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REPORT

Can collective action address the "tragedy of the commons" in groundwater management? Insights from an Australian case study

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Abstract

Co-management through local collective action appeals as a way of effectively responding to critical groundwater management issues, including groundwater quality degradation and pumping that lowers water tables. Co-management may also build sufficient trust for stakeholders to agree to investigate, and potentially implement, new opportunities for the use and management of groundwater resources. This paper examines the potential of collective action to underpin co-management and lead to improved groundwater management. The case study is the Angas Bremer (AB) irrigation district in South Australia, which provides a rare example of community-lead groundwater management since the late 1970s. The key questions were: (1) Was the AB an example of collective action, and did that spark successful co-management? and, (2) What were the key outcomes of collective action throughout the years? Data were gathered through semi-structured interviews with key stakeholders. By working together, and with government departments, AB irrigators successfully recovered an aquifer that was at risk of depletion and salinization. Drawing on this evidence, it is suggested that co-management through local collective action may be a useful option for those setting out to improve the social acceptability of new groundwater initiatives in farming landscapes, including managed aquifer recharge (MAR) and conjunctive use of surface water and groundwater.

Keywords Groundwater management · Australia · Collective action · Co-management · Millennium drought

Introduction

Groundwater represents almost 99% of all available freshwater on Earth and is a critical component of water supplies (FAO 2015), especially in arid and semi-arid regions, and during droughts (Bekkar et al. 2009). Access to groundwater is usually achieved through wells, and once the technology and energy are available, groundwater abstraction costs are typically low and mainly related to energy requirements (Schlager 2007). Population growth, industrialization and urbanization have substantially increased the demand for groundwater. In fact, the global groundwater abstraction rate has at least tripled during the past 50 years (WWDR 2015). Development of groundwater resources has come with high social and environmental impacts (Jakeman et al. 2016) and, indeed, economic costs related to regional groundwater quality and availability (Brouwer et al. 2018). In many instances, groundwater is being extracted much faster than aquifers are being replenished, to the extent that some aquifers can no longer be readily accessed or have been polluted by incursions of saline water (Werner et al. 2011), leading to important and sometimes irreversible impacts (Bekkar et al.2009).

In Australia, a 90% increase in groundwater use was reported between 1985 and 2000, and current pumping volumes are well above recharge rates (Jakeman et al. 2016). In many parts of the Murray-Darling Basin (MDB), Australia's foodbowl, aquifer overdraft has led to water-table declines, increased salinity, and reduced stream flows to wetlands (Jakeman et al. 2016), resulting in negative socio-economic and environmental impacts (Fienen and Arshad 2016). Aquifer overdraft typically

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increases pumping costs and, in some cases, drying up of wells, which negatively impact farmer's livelihoods and agricultural production (Schlager 2007).

The degradation of groundwater resources has been, at least in part, attributed to the reality that groundwater is a largely invisible (and seemingly abundant) resource, making it much more challenging to understand and monitor (Hammani et al. 2009). Indeed, the impacts of aquifer degradation can remain unrecognized for decades (Jakeman et al. 2016). Such timeframes extend well beyond those typically considered by policy makers and resource managers (Schlager 2007; Jakeman et al. 2016; Green 2016) and this has contributed to what is now widely recognized as a failure of governance (Skurray 2015; Foster and van der Gun 2016). Not surprisingly, there have typically been limited funds allocated for research or management of groundwater (FAO 2015; Re 2015).

At least some of these negative outcomes reflect the "tragedy of the commons" (Hardin 1968) as it applies to groundwater. Aquifers in the MDB typically extend across a region and, therefore, across many property boundaries and under those conditions, each aquifer can be considered a common-pool resource (CPR). As Olson (1965) and Hardin (1968) explained, CPRs are vulnerable to overexploitation because those accessing CPRs are likely to act as self-interested beings, maximizing their short-term interests by consuming the resource to their maximum capacity, even if that compromises the long-term sustainability of the resource or the socially optimum outcome. The apparent conflict between private and public interests in CPR governance has been linked to the "prisoner's dilemma" in game theory (Ostrom 2000). This dilemma explains that an individual is better off in the short-run if they choose not to cooperate with others, although cooperating ultimately leads to a mutually beneficial social outcome (Ostrom 2000, 2007). Applying her ideas in the fishing industry, Ostrom (2000) was able to demonstrate that collective action by stakeholders (i.e. those with a direct interest in the resource) can lead to governance arrangements that resolve the "tragedy of the commons". This report defines collective action, as "the action taken by a group (either directly or on its behalf through an organization) in pursuit of members' perceived shared interests" (Vanni 2014, p. 21). Co-management is defined as the sharing of responsibility and authority for the management of a resource between a government and local resource users (Pomeroy 1995). Both approaches can occur independently; however, this report draws on a case study where collective action was the foundation for co-management.

There is now a large body of literature confirming that local collective action can develop effective institutions and lead to more sustainable management of CPR (e.g. Wade 1987; Ostrom 1990; Baland and Platteau 1996; Agrawal 2001). Studies in Spain (Lopez-Gunn 2003; Lopez-Gunn and Cortina 2006; Esteban and Albiac 2012; Rica 2014), the USA (Cody et al. 2015), Philippines (Hearne 2014), China (Wang 2013), India (Kumar 2011; Sravanthi and Speelman et al 2015; Varua 2016), South Africa (Karar 2016), and Bangladesh (Afroz et al. 2016) have examined the implications of different institutional models of groundwater governance such as command and control, co-management and self-governance through water-user groups. Despite the existing literature examining the role of collective action in groundwater management, Mitchell et al. (2011), in their extensive review of social research examining groundwater governance, highlighted the limited extent of research examining collective action in Australia. Skurray (2015) and Baldwin (2008) examined examples of poor groundwater management and suggested that collective action and co-management were needed to achieve better outcomes in the future. Cuadrado-Quesada (2014) explored the role of participation and conditions for achieving sustainable groundwater governance and spatial planning, by comparing the Angas Bremer (AB) experience in South Australia (SA) with the Guacimo example in Costa Rica. Drawing on this comparison the author suggests, amongst other conclusions, that a sustainability crisis is likely to increase water user participation, however not exploring the role that collective action plays in successful co-management.

