concern, monitoring and information feedbacks, linked to the Kruger National Park (KNP).	Water Research Commission: Shared Rivers Initiative. Water Research Commission: Implementation of Strategic Adaptive Management (SAM).	Blending of the contextual environmental profile of Crocodile River condition into adaptive planning, operations, evaluation and learning.
2010	Formalisation of the CROCOC committee.	Water Research Commission: building capacity for adaptive management through action research.	Based on user's needs, IUCMA takes on the role of EWR implementation facilitator, endorsed by DWAF resource-directed measures.
	First Catchment Management Strategy drafted for Inkomati Water Management Area.	SAM embraced as guiding philosophy, and there is recognition of IUCMA as a 'learning organisation'.	Broad acceptance by stakeholders of SAM principles.
	Acceptance of 'Present Day' flows for 'C' Ecological Category river.	IWR Water Resources Naturalised flows.	~1 year iterative process to revisit EWR implementation factors – this ultimately drives transparency and acceptance. KNP also recognises need to make concessions.
2011	Quorum established (IUCMA, the environment, irrigation boards and municipal use).	Sector representation required for water resource-related decision making.	Environmental sector concedes that reserve non-compliance not always because of irrigation abstractions – also factors such as river flow lags and prevailing weather conditions.
2012–2013	Water quality issues start being discussed – integrating with river operations.	National Research Foundation: Integrated Water Quality Management Process.	Users recognise water quality concerns as a key matter of reporting in river operations.
	Sabie River EWR reporting.	Sabie river included into CROCOC reporting, following operating rules study.	Similar set of stakeholders concerned. SAM EWR implementation framework adopted in the Sabie River system.
	First stakeholder consensus assessment.	IUCMA conducts stakeholder reviews.	-
2014	First presentation of SAM outcomes to transboundary audience.	3rd River Environmental Management Committee (REMCO) meeting, Mbombela.	Recognition through bilateral partnerships to continue support for SAM tool development, roll-out to other catchment management agencies (CMAs).
2015–2016	Severe drought, but Crocodile River flows are maintained.	CROCOC sub-committee established (KNP, IUCMA, and Crocodile River Major Irrigation Board) for stretch of river along KNP's southern boundary.	Recognition that technical sub-committees required, for local-level operation of the river – to speed up decision making. There is also an increased need for new technology, promoting information sharing and recording of decisions.
	Informal transboundary co-operation.	Inclusion of representatives from Mozambique in 'river operations' and WhatsApp groups.	Quicker and more efficient 'hydro-diplomacy'.
	Establishment of river operations committee for the Lower Olifants River.	Drought mitigation through temporary transfer of bulk water allocations.	Mutual recognition of shared water security interests between regional water board, KNP and irrigated agriculture. Process facilitated by local non-governmental organisations with long-term SAM implementation experience; also using experiences from Crocodile River SAM – similar information feedbacks and rapid response system development.
	Delegation revoked for river operations.	-	Stakeholders decide to bypass politics because of a real need to continue their co-operation because of pressing water management and security concerns.
2017	Water Quality Compliance reporting.	Gazettes of Resource Quality Objectives in late 2016.	-
2018	Change in the IUCMA's top management.	New management embraces success of CROCOC and provides its full support.	Stakeholders trust in CROCOC and related river management processes – remains intact.
2019	Transboundary acceptance of SAM principles.	5th REMCO meeting, Maputo.	Experiences shared to a broader audience, including Lusophone member state (Mozambique). Similar SAM principles adopted in neighbouring catchments.

complex management problems (*vis-à-vis* Ernst 2019; Pahl-Wostl et al. 2007). This research study shows that execution of this learning relies critically on champions – people who with their enlightenment can motivate stakeholders whilst they coordinate, share and disseminate information and knowledge (Stirzaker et al. 2011). Movement away from 'command and control' management styles is also vital, and in particular the tendency to seek and implement optimal 'once-off technical' solutions to problems. Emerging capacity for adaptive and transformative learning emboldens CMAs and stakeholders to adapt their management and transform their governance. Thus, this guides the complex and uncertain process of Ecological Reserve planning and implementation to achieve agreed objectives.