The interdisciplinary research here presented joints efforts between hydrogeologists and social researchers to address a complex but critical aspect of integrated groundwater management, answering calls by, for example, Silliman et al. (2008) and Barthel et al. (2017). The report focuses on the effectiveness of collective action in achieving more sustainable groundwater management and on links between collective action and co-management. The report therefore addresses an important gap identified by Mitchell et al. (2011) that remains to this time, using the AB irrigation district as the case study. AB irrigators have worked collectively to address groundwater sustainability issues and, with SA State Government support, were able to reduce groundwater extractions by 80% between 1978 and 2001 (ABRWM 2017). Importantly, the examination of the AB case study is timely from a policy perspective given the response of governments to the coal seam gas industry (i.e. bans on exploration placed in both New South Wales and Victoria largely as a result of concerns about risks to groundwater), and research identifying social acceptability concerns associated with opportunities for conjunctive use of surface and groundwater in landscapes where farming and environmental interests coexist (e.g. Ticehurst and Curtis 2019). This research confirms that institutional arrangements should involve affected communities in decision-making and that there is no "one-size-fits-all" solution for managing in different contexts.

Collective action and co-management

Command-and-control and market-based instruments have been the most commonly used approaches employed to improve groundwater governance (Steins and Edwards 1999; Skurray 2015). However, as Bekkar et al. (2009) point out, there is no direct relationship between groundwater management rules and behavior. When top-down policies conflict with local practice there is likely to be limited compliance with laws and regulations (Clark and Brake 2009). Over the past 20 years, water-policy reforms have embraced co-management (Mitchell et al. 2012), which involves the sharing of power between users and governments (Sen and Nielsen 1996). Co-management strengthens the motivation of local users to voluntarily contribute to management initiatives (Curtis et al. 2014). Being involved in the decision-making process, resource users have more information on the gravity of the issue, and hence are more willing to change their practices, leading to more successful outcomes in comparison to government legislation alone (Ross et al. 2008). Additionally, co-management, which emphasizes local organizations such as water-user associations (Lopez-Gunn and Cortina 2006), allows for the wealth of local knowledge to be understood and used to ameliorate management practices (Jakeman et al. 2016; Clark and Brake 2009).

According to Ostrom (2000), resource users, who engage in collective action and enforce some of their own rules, tend to manage their resource more effectively compared to when rules are imposed on them externally. Tang (1992) studied 47 irrigation systems around the world and Lam (1998) studied 100 irrigation systems in Nepal, and both concluded that community-managed irrigation systems performed significantly better than government-managed irrigation systems (Schlager 2007). For example, Lopez-Gunn (2003), and Esteban and Albiac (2012) concluded the sustainable management of the Western La-Mancha aquifer in Spain failed because it was based on command-and-control policies, where the government imposed strict management plans. In this case those imposed rules were violated by illegal groundwater pumping. On the other hand, the Eastern La-Mancha aquifer was managed through a collaborative approach (i.e. co-management), where community-based water-user associations were established and worked closely with government officials. This collaborative approach stabilized what had been declining water tables.

The concept of "stakeholder participation" is at the heart of the co-management regime. Although scientists and policy-makers tend to undervalue the importance of stakeholder participation in groundwater management, focusing more on technical challenges (Silliman et al. 2008), it is increasingly accepted that all those with an interest or stake need to be engaged (Ostrom 1990; Clark and Brake 2009; Lacroix and Megdal 2016) "in a process of dialogue, learning and action" (Mitchell et al. 2011, p. 3). Engaging stakeholders in this way incorporates the community's values in decisions, allowing for trust to be built between policy-makers, managers and those being affected by the policy or its implementation, consequently improving the government's accountability (Clark and Brake2009). Stakeholder engagement encourages mutual learning between water users, technical experts and policy-makers, allowing for a broad range of interests, knowledge and perceptions to be considered, ensuring all opinions are heard and dealt with before conflict arises (Curtis et al. 2016). Stakeholder engagement can also be expected to enhance social acceptability of policies and build long-term commitment amongst water users to rules and management practices (Clark and Brake 2009; Curtis et al. 2016). Despite the evidence of co-management benefits, efforts to implement co-management are not always successful. Adams (2015) concluded that failures of co-management are linked to (1) unequal distribution of power, (2) limited downward accountability of co-management leaders, (3) poor monitoring and local-rules enforcement, (4) low resource value, and (5) imposition of a co-management structure leading to "forced" participation.

Evidence suggests co-management is more successful if it evolves from collective action where users coordinate their activities, develop rules to monitor compliance and mobilize the required financial and human resources (Katon et al. 1999). Much of the success of collective action is therefore in engaging and building social and human capital (Afroz et al. 2016; Curtis et al. 2016). Human capital denotes the individuals' skills and capabilities, e.g. leadership, personality attributes, social skills, communication skills and intelligence. Social capital represents networks, social relations and trust that arises between people when interacting, as well as positive social norms. Typically, successful collective action initially draws upon locally evolved norms, the presence of community leaders and trust between stakeholders (Ostrom 2000); thus, human and social capital facilitate collective action, which in turn adds to the store of capital in a community (Mitchell et al. 2012).

Case study

The AB irrigation district, officially delineated by a prescribed well area (PWA) of around 250 km^2, is located 60 km south east of SA's capital of Adelaide and 30 km from the entrance of the Murray River to the Southern Ocean (ABRWM 2017; Fig. 1). The AB is at the lower end of the Murray-Darling Basin (MDB), which covers 14% of Australia's land mass. The MDB is Australia's food bowl, producing around 39% of the country's agricultural products by value (MDBA 2017a). Being at the lower end of the MDB makes AB irrigators (~160) especially vulnerable, as they have no control over water management occurring upstream. Furthermore, SA is the driest state in Australia (DEW 2017), which makes finding alternative water sources more challenging. The economy of the area is supported by a thriving wine industry that depends on irrigation water, largely pumped from groundwater,

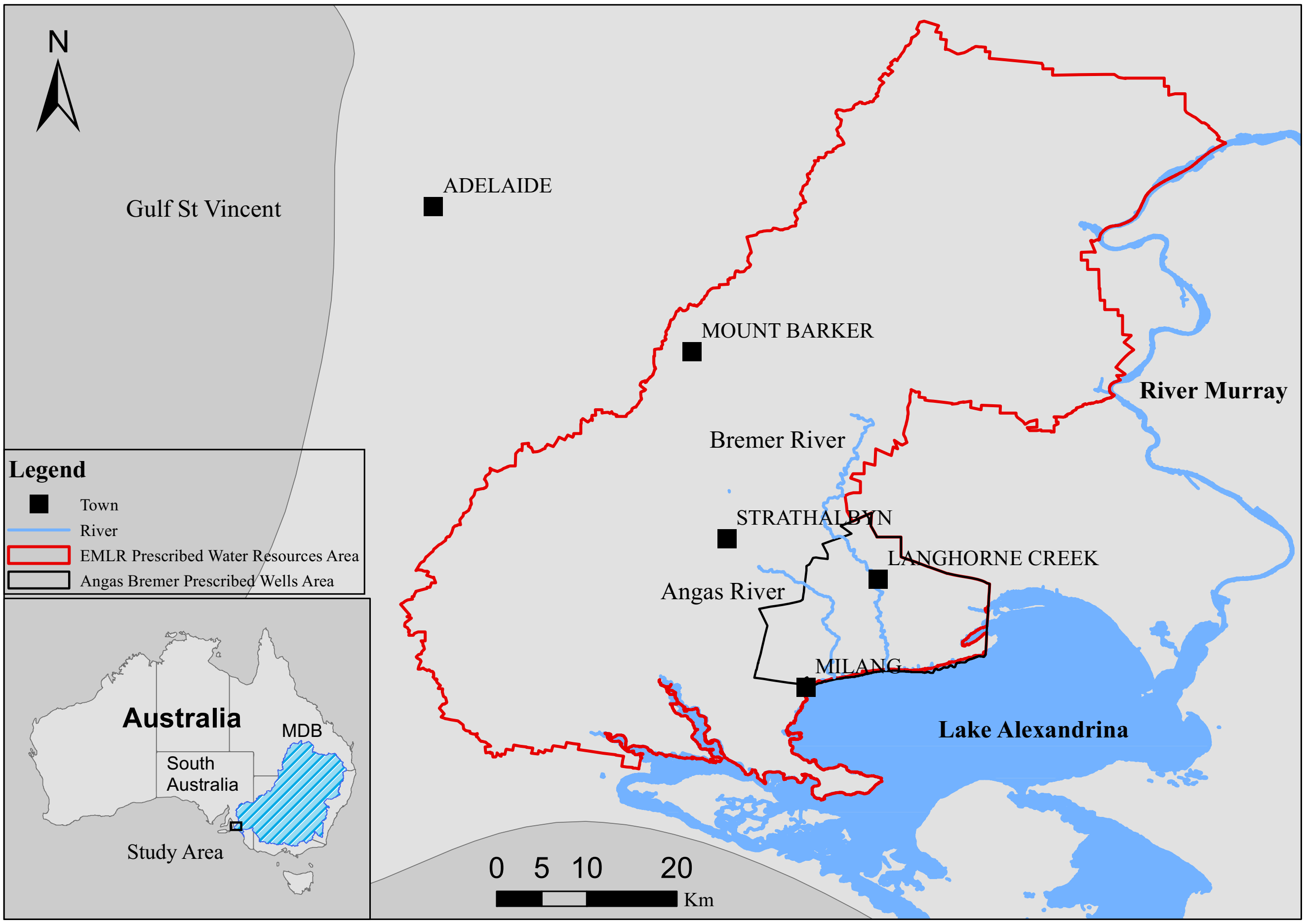

Fig. 1 Location of the study area – Angas-Bremer Prescribed Wells Area, within the Murray-Darling Basin (MDB)

although surface water has also been part of the management plans since the mid-1990s. The introduction of electrical pumps in the 1950s resulted in a large expansion in irrigation (mainly lucerne at the time) from the deep semi-confined Murray Group Limestone aquifer (MGLA), which is considered to be the main aquifer in the region, as described by Zulfic and Barnett (2007). The AB irrigators water 7,100 ha including 5,400 ha of wine grapes, 470 ha of lucerne pasture and 430 ha of potatoes (Thomson 2008). AB's main town is Langhorne Creek, which gives its name to a prime winegrowing region.

During the 1960s and 1970s, there was no control over groundwater pumping and, by 1981, the annual groundwater extraction in the AB had reached 26,600 ML, which was estimated to be four times the amount of annual natural aquifer recharge of 6,000 ML (Thomson 2008)—a clear example of a CPR facing the "tragedy of the commons". This level of extraction created a cone of depression in the semi-confined aquifer, and groundwater with higher salinity infiltrated the semi-confined aquifer (Howles 1994). The extent of overexploitation of the aquifer became evident to AB irrigators when the reduced quality and quantity of the groundwater was negatively impacting their crops (Cresswell and Gibson 2004).

The Angas and Bremer rivers (ephemeral rivers with a low salinity of >1,000 mg/L) rise from the Mount Lofty Ranges, cross the irrigation district, and discharge into the Lake Alexandrina, the terminal lake of the Murray-Darling system (Harris 1993). According to Cresswell and Gibson (2004), the region has a Mediterranean climate of hot, dry summers and cool, moist winters. Average rainfall ranges from 490 mm/year in the northwest at Strathalbyn weather station to 380 mm/year at Langhorne Creek weather station closer to Lake Alexandrina (Zulfic and Barnett 2007). Average evaporation is high throughout the year, with pan evaporation values of 1,600 mm/year in the north reducing to 1,150 mm/year at the coast (Cresswell and Gibson 2004).