Findings in this article support the case for multiple CMAs across South African water management areas, overbids for a single (centralised) CMA. Whilst managing environmental water, it is imperative that practitioners and stakeholders retain their autonomy – utilising their unique set of resources they keep distinguishing interdependent roles, self-organise and pursue opportunities to experiment, learn, innovate and adapt. Full delegation of all Ecological Reserve management-related responsibilities (e.g. *National Water Act: Water resource protection mechanisms*), to the applicable regional CMA and stakeholder base, must, therefore, be considered in South Africa. Such an arrangement engenders decentralised, polycentric, flexible and more informal governance (Folke et al. 2005; Gunderson, Holling & Light 1995), which

promotes adaptive and transformative learning in uncertain contexts (Pahl-Wostl 2009). This learning enables a positive change across the range of ecological, social and economic outcomes that are essential for success in environmental water programmes worldwide.

Acknowledgements

The authors acknowledge the Inkomati-Usuthu Catchment Management Agency (IUCMA) for supporting this work. The authors thank stakeholders of the Crocodile River Operations Committee for their active involvement and also for the time taken to complete the interviews. They are also grateful to Brian Jackson for enabling their involvement within the broader Crocodile River SAM project led by IUCMA and for his continued support. The authors also acknowledge Tendai Sawunyama (IUCMA) for the support rendered. Melissa Parsons provided useful inputs for an early version of the research article. The authors also thank two anonymous reviewers for their constructive critique and suggestions on the article, thereby improving it greatly.

Competing interests

The authors declare that they have no competing interests with regard to the writing of this article.

Authors' contributions

E.S.R., R.M.P. and J.V. were involved extensively with implementation of Crocodile River strategic adaptive management (SAM) over the study period, working with monitoring, feedback and learning processes related to water resource management and the Ecological Reserve. C.A.M. conceptualised and compiled the article, and wrote it in conjunction with significant writing inputs from E.S.R. and finalising the manuscript data requirements and editing. R.M.P. assisted with writing components of the Results section. C.A.M. designed and conducted the social learning stakeholder interviews, and completed the analysis. E.S.R. and R.M.P. assisted with Figure 5, Table 2 and compiled Online Appendix 3.

Funding information

The South African Water Research Commission (associated with SANParks) and IUCMA provided funding for completing applied components of the work. Early conceptualisation of the article occurred during a PhD study funded via an Australian Government PhD Scholarship (University of New England). A Keith and Dorothy Travelling Scholarship allowed for investigation into the social learning component.

Data availability statement

The data provided in this article may be used, however, any raw data cannot be provided as it is protected via rules of the Ethics Office, Research Development and Integrity Division, University of New England.

Disclaimer

The views and opinions expressed in this article are those of the authors, and do not necessarily reflect official policy or position of any affiliated agency of the authors.