The MGLA is a heterogeneous aquifer of 75–100 m thickness, constituted of fossiliferous limestone with sandy and marly interbeds, presenting both primary and secondary porosities (Zulfic and Barnett 2007). It has varying transmissivities of 100 m^2/day to the north of Langhorne Creek, 500 m^2/day in the southern part and 1,500 m^2/day in cavernous areas. The aquifer is used for irrigation because of its (1) low salinities of 1,500–3,000 mg/L in the central part near the rivers (although it increases up to 10,000 mg/L near the basin margins), and (2) high yields of up to 40 L/s, depending on the hydraulic properties of the aquifer (Zulfic and Barnett 2007). The MGLA is covered by a Quaternary layer, which forms a shallow, unconfined aquifer comprised of 10–35 m of sands, silts and clays. The Quaternary aquifer has low-quality groundwater (salinity ranges from 1000 mg/L along the rivers to 30,000 mg/L away from the rivers) and low yields (~5 L/s) when compared to the MGLA (Howels 1994). Zulfic and Barnett (2007) consider the MGLA to be recharged mainly through lateral recharge; however, some recharge occurs through vertical leakage from the overlaying Quaternary aquifer in the rivers vicinity. They consider direct rainfall recharge to be insignificant.

Data collection and analysis

Semi-structured interviews with key stakeholders were used to understand individual's perspectives and experiences with groundwater management. Individuals with knowledge of and first-hand experience with AB's water management between the 1950s and 2017 were targeted. Four main stakeholder groups were identified: (1) irrigators who were part of the Angas Bremer Water Resource Advisory Committee (ABWRAC, from now on referred to as the "AB advisory committee"), (2) members of the Government department responsible for water resources, (3) members of the regional Natural Resources Management (NRM) board, and (4) members of the Langhorne Creek Gape and Wine Association/industry groups. Interviewees were chosen through the snowballing technique—a process where a stakeholder group contact is identified and then invited to identify possible interviewees (Neuman 2014). Interviewee selection was also informed by the period and duration of involvement with AB's water management processes. In every stakeholder group, interviewees who have been involved with AB since the late 1970s up until 2017 were identified (Table 1). The sample size (14 interviewees) was determined through theoretical saturation—a point at which no new ideas relevant to the key questions emerged from the interview data (Neuman 2014). It is worth noting that the various departments responsible for water resources has changed structure and name numerous times throughout the years such as: SA Department of Primary Industries, SA Department of Mines and Energy (SADME), Department of Water Land and Biodiversity Conservation, and Department of Environment, Water and Natural Resources (DEWNR). During the final stage of editing this manuscript the name changed to Department for Environment and Water (DEW). For the sake of simplicity and brevity, "Government department" is used to refer to the department responsible for water resources in SA throughout this report, unless clearly stated otherwise.

All interviews were recorded digitally and transcribed verbatim using the F4 software. NVivo (version 10) a qualitative data analysis software package was used to manage and structure transcribed interview data. Interview data were then examined to identify themes and related concepts, a process known as coding (Burnard 2008). During coding, the researchers searched for interview passages that addressed (1) the level of participation in public meetings and the level of community involvement in the development of water-management policies, and (2) examples of outcomes of involvement such as the development of management plans, pipelines constructed and aquifer-recovery indicators.

Table 1 Interviewees list, including their stakeholder group and start year of involvement in Angas Bremer water resources management

Interviewee	Stakeholder group	Start of involvement
I1	Government department	2007
I2	Government department	~1980
I3	Government department	1990
I4	Government department	1985
I5	AB advisory committee	1980
I6	AB advisory committee	1970
I7	AB advisory committee	2004
I8	AB advisory committee	2011
I9	NRM	1999
I10	NRM	2003
I11	NRM	2008
I12	NRM	2006
I13	Industry	2002
I14	Industry	1990

Results

Figure 2 presents a timeline of the main groundwater management processes and outcomes, and a summary of the extent of collective action for the AB irrigation district from 1950 to 2017. Information in Fig. 2 and the notes below are structured around five distinct governance phases. The section begins with a summary of each phase. Quotes from interviews are included in the subsequent explanation of each phase to illustrate key points.

Phase 1: "tragedy of the commons" exposed and collective action begins

Phase 1 (1950–1979) corresponds to the start of groundwater pumping, and increased irrigator concerns over aquifer overdraft. It is characterized by low levels of collective action, with no-to-little government intervention. Phase 1 is an example of the "tragedy of the commons". During the 1950s, 1960s and 1970s there were no regulations and groundwater extractions increased rapidly. The beginning of collective action occurs towards the end of this phase when a few irrigators who realized that their crops were being negatively impacted by increased salinity, set up monitoring systems on their farms to provide monthly audits of both water-table depths and salinity levels. As noted by a Government department hydrogeologist:

> "Because they were concerned about it, in the 1960s, 8 to 10 people set up a system of measuring of bore water