References

- Adams, V.M., Moon, K., Álvarez-Romero, J.G., Bodin, Ö., Spencer, M. & Blackman, D., 2018, 'Using multiple methods to understand the nature of relationships in social networks', *Society and Natural Resources* 31(7), 755–772. <https://doi.org/10.1080/08941920.2018.1425514>
- Albert, J.S., Destouni, G., Duke-Sylvester, S.M., Magurran, A.E., Oberdorff, T., Reis, R.E. et al., 2021, 'Scientists' warning to humanity on the freshwater biodiversity crisis', *Ambio* 50, 85–94. <https://doi.org/10.1007/s13280-020-01318-8>
- Allan, C. & Stankey, G.H., 2009, 'Synthesis of lessons', in C. Allan & G.H. Stankey (eds.), *Adaptive environmental management: A practitioner's guide*, pp. 341–346, Springer, Collingwood.
- Anderson, E.A., Jackson, S., Tharme, R.E., Douglas, M., Flotemersch, J.E., Zwartveen, M. et al., 2019, 'Understanding rivers and their social relations: A critical step to advance environmental water management', *Water* 6(6), e1381. <https://doi.org/10.1002/wat2.1381>
- Argyris, C. & Schon, D., 1978, *Organizational learning: A theory of action perspective*, Addison Wesley, Reading, MA.
- Bailey, A. & Pitman, W., 2016, *Water Resources of South Africa 2012 (WR2012): Executive summary*, Research Report, Project No. K5/2143/1, Water Research Commission, Pretoria.
- Bain, M.B. & Stevenson, N.J., 1999, *Aquatic habitat assessment: Common methods*, American Fisheries Society, Bethesda, MD.
- Biggs, H., Du Toit, D., Etienne, M., Jones, N., Leitch, A., Lynam, T. et al., 2008, *A preliminary explanation of two approaches for documenting 'mental models' held by stakeholders in the Crocodile Catchment, South Africa*, Research Report, Water Research Commission, Pretoria.
- Biggs, H., Ferreira, S., Freitag-Ronaldson, S. & Grant-Biggs, R., 2011a, 'Taking stock after a decade: Does the "thresholds of potential concern" concept need a socio-ecological revamp?', *Koedoe* 53(2), Art1002. <https://doi.org/10.4102/koedoe.v53i2.1002>
- Biggs, H., Breen, C., Slotow, R., Freitag-Ronaldson, S. & Hickings, M., 2011b, 'How assessment and reflection relate to more effective learning in adaptive management', *Koedoe* 53(2), Art. #1001, 13 pages. <https://doi.org/10.4102/koedoe.v53i2.1001>
- Biggs, D., Abel, N., Knight, A.T., Leitch, A., Langston, A. & Ban, N.C., 2011c, 'The implementation crisis in conservation planning: Could mental models help?', *Conservation Letters* 4(3), 169–183. <https://doi.org/10.1111/j.1755-263X.2011.00170.x>
- Biggs, H. & Rogers, K.H., 2003, 'An adaptive system to link science, monitoring and management in practice', in J.T. Du Toit, K.H. Rogers & H.C. Biggs, H.C. (eds.), *The Kruger experience: Ecology and management of savanna heterogeneity*, pp. 59–80, Island Press, Washington, DC.
- Biggs, H.C., Clifford-Holmes, J.K., Freitag, S. & Venter, F.J., 2017, 'Cross-scale governance and ecosystem service delivery: A case narrative from the Olifants River in north-eastern South Africa', *Ecosystem Services* 28(Part B), 173–184. <https://doi.org/10.1016/j.ecoser.2017.03.008>
- Biggs, R., Rhode, C., Archibald, S., Kunene, L.M., Mutanga, S.S., Nkuna, N. et al., 2015, 'Strategies for managing complex social-ecological systems in the face of uncertainty: Examples from South Africa and beyond', *Ecology and Society* 20(1), 52. <https://doi.org/10.5751/ES-07380-200152>
- Chen, Y., Colloff, M.J., Lukaszewicz, A. & Pittcock, J., 2020, 'Trickle, not a flood: Environmental watering in the Murray-Darling Basin, Australia', *Marine and Freshwater Research*. <https://doi.org/10.1071/MF20172>
- Cilliers, P., 2008, 'Complexity theory as a general framework for sustainability science', in M. Burns & A. Weaver (eds.), *Exploring sustainability science – A Southern African perspective*, pp. 9–26, African Sun Media, Stellenbosch.
- Clarke, K.R. & Warwick, R., 2001, *Change in marine communities: An approach to statistical analysis and interpretation*, 2nd edn., Plymouth Marine Laboratory PRIMER-E Ltd, Plymouth.
- Cundill, G., Cumming, G.S., Biggs, D. & Fabricius, C., 2011, 'Soft systems thinking and social learning for adaptive management', *Conservation Biology* 26(1), 13–20. <https://doi.org/10.1111/j.1523-1739.2011.01755.x>
- Daniel, S.E. & Walker, G.B., 1996, 'Collaborative learning: Improving public deliberations in ecosystem-based management', *Environmental Impact Assessment Review* 16(2), 71–102. [https://doi.org/10.1016/0195-9255\(96\)00003-0](https://doi.org/10.1016/0195-9255(96)00003-0)
- Dickens, C.W.S. & Graham, P.M., 2002, 'The South African Scoring System (SASS) version 5 rapid bioassessment method for rivers', *African Journal of Aquatic Science* 27(1), 1–10. <https://doi.org/10.2989/16085914.2002.9626569>
- DWA (Department of Water Affairs), 2010, *Comprehensive reserve determination study for selected water resources (rivers, groundwater and wetlands) in the Inkomati Water Management Area, Mpumalanga*, Report No 26/8/3/10/12/015, Department of Water Affairs, Pretoria.
- DWAF (Department of Water Affairs and Forestry), 1997, *White paper on a national water policy for South Africa*, Department of Water Affairs and Forestry, Pretoria.
- DWAF (Department of Water Affairs and Forestry), 2007, *Guidelines for the development of catchment management strategies: Towards equity, efficiency and sustainability in water resources management*, Department of Water Affairs and Forestry, Pretoria.

- DWAF (Department of Water Affairs and Forestry), 2008, *The development of a real-time decision support system (DSS) for the Crocodile East River system – Inception report*. Project No WP 9429, Clear Pure Water with Water for Africa and Dormehl Technology, on behalf of the Directorate: Water Resource Planning Systems, Pretoria.
- Ernst, A., 2019, 'Review of factors influencing social learning within participatory environmental governance', *Ecology and Society* 24(1), 3. <https://doi.org/10.5751/ES-10599-240103>
- Fabricius, C. & Cundill, G., 2014, 'Learning in adaptive management: Insights from published practice', *Ecology and Society* 19(1), 29. <https://doi.org/10.5751/ES-06263-190129>
- Folke, C., Hahn, T., Olsson, P. & Norberg, J., 2005, 'Adaptive governance of social-ecological systems', *Annual Review of Environment and Resources* 30, 441–473. <https://doi.org/10.1146/annurev.energy.30.050504.144511>
- Garmestani, A.S. & Allen, C.R., 2015, 'Adaptive management of social-ecological systems: The path forward', in C.R. Allen & A.S. Garmestani (eds.), *Adaptive management of social-ecological systems*, pp. 255–260, Springer, Dordrecht.
- Gunderson, L., 2015, 'Lessons from adaptive management: Obstacles and outcomes', in C.R. Allen & A.S. Garmestani (eds.), *Adaptive management of social-ecological systems*, pp. 27–38, Springer, Dordrecht.
- Gunderson, L.H., Holling, C.S. & Light, S.S. (eds.), 1995, *Barriers and bridges to the renewal of ecosystems and institutions*, Columbia Press, New York, NY.
- Hargrove, R., 2002, *Masterful coaching*, rev. edn., Jossey-Bass/Pfeiffer, Wiley, Hoboken, New Jersey.
- Harwood, A., Johnson, S., Richter, B., Locke, A., Yu, X. & Tickner, D., 2017, *Listen to the river: Lessons from a global review of environmental flow success stories*, WWF-UK, Woking.
- Huxham, C. & Vangen, S., 2000, 'Leadership in the shaping and implementation of collaboration agendas: How things happen in a (not quite) joined-up world', *Academy of Management Journal* 43(6), 1154–1175. <https://doi.org/10.5465/1556343>
- Iaquinto, B., Ison, R. & Faggian, R., 2011, 'Creating communities of practice: Scoping purposeful design', *Journal of Knowledge Management* 15(1), 4–21. <https://doi.org/10.1108/136732711111108666>
- Inkomati Catchment Management Agency (ICMA), 2010, *The Inkomati Catchment Management Strategy. A first-generation catchment management strategy for the inkomati water management area*.
- Ison, R. & Watson, D., 2007, 'Illuminating the possibilities for social learning in the management of Scotland's water', *Ecology and Society* 12(1), 21. <https://doi.org/10.5751/ES-02020-120121>
- Jackson, B., 2015, 'An adaptive operational water resources management framework for the crocodile river catchment, South Africa', MSc thesis, University of KwaZulu-Natal, Pietermaritzburg.
- Jewitt, G., Heritage, G., Weeks, D., Mackenzie, J., Van Niekerk, A., Görgens, A. et al., 1998, *Modelling abiotic-biotic links in the Sabie River*, Report No 777/1/9, Water Research Commission, Pretoria.
- Kingsford, R.T., Bino, G. & Porter, J.L., 2017a, 'Continental impacts of water development on water birds, contrasting two Australian river basins: Global implications for sustainable water use', *Global Change Biology* 23(11), 4958–4969. <https://doi.org/10.1111/gcb.13743>
- Kingsford, R.T., Roux, D.J., McLoughlin, C.A., Conallin, J. & Norris, V., 2017b, 'Strategic adaptive management (SAM) of intermittent rivers and ephemeral streams (IRES) – Juggling temporal and spatial scales, cultures and governance', in T. Datry, N. Bonada & A. Boulton (eds.), *Intermittent rivers and ephemeral streams: Ecology and management*, pp. 535–562, Academic Press, Burlington.
- Kleynhans, C.J. & Louw, M.D., 2007, *Module A: EcoClassification and EcoStatus determination in river EcoClassification: Manual for EcoStatus determination (version 2)*, Report. Joint Water Research Commission and Department of Water Affairs and Forestry, Pretoria.