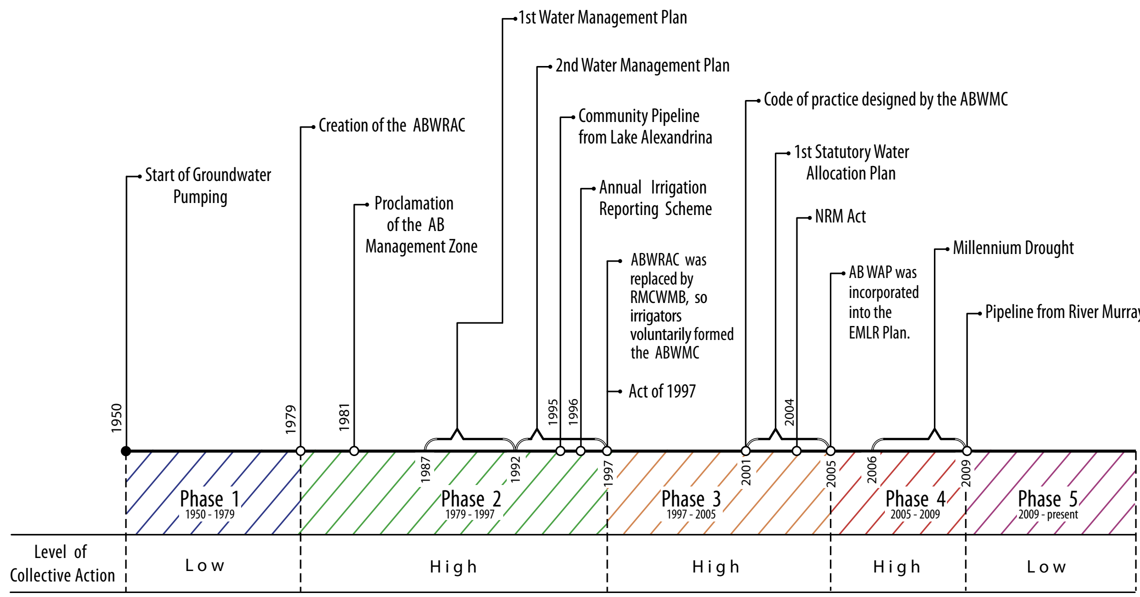

Fig. 2 Management-events timeline and level of collective action in Angas Bremer (1950–present)

> levels and salinity levels on a monthly basis. They did all that by themselves, nobody from the Government department was there at all."

Over time, irrigator concern about declining groundwater quality led to requests to government for investigation of AB groundwater resource condition (Harris 1993). As noted by an NRM officer:

> "My understanding is that they [irrigators] actually lobbied the government to do investigations down there."

The role of key community members has been crucial for mobilizing the AB irrigators as a collective, and being the driving force of the series of successful management reforms that followed in the later phases of AB's groundwater management. As stated by an NRM staffer:

> "They had very strong local leaders, who didn't see any boundaries of what they could achieve…as leaders they were well respected in the local environment."

Phase 2: the SA State Government agrees to co-management, and collective action leads to recovery of the aquifer and improved farm viability

Phase 2 (1979–1997) started with the creation of the AB advisory committee and finished with this committee being replaced by the River Murray Catchment Water Management Board (RMCWMB- from now on referred to as the "RM catchment board"), which was responsible for managing the Murray-Darling Basin within South Australia, a much larger area then AB. This was a period with a strong co-management regime between the SA State Government department and AB irrigators, as well as high level of collective action within the community. In response to evidence of aquifer decline, in 1979, AB irrigators (approximately 160 farmers) formed the AB advisory committee. The committee included irrigators and other stakeholders, including professional hydrogeologists, water managers and other specialists from SA State Government (Muller 2002). As stated by an irrigator:

> "It was a proactive movement by the community to try and control our own destiny."

AB advisory committee provided advice to the SA State Government and developed and executed water-management policies and plans (Muller 2002). Since there had been no restrictions on groundwater extractions, nor water licenses, the first step that the AB advisory committee took was to lobby for the area to be proclaimed as a water management zone (Howles 1994). That proclamation occurred in 1981 and meant that all irrigators had to purchase water licenses and comply with the requirements of the *Water Resource Act 1976* (Howles 1994). As noted by an irrigator member of the AB advisory committee:

> "… one of the first things we did was asking the Minister to proclaim the area in 1980. So, we proclaimed the area and everybody was metered [measured groundwater pumping]."

AB advisory committee then worked with the SA State Government department to successfully develop and implement the first two Water Management Plans (WMPs; i.e. in

1987 and 1992). These plans facilitated the reduction of groundwater extractions by imposing a 30% cut in groundwater entitlements and then enabling irrigators to access similar volumes of surface water from Lake Alexandrina. The logic behind moving to surface water was that the volume of surface water diverted was unlikely to impact Lake Alexandrina's ecology (Howles 1994). To achieve this change, AB irrigators had to privately fund and construct pipelines to transport water from Lake Alexandrina to the AB, As stated by an irrigator:

> "… two management plans were written in a collaborative way with the Government department. The first cut on groundwater extraction was 30%, so part of one of those later plans was that we had to encourage people to get water from the lake instead, which was quite close to a lot of irrigators. Irrigators needed an incentive, so one of the plans was that if you get the funds and do it yourself (get water from the lake) you'd go back to your initial water allocation, so you get that 1/3 back. That gave them the ability to go to the bank, get money and fund it for themselves. So, a number of them did that."

And by a SA State Government department hydrogeologist:

> "So, the main factor in the reduction of pumping water was say instead of using groundwater we can now access the water from the lake. So, people said 'ok we'll stop pumping groundwater and we'll pump from the lake'. And that's why there was loads of reduction because they transitioned. And the lake water quality is better salinity, so better quality for irrigating grapes."

The AB advisory committee also developed innovative strategies to encourage managed aquifer recharge (MAR) within the WMPs, using water from the Lake Alexandrina. The first of these initiatives provided irrigators with the right to extract 50% of the volume of lake water artificially recharged into the aquifer. The second allowed irrigators to roll over for up to 3 years any unused lake water stored in the aquifer (Thomson 2008).

At this time most AB farmers were growing lucerne and the returns from that enterprise were insufficient to justify the costs of constructing a pipeline to the farms not adjacent to the lake (Harris 1993). This all changed with the 1990s wine-industry boom, when the price paid for wine-grapes increased from 400 to 1,000 \$/t. Between 1986 and 2002 the area of lucerne in the district fell from 2,000 to 500 ha, and the area of grapes increased from 400 to 5,400 ha (Thomson 2002). And grapes require much less water (~2.5 ML/ha) compared to lucerne (~10 Ml/ha). As a result, many irrigators switched to grapes and were able to justify the costs of piping water up to 14 km from Lake Alexandrina. Those with surplus water were able to trade water (Muller 2002). In 1995, 42 growers formed the Langhorne Creek Water Company, which designed, financed and built a community pipeline from Lake Alexandrina (ABRWM 2017). As stated by an AB irrigator:

> "And then the Langhorne company was formed by the idea that some of us that are further back [away from Lake Alexandrina] can't do it individually. That was when the water company was formed and put one big pipeline funded communally, something like 23 people, where a number of community members put their own funds into raise \$2.3 million and put a community scheme in."