- Kleynhans, C.J., Louw, M.D., Birkhead, A., Thirion, C., Deacon, A. & Angliss, M., 2009, *On the way to implementation: Ecological reserve monitoring*, Unpublished report.
- Lynam, T., Mathevet, R., Etienne, M., Stone-Jovicich, S., Leitch, A., Jones, N. et al., 2012, 'Waypoints on a journey of discovery: Mental models in human-environment interactions', *Ecology and Society* 17(3), 23. <https://doi.org/10.5751/ES-05118-170323>
- Mackenzie, J.A., Van Coller, A.L. & Rogers, K.H., 1999, *Rule based modelling for management of riparian systems*, Report No. 813/1/99, Water Research Commission, Pretoria.
- McLoughlin, C.A., MacKenzie, J., Rountree, M. & Grant, R., 2011a, *Implementation of Strategic Adaptive Management for freshwater protection under the South African national water policy*, Research Report Number 1797/1/11, Water Research Commission, Pretoria.
- McLoughlin, C.A., Deacon, A., Sithole, H. & Gyedu-Ababio, T., 2011b, 'History, rationale, and lessons learned: Thresholds of potential concern in Kruger National Park river adaptive management', *Koedoe* 53(2), Art. #996, 27 pages. <https://doi.org/10.4102/koedoe.v53i2.996>
- McLoughlin, C.A. & Thoms, M.C., 2015, 'Integrative learning for practicing adaptive resource management', *Ecology and Society* 20(1), 34. <https://doi.org/10.5751/ES-07303-200134>
- McLoughlin, C.A., Thoms, M.C. & Parsons, M., 2020, 'Reflexive learning in adaptive management: A case study of environmental water management in the Murray Darling Basin, Australia', *River Research and Applications* 36(4), 681–694. <https://doi.org/10.1002/rra.3607>
- Millennium Ecosystem Assessment, 2005, *Ecosystems and human wellbeing: Biodiversity synthesis*, World Resources Institute, Washington, DC.
- Moon, K. & Adams, V.M., 2016, 'Using quantitative influence diagrams to map natural resource managers' mental models of invasive species management', *Land Use Policy* 50, 341–351. <https://doi.org/10.1016/j.landusepol.2015.10.013>
- Mostert, E., Pahl-Wostl, C., Rees, Y., Searle, B., Tabara, D. & Tippett, J., 2007, 'Social learning in European River-basin management: Barriers and fostering mechanisms from 10 river basins', *Ecology and Society* 12(1), 19. <https://doi.org/10.5751/ES-01960-120119>
- Muro, M. & Jeffrey, P., 2012, 'Time to talk? How the structure of dialog processes shapes stakeholder learning in participatory water resources management', *Ecology and Society* 17(1), 3. <https://doi.org/10.5751/ES-04476-170103>
- Nel, J.L. & Roux, D.J., 2018, 'Planning for the protection and management of freshwater ecosystems inside and outside protected areas', in C.M. Finlayson, A.H. Arthington & J. Pittock (eds.), *Freshwater ecosystems in protected areas: Conservation and management*, pp. 204–220, Routledge, New York, NY.
- O'Keefe, J. & Rogers, K.H., 2003, 'Heterogeneity and management of the Lowveld rivers', in J.T.D. Du Toit, K.H. Rogers & H.C. Biggs (eds.), *The Kruger experience: Ecology and management of savanna heterogeneity*, pp. 447–468, Island Press, Washington, DC.
- Pahl-Wostl, C., 2009, 'A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes', *Global Environmental Change* 19(3), 354–365. <https://doi.org/10.1016/j.gloenvcha.2009.06.001>
- Pahl-Wostl, C., 2015, *Water governance in the face of global change: From understanding to transformation*, Springer, Cham.
- Pahl-Wostl, C., Becker, G., Knieper, C. & Sendzimir, J., 2013, 'How multilevel societal learning processes facilitate transformative change: A comparative case-study analysis on flood management', *Ecology and Society* 18(4), 58. <https://doi.org/10.5751/ES-05779-180458>
- Pahl-Wostl, C., Craps, M., Dewulf, A., Mostert, E., Tabara, D. & Taillieu, T., 2007, 'Social learning and water resources management', *Ecology and Society* 12(2), 5. <https://doi.org/10.5751/ES-02037-120205>
- Pahl-Wostl, C. & Hare, M., 2004, 'Processes of social learning in Integrated Resources Management', *Journal of Community and Applied Psychology* 14(3), 193–206. <https://doi.org/10.1002/casp.774>
- Pahl-Wostl, C., Mostert, E. & Tabara, D., 2008, 'The growing importance of social learning in water resources management and sustainability science', *Ecology and Society* 13(1), 24. <https://doi.org/10.5751/ES-02352-130124>
- Pahl-Wostl, C., Nilsson, C., Gupta, J. & Tickner, K., 2011a, 'Societal learning needed to face the water challenge', *Ambio* 40, 549–553. <https://doi.org/10.1007/s13280-011-0149-1>
- Pahl-Wostl, C., Jeffrey, P., Isendahl, N. & Brugnach, M., 2011b, 'Maturing the new water management paradigm: Progressing from aspiration to practice', *Water Resources Management* 25, 837–856. <https://doi.org/10.1007/s11269-010-9729-2>
- Palmer, M.A., Lettenmaier, D.P., LeRoy Poff, N., Postel, S.L., Richter, B. & Warner, R., 2009, 'Climate change and river ecosystems: Protection and adaptation options', *Environmental Management* 44, 1053–1068. <https://doi.org/10.1007/s00267-009-9329-1>
- Petersen, R., Riddell, E., Sithole, H., Shikwambana, P., Venter, J. & Nzima, N., 2019, *Status Report of the hydrology and aquatic ecosystems in the Kruger National Park*, Unpublished Internal Report 11/2020, Scientific Services, South African National Parks, Skukuza.
- Pittock, J., Finlayson, M., Arthington, A.H., Roux, D., Matthews, J.H., Biggs, H. et al., 2015, 'Managing freshwater, river, wetland and estuarine protected areas', in G.L. Worboys, M. Lockwood, A. Kothari, S. Feary & I. Pulsford (eds.), *Protected area governance and management*, pp. 569–608, ANU Press, Canberra.
- Pittock, J. & Max Finlayson, C., 2011, 'Australia's Murray-Darling Basin: Freshwater ecosystem conservation options in an era of climate change', *Marine and Freshwater Research* 62(3), 232–243. <https://doi.org/10.1071/MF09319>
- Pollard, S., Biggs, H. & Du Toit, D.R., 2014, 'A systemic framework for context-based decision making in natural resource management: Reflections on an integrative assessment of water and livelihood security outcomes following policy reform in South Africa', *Ecology and Society* 19(2), 63. <https://doi.org/10.5751/ES-06312-190263>
- Pollard, S. & Du Toit, D., 2007, *Guidelines for strategic adaptive management: Experiences from managing the rivers of the Kruger National Park*, UNEP/GEF Project No. GF/2713-03-4679, EPP Project, IUCN, Gland.
- Pollard, S. & Du Toit, D., 2011a, *Towards the sustainability of freshwater systems in South Africa: An exploration of factors that enable or constrain meeting the Ecological Reserve within the context of Integrated Water Resources Management in the catchments of the lowveld*, Research Report No. TT 477/10, Water Research Commission, Pretoria.
- Pollard, S. & Du Toit, D., 2011b, *The Shared Rivers Initiative Phase 1. Towards the sustainability of freshwater systems in South Africa: An exploration of factors that enable or constrain meeting the Ecological Reserve within the context of Integrated Water Resources Management in the catchments of the lowveld*, Report Number TT 477/10, Water Research Commission, Pretoria.
- Pollard, S., Du Toit, D. & Biggs, H., 2011a, 'River management under transformation: The emergence of strategic adaptive management of river systems in the Kruger National Park', *Koedoe* 53(2), Art1011. <https://doi.org/10.4102/koedoe.v54i1.1011>
- Pollard, S., Mallory, S., Riddell, E. & Sawunyama, T., 2011b, *Towards improving the assessment and implementation of the reserve: Real-time assessment and implementation of the ecological reserve*, Final Report, Report Number K8/881/2, Water Research Commission, Pretoria.
- Reed, M.S., Evelyn, A.C., Cundill, G., Fazey, I., Glass, J., Laing, A. et al., 2010, 'What is social learning?', *Ecology and Society* 15(4), r1. <https://doi.org/10.5751/ES-03564-1504r1>