The ability to (1) swap groundwater for surface-water licenses and (2) trade surplus water were key policies that facilitated the recovery the aquifer, because the irrigators' private economic interest was not compromised. Increasing surface-water irrigation, instead of groundwater, had positive impacts by replenishing the MGLA, which recovered to predevelopment levels (Zulfic and Barnett 2007). However, using surface water for irrigation increased the risk of waterlogging and root-zone salinity. To mitigate this risk, in 1996 a group of concerned irrigators developed a voluntary, privately funded reporting scheme known as the Irrigation Annual Report. Each participating AB irrigator installed a 6-m-deep well to monitor and then reported the aquifer's salinity and water-table levels (Muller 2002). Public meetings and workshops were held each year to present and analyze those data, including the effects of imported Lake Alexandrina water (Muller 2002). As noted by an AB irrigator:

> "And one of the things that we did was each irrigator put in a well to monitor the groundwater that was coming up in the root zone. And I think they had to measure that 4 times a year as part of their annual reporting project, but of course the individual farmers once they had the wells they would do more monitoring ….See, that didn't happen in any other areas of the state."

Phase 3: collective action and co-management continue under administrative changes

Phase 3 (1997–2005) began with the formation of the Angas Bremer Water Management Committee (ABWMC; from now on referred to as the "AB management committee"), a community-based voluntary committee to support the recently formed a government-based RM catchment board, and concluded with the integration of the AB Water Allocation Plan (WAP) into the Eastern Mount Lofty Ranges (EMLR) NRM board. During this period the co-management regime established in phase 2 remained, and a high level of collective action continued. With the new national *Water Resources Act of 1997*, a formal WAP had to be developed for the AB irrigation district, which would replace the former WMP developed by AB advisory committee. In accordance with the new legislation, the RM catchment board replaced the AB advisory committee (Muller 2002). The RM catchment board was responsible for the development and the implementation of the WAP 1997–2002, meaning that the AB advisory committee no longer had a clear role in developing the new WAP (Muller 2002). Despite these changes, and as is explained in the following, both collective action and co-management continued.

The community still wanted a voice in policy development, thus they created the voluntary group AB management committee, consisting of local irrigators, technical staff from the SA State Government department and RM catchment board. This new partnership between the AB management committee and the RM catchment board ensured that innovative policies were being developed and implemented "in a technically robust manner whilst remaining under community ownership" (Muller 2002, p. 3). For example, the AB management committee introduced the AB Code of Practice (CoP) in 2001, where all AB irrigators were required to (1) plant 2 ha of native vegetation for every 100 ML of water entitlement to prevent waterlogging; and () install the FullStop device—a wetting-front detector that monitors root-zone salinity (Muller 2002). The CoP was funded and managed by the irrigators and became a legal requirement as part of their water license. This provides an example of grassroots level collective action that aided in improving groundwater management (ABRWM 2017). As stated by an SA State Government NRM staffer:

> "It is unlikely that a Government body could have implemented such rigorous policies so rapidly without community leadership and involvement. The successful development and implementation of the CoP has required the cooperation of all 160 irrigators in the region and is admirably administered by the AB management committee."

The relationships developed through collective action and co-management not only allowed for information to be shared, encouraging mutual learning between users, managers and policy-makers, but also built trust between those stakeholders. Strong leadership by community leaders facilitated coordination and organization within the community, as well as helped build networks and trustworthy relationships (social capital) with formal institutions. As stated by an AB irrigator:

> "Communities don't trust Governments… and don't trust anything that takes money off them. You've got to build the bridge, Governments can't build bridges… You need the locals to help build the bridge."

A key outcome from 20 years (1981–2001) of co-management arising from collective action was the reduction of groundwater extractions by 80%. This, together with MAR, returned the groundwater and salinity levels to approximately their predevelopment levels, whilst simultaneously increasing farmers' profitability (Muller 2002). As quoted by an AB irrigator:

> "Well, we saved our resource."

Phase 4: NRM reduces co-management but the millennium drought promotes collective action

Phase 4 (2005–2009) started with the integration of AB WAP into the EMLR catchment area and concluded with the end of the Millennium drought that affected much of eastern Australia for almost a decade. During this phase, the AB community successfully lobbied for the government to fund a pipeline to bring water from the Murray River to AB. This was a period in which co-management was weaker as the NRM board was heavily involved in AB's water management. However, collective action remained at a high level largely as a response to the crisis created by the Millennium drought. In 2004, the SA State Government introduced the *NRM Act 2004* recognizing that all natural resources (i.e. water, land, soil, fauna and flora) interact with each other and hence need to be managed as an integrated whole. This change in legislation meant that in 2005, the AB PWA was incorporated into a much larger management area, the EMLR (Fig. 1; EMLR WAP 2013). Regional NRM boards were established as a state-level advisory body and were responsible for the preparation of the WAPs (EMLR WAP 2013) encompassing the whole of EMLR region.

NRM boards were expected to work with local committees and key stakeholders (Cuadrado-Quesada 2014); however, the AB community was much less involved in the development of the new plans as they now incorporated a much wider area than the AB, leading to a loss in local relevance. Phase 4 is characterized by the work of the NRM boards, as well as the Millennium drought, which was particularly severe during 2006–2009.

Despite this important change in governance structures, which weakened co-management, the AB irrigators were facing a major crisis (i.e. the Millennium drought) and this motivated the community to act collectively. As a result of the Millennium drought, reduced flows from the River Murray lowered water availability and increased water salinity in Lake Alexandrina making the water unsuitable for irrigation. The AB community effectively lobbied for the construction of a government-funded 110-km-long pipeline to pump water directly from the River Murray (rather than from Lake Alexandrina). As noted by an AB irrigator:

> "The Government put a pipeline and it worked well. That held it all together."