- Riddell, E.S. & Jewitt, G.P.W., 2010, *Deliverable no. 1: Project K5/1935 Report providing updated catchment information and identifying study focus areas. A management tool for the Inkomati Basin with focus on improved hydrological understanding for risk-based operational water management*, Unpublished report, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg.
- Riddell, E.S., Pollard, S.R., Mallory, S. & Sawunyama, T., 2014, 'A methodology for historical assessment of compliance with environmental water allocations: Lessons from the Crocodile (East) River, South Africa', *Hydrological Sciences Journal* 59(3–4), 1–13. <https://doi.org/10.1080/02626667.2013.853123>
- Rist, L., Campbell, B.M. & Frost, P., 2013, 'Adaptive management: Where are we now?', *Environmental Conservation* 40(1), 5–18. <https://doi.org/10.1017/S0376892912000240>
- Rogers, K.H., 2003, 'Adopting a heterogeneity paradigm: Implications for management of protected areas', in J.T. Du Toit, K.H. Rogers & H.C. Biggs (eds.), *The Kruger experience: Ecology and management of savanna heterogeneity*, pp. 41–58, Island Press, Washington, DC.
- Rogers, K.H. & Bestbier, R., 1997, *Development of a protocol for the definition of the desired state of riverine systems in South Africa*, Department of Environmental Affairs and Tourism, Pretoria.
- Rogers, K.H. & Biggs, H., 1999, 'Integrating indicators, end points and value systems in the strategic management of the rivers of the Kruger National Park', *Freshwater Biology* 41(2), 439–451. <https://doi.org/10.1046/j.1365-2427.1999.00441.x>
- Rogers, K.H. & Luton, R., 2011, *Strategic adaptive management as a framework for implementing integrated water resources management in South Africa*, Report No. KV 245/10, Water Research Commission, Pretoria.
- Rogers, K.H., Luton, R., Biggs, H., Biggs, R., Bignaut, S., Choles, A.G. et al., 2013, 'Fostering complexity thinking in action research for change in social-ecological systems', *Ecology and Society* 18(2), 31. <https://doi.org/10.5751/ES-05330-180231>
- Rogers, K.H., Roux, D. & Biggs, H., 2000, 'Challenges for catchment management agencies: Lessons from bureaucracies, business and resource management', *Water SA* 26(4), 505–512.
- Rountree, M.W. & Rogers, K.H., 2004, 'Channel pattern changes in the mixed bedrock/alluvial Sabie river, South Africa: Response to and recovery from large infrequent floods', in D.G. De Jalon & P. Vizcaino (eds.), *Proceedings of the fifth international symposium on ecohydraulics*, pp. 318–324, International Association for Hydro-Environment Engineering and Research, Madrid.
- Roux, F., Diedericks, G., Hoffmann, A.C., Selepe, M., Scherman, P. & Riddell, E., 2018, *Ecstatus of the crocodile river catchment, Inkomati river system, Phase II (2017)*, Report prepared for the Inkomati-Usuthu Catchment Management Agency, Mpumalanga Tourism and Parks Agency, Nelspruit.
- Roux, D.J. & Foxcroft, L.C., 2011, 'The development and application of strategic adaptive management within South African National Parks', *Koedoe* 53(2), Art1049. <https://doi.org/10.4102/koedoe.v54i1.1049>
- Roux, D.J., Murray, K. & Hill, L., 2010, *Learning strategy framework for the Inkomati Catchment Management Agency*, Water Research Commission, Pretoria.
- Roux, D.J., Nel, J.L., Cundill, G., O'Farrell, P. & Fabricius, C., 2017, 'Transdisciplinary research for systemic change: Who to learn with, what to learn about and how to learn', *Sustainability Science* 12, 711. <https://doi.org/10.1007/s11625-017-0446-0>
- Roux, D.J. & Nel, J.L., 2013, 'Freshwater conservation planning in South Africa: Milestones to date and catalysts for implementation', *Water SA* 39(1), 15. <https://doi.org/10.4314/wsa.v39i1.15>
- Russell, I.S., 1997, *Monitoring the conservation status and diversity of fish assemblages in the major rivers of the Kruger National Park*, PhD thesis, University of the Witwatersrand, Johannesburg.
- Schoeman, J., Allan, C. & Finlayson, C.M., 2019, 'Exploring the multiple meanings of adaptive management: A case study of the Lachlan Catchment in the Murray-Darling Basin', *Environmental Management* 64, 470–482. <https://doi.org/10.1007/s00267-019-01203-5>
- Smit, I.P.J. & Bond, W.J., 2020, 'Observations on the natural history of a savanna drought', *African Journal of Range and Forage Science* 37(1), 119–136. <https://doi.org/10.2989/10220119.2020.1723695>
- Stankey, G.H., Clark, R.N. & Bormann, B.T., 2005, *Adaptive management of natural resources: Theory, concepts and management institutions*, General Technical Report PNW-GTR-654, U.S. Forest Service, Pacific Northwest Research Station, Portland, OR.
- Stirzaker, R., Biggs, H., Roux, D. & Cilliers, P., 2010, 'Requisite simplicities to help negotiate complex problems', *Ambio* 39, 600–607. <https://doi.org/10.1007/s13280-010-0075-7>
- Stirzaker, R.J., Roux, D.J. & Biggs, H.C., 2011, 'Learning to bridge the gap between adaptive management and organisational culture', *Koedoe* 53(2), Art. #1007, 6 pages. <https://doi.org/10.4102/koedoe.v53i2.1007>
- Susskind, L., Camacho, A.E. & Schenk, T., 2012, 'A critical assessment of collaborative adaptive management in practice', *Journal of Applied Ecology* 49(1), 47–51. <https://doi.org/10.1111/j.1365-2664.2011.02070.x>
- Thoms, M.C., Rose, T. & Dyer, F., 2020, 'Riverine landscapes, water resource development and management: A view from down under', *River Research and Applications* 36(4), 505–511. <https://doi.org/10.1002/rra.3622>
- Tickner, D., Opperman, J.J., Bell, R.A., Acreman, M., Arthington, A.H., Bunn, S.E. et al., 2020, 'Bending the curve of global freshwater biodiversity loss: An emergency recovery plan', *BioScience* 70(4), 330–342. <https://doi.org/10.1093/biosci/biaa002>
- Todd, C. & Thirion, C., 2011, *Macroinvertebrate Thresholds of Potential Concern (TPCs) and Ecological Specifications (EcoSpecs) in the Sabie and Crocodile Rivers, Kruger National Park*, Unpublished Report.
- Van Coller, A.L., Rogers, K.H. & Heritage, G.L., 2000, 'Riparian vegetation-environment relationships: Complementarity of gradients versus patch hierarchy approaches', *Journal of Vegetation Science* 11(3), 337–350. <https://doi.org/10.2307/3236626>
- Varady, R.G., Scott, C.A., Wilder, M., Morehouse, B., Pablos, N.P. & Garfin, G.M., 2013, 'Transboundary adaptive management to reduce climate-change vulnerability in the western U.S. – Mexico border region', *Environmental Science & Policy* 26, 102–112. <https://doi.org/10.1016/j.envsci.2012.07.006>
- Vorosmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P. et al., 2010, 'Global threats to human water security and river biodiversity', *Nature* 467, 555–561. <https://doi.org/10.1038/nature09440>
- Webb, J.A., Watts, R.J., Allan, C. & Conallin, J.C., 2018, 'Adaptive management of environmental flows', *Environmental Management* 61, 339. <https://doi.org/10.1007/s00267-017-0981-6>
- Weeks, D., O'Keeffe, J., Fourie, A. & Davies, B., 1996, *A pre-impoundment study of the Sabie-Sand river system, Mpumalanga with special reference to predicted impacts on the Kruger National Park*, vol. 3, Report Number 294/3/96, Water Research Commission, Pretoria.
- Wenger, E., 1998, *Communities of practice: Learning, meaning, and identity*, Cambridge University Press, Cambridge. <https://doi.org/10.1017/CBO9780511803932>
- WWAP (United Nations World Water Assessment Programme/UN-Water), 2018, *The United Nations World Water Development Report 2018: Nature-based solutions for water*, United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris.
- WWF, 2020, *Living planet report 2020 – Bending the curve of biodiversity loss*, R.E.A. Almond, M. Grooten & T. Petersen (eds.), World Wide Fund for Nature (WWF), Gland.