Interestingly, the pipeline construction was only completed after the end of the drought, which means it did not help during the drought, but it serves as a safeguard for a future water crisis. As stated by an NRM staffer:

> "They've [AB community] almost drought proofed themselves in a way, so initially a lot of this work was done on the back of groundwater obviously becoming too salty, so now they have access to better quality water through the river, they've also got pipelines from the lake. During the drought the lake water was either too far out to get to or was too salty, so that motivated them [AB community] to go to the river pipeline with better quality water. We've sort of nailed the salinity problem, we've got access to better quality water …"

Phase 5: regional NRM takes effect and collective action declines post-drought

Phase 5 (2009 to present) started with the pipeline connecting the River Murray to AB and the end of the drought, and is the current phase. This is a period of low co-management and low collective action, in which there have been no significant changes in water governance. According to most of the interviewees, collective action has declined significantly since the end of Millennium drought. An NRM officer emphasizes the fact that the AB management committee is currently weaker, linking that to an absence of a present water crisis. The officer also assumes that the AB is drought-proofed by the construction of the pipeline directly from the River Murray (as noted in phase 4), which leads to the belief that there are no more concerns about (ground) water security in AB, as quoted in the following:

> "The group has struggled over the last few years with membership. I think one of the issues now with the AB is not really an issue - they've almost drought proofed themselves in a way."

The extent of collective action has also been impacted by a lack of funding from the NRM board, which has undermined the viability of the AB management committee. As stated by an irrigator:

> "The Government sort of gone a lot hands off with groundwater management in AB. Monitoring and data collection has decreased significantly."

And stated by an NRM officer:

> "Recently they [AB management committee] put out their 2015/16 irrigation annual report, which they get funded by the NRM to do. In the past they [AB management committee] might have been pretty assured of getting it and now it's a bit of a battle. But the other thing that's changed too is that the AB's groundwater resource was prescribed long before the rest of the Eastern Mount Lofty. And that's now been incorporated into that. So instead of being a stand-alone WAP, it's now part of the Eastern Mount Lofty, which means that some of the monitoring requirements at the broader scale are not as detailed as what the AB collects."

Some interviewees have stated that the AB is now 'drought-proofed'. Interestingly, two members of the AB management committee, who have been involved in the committee since its beginning, have a different perspective. They consider the current period without a crisis should be used to prepare the region for future crises. One of the committee members comments as follows:

> "I said now what we should be doing is what would happen next time there is a drought and the lake dries up, we should start working now on what we are going to do. Work with the department, set it up now, and pull it out of the shelf when we need it. And I was thinking of banking [MAR] – establish some sort of water bank, encourage people to [artificially] recharge. I had this idea that AB could move with the Government department towards that area, do a 'what-would-happen' plan. And start that before we got in big trouble. That would have been great work for the committee but it didn't happen because it wasn't in the national water plan, so the NRM couldn't do it."

Discussion

The AB case study provides important empirical evidence to support the claim of Mitchell et al. (2012) that co-management is more effective when underpinned by local collective action. The results from the AB case study also support Lopez-Gunn (2003) and Esteban and Albiac (2012) who conclude that collective action can lead to aquifer recovery. Indeed, almost all interviewees (13/14) said that AB aquifer recovery was at least in part a result of the community driving policy and planning facilitated by key community leaders. In AB, collective action provided the foundation for effective collaboration (i.e. co-management) between AB irrigators and the SA State Government department. The AB community lobbied for the region to be proclaimed as a water management zone in which allocation limits were set, proposed reducing of extraction limits, promoted MAR as a proactive management approach, proposed the plantation of native vegetation to prevent waterlogging, and actively engaged in management discussions with the government department. Additionally, the AB community developed a very robust system of monitoring and reporting, which assisted the community and the SA State Government hydrogeologists to develop and share a common understanding of groundwater degradation. Re (2015) defends a similar approach to improve knowledge and effective management of groundwater systems. As Ostrom (1992, 2001) explained, a shared understanding of the nature and condition of a natural resource is critical for effective management of CPR. According to Ostrom (2001, p. 9), "the capacity of users to create their own rules, and establish the means of monitoring, constitutes a key factor that helps individuals to solve their collective-action problems".

In addition to creating a shared understanding of the resource, this collaboration enabled trust to be built. Trust is a critical element of social capital and an important ingredient in successful co-management, and is essential for public participation as it determines the acceptability of management policies (Sharp and Curtis 2014; Meinzen-Dick et al. 1999). DeVos (2011) emphasizes that collective action is not only a matter of constructing strong institutions, but also a matter of building trust between the government and users, as well as trust amongst users. AB is traditionally a small homogenous community, where trustworthy relationships between irrigators have been well established, cemented and maintained due to frequent and highly personalized interaction, increasing the willingness of irrigators to work together. Being a small groundwater basin when compared to national-scale groundwater systems (e.g. Great Artesian Basin and MDB), with strong leaders, was a key factor in building social capital, but also in the ability to enforce rules and avoid free-rider problems through peer pressure. Furthermore, the small size of the basin allowed irrigators to initially notice the direct impact of their lack of groundwater management, and later on observe the positive impacts of their changed water management practices.

However, the co-management regime, which allowed information sharing and collaboration between irrigators and government officials, bridged the gap between users and managers. This collaboration (i.e. co-management) involved direct, in-person and on-going interactions between AB irrigators and SA State Government officials, which in turn helped to build the trust that ultimately permitted effective changes in groundwater management to be implemented.

Lopez-Gunn (2012) and Cuadrado-Quesada (2014) have suggested that trustworthy relationships between users are necessary but not sufficient for effective groundwater governance, arguing that collective action is not possible without the support and collaboration of formal institutions. Although collective action in AB emerged independently of formal institutions in the early phases, the creation of the management plans and the changes in policy (i.e. swapping groundwater licenses for surface-water licenses, and trading water surplus) would have not been possible without the effective collaboration with the Government department. The Government department provided funds for ABWRC activities, provided technical advice, promoted a collaborative environment, and allowed the ABWRC to have an active role in the creation of WMPs and to participate in decision-making. Ultimately, this contributed to an effective co-management regime (which capitalized on local collective action) from 1979 to 2005 during phases 2 and 3 (Fig. 2). In fact, Ostrom (2001) emphasized the importance of enabling resource-users participation by giving them decision-making authority. Ostrom (2001, p. 16) explained that the opposite approach, in which agencies deny users the opportunity for self-organization, "… destroys an immense stock of social capital". Such an outcome may not be evident in the AB case study, probably due to the absence of a water crisis, but it is possible that contemporary polices and arrangements will have such outcome. Indeed, phases 4 and 5 are characterized by low co-management levels, and phase 5 by low collective-action levels (Fig. 2). Some interviewees argued that currently, with the incorporation of AB into the EMLR region, the committee's influence in decision-making has decreased, which has led to the lowest levels of collective-action in decades. This resulted in the AB management committee shrinking in size and in participation, and therefore in its capacity to contribute to groundwater management.

Collective action engages and helps develop social and human capital that enhances the capacity of a community to meet future challenges (Ranjan 2014), which was found in the AB community in terms of groundwater management. For example, the networks established through earlier collective action in the AB enabled irrigators to respond to the Millennium drought by lobbying for the construction a 110-km-long pipeline to directly access water from the River Murray. However, the results show SA Government agencies and community do not appear to be preparing for future droughts, which is an unfortunate example of the hydro-illogical cycle, a process described by Silverman (1978) and Wilhite (2011), who build on earlier observations by Tannehill (1947). The hydro-illogical cycle is an approach to water management in which water managers and/or users react in a panic mode to crises (e.g. droughts, floods), but do not take proactive actions during periods of no crisis to be prepared for the next emergency period. This is in accordance with Margerum (2007, p. 149) who states "in an era of declining management resources, it is difficult for agencies to put resources toward long-term preventative efforts when there are immediate, short-term demands". During phase 5 in AB, resourcing shifted towards the more pressing issues of NRM boards managing natural resources holistically (e.g. securing environmental flows in rivers, establishing flood levies, promoting irrigation efficiencies, providing for vegetation health and preserving biodiversity). This meant that the EMLR NRM Board, which was the chief provider for the AB committee, started to substantially and continuously reduce its funding towards the committee, which in turn led to the reduction in monitoring data and regular contact with on-ground technicians, hindering collective action within AB. Some interviewees argue that recent arrangements established by the SA State Government agencies, as part of wider approaches to co-management of natural resources, are undermining the capacity and commitment of AB irrigators to continue investing in measures such as MAR to keep the aquifer in good state, and to be prepared for future droughts. In a related study of another irrigation district in the MDB, Ticehurst and Curtis (2019) identified several MAR options that on initial analysis would achieve more agricultural production with less water. However, there were concerns about the extent the most viable MAR options would have third-party impacts (e.g. ability of others to pump groundwater) or negative environmental impacts (e.g. on groundwater dependent ecosystems). The authors concur with Ticehurst and Curtis (2019) that the social acceptability of the most viable MAR opportunities would be enhanced if local people were engaged in decision making and future management of the resource through collective action.

Conclusions

Collective action that underpinned co-management of groundwater resources in AB led to significant changes in governance and on-farm management that have in turn materially improved livelihoods and resource condition. The AB community of irrigators, working together with the SA State Government department, achieved (1) an 80% reduction in groundwater pumping by trading groundwater licenses with surface-water licenses, (2) a change in crops from lucerne to wine grapes, which meant a much higher profit and a lower water consumption, (3) aquifer recovery in terms of reduced salinities and raised groundwater levels through reducing abstraction and implementing MAR, and (4) construction of pipelines from Lake Alexandrina and River Murray, which are believed to increase water security for the region.

This study confirms that co-management can be successful when it starts from a community level through collective action. The AB community initiated the co-management process by (1) requesting for the Government department to conduct hydrological investigations in the area, (2) forming the AB advisory committee, followed by the AB management committee, and (3) lobbing for the area to be proclaimed as a water management zone in which limits to allocations were to be imposed. This high level of organization and collective action, underpinned by charismatic and dedicated community leaders, allowed the community to have a strong voice in water-management decisions, including drafting WMPs and WAPs. This is consistent with the literature that argues that when local stakeholders are involved in decision-making processes, they take ownership of the problem and are more likely to accept, comply with and contribute to management policies. On the contrary, if government departments are not collaborative, the effectiveness of community collective action leading to co-management is compromised. The results of this study show that during the phases when community collective action was high, groundwater management was more successful with more and better outcomes, as opposed to the phases where collective action was low. Currently (phase 5), the environmental management focus has shifted away from groundwater, which poses a serious risk for the future in the case of water crisis (e.g. droughts) in the region.

Although the consideration of local conditions is at the core of legislation such as the WAPs, this report shows that the current engagement process between government agencies and local users needs significant improvement to be efficient, which has been the case in the past. Even though the AB irrigators have not only recovered the aquifer but also increased water security by diversifying their source through a pipeline from River Murray, it does not mean that either the community or the Government department have sufficiently learnt lessons from this successful case. The pipeline may have provided short- to medium-term security; however, the AB community is dependent on MDB management occurring upstream, over which they have no control. In fact, there are recent reports of illegal and uncontrolled water extractions in the MDB, "…disadvantaging downstream communities and expropriating environmental water" (MDBA 2017b). The risk of upstream over-extraction is aggravated by unprecedented climatic conditions linked to climate change, and as such, the AB community and government departments should plan for more severe climatic scenarios, and continue investing in measures to adapt to drier seasonal conditions (e.g. MAR, conjunctive management and monitoring). Keeping the aquifer in a good state to respond to future drought sis currently not being promoted due to low levels of collective action and co-management. Consequently, this research provides valuable lessons for contemporary NRM policy makers. Co-management through local collective action may be a powerful option for those setting out to improve the effectiveness and social acceptability of new groundwater initiatives in farming landscapes, including MAR, reduction of allocations and diversification of water sources.

Although this report illustrates the positive role of collective action in underpinning successful co-management of groundwater resources, research questions related to the topic remain, both in the AB irrigation district and globally. Those questions include (1) What factors facilitate or impede collective action?, (2) Are the biophysical measures of the outcomes of collective action consistent with stakeholder perceptions of outcomes? and (3) What processes are most likely to enable long-term thinking by governments and stakeholders as they respond to or anticipate climate-change scenarios?

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