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Analysis

An ecosystem services approach to estimating economic losses associated with drought

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ABSTRACT

A consistent methodology enabling the estimation of the economic losses associated with drought and the comparison of estimates between sites and across time has been elusive. In this paper, we develop an ecosystem service approach to fill this research gap. We apply this approach to analysis of the Millennium Drought in the South Australian portion of the Murray–Darling Basin which provided a natural experiment for the economic estimation of hydrological ecosystem service losses. Cataloguing estimates of expenditures incurred by Commonwealth and State governments, communities and individuals, we find that nearly \$810 million was spent during the drought to mitigate losses, replace ecosystem services and adapt to new ecosystem equilibria. The approach developed here is transferable to other drought prone regions, providing insights into the potentially unexpected consequences of drought and ecosystem thresholds and socioeconomic and political tipping points after which ecosystem restoration may become very costly. Our application to the South Australian Murray–Darling Basin demonstrates the potential of this approach for informing water, drought preparedness and mitigation policy, and to contribute to more robust decision-making.

1. Introduction

The ecosystem services literature provides frameworks for cataloguing the multiple services provided by natural systems (Costanza et al., 1997; Millennium Ecosystem Assessment [MEA], 2003; The Economics of Ecosystems and Biodiversity [TEEB], 2010). These frameworks classify services as provisioning, regulating, habitat and cultural and amenity services. This paper is concerned with hydrological ecosystem services, the benefits that people derive from freshwater resources (Brauman et al., 2007), and how their supply was impacted by Australia's Millennium Drought (1997–2010).

Droughts affect more people than any other natural hazard (Wilhite, 2000) and can have severe and direct impacts on hydrological ecosystem services, for example affecting the supply and quality of water resources for municipal, industrial and agricultural use (Brown et al., 2002; Covich, 2009; Rosegrant, 1997). Droughts can also have important indirect effects, for example reduced water supply may force industrial users to reduce economic output thereby negatively affecting downstream industries (Mysiak and Markandya, 2009). Competing with these consumptive uses, riparian, wetland, and estuarine ecosystems require water to sustain them and the hydrological ecosystem services they provide.

Valuing natural capital in an ecosystem services framework can improve planning and decision-making (Daily et al., 2009) and enable more robust assessment of the ecological, socioeconomic and cultural trade-offs of ecosystem service loss (de Groot, 2010). Evaluating historical experiences of drought is one method to identify and estimate costs of hydrological ecosystem service losses. Greater understanding of drought impacts on ecosystem services can inform water reform, underpin efforts to support drought planning and adaptation (Covich, 2009), and provide a basis upon which budgets for mitigation and disaster assistance strategies may be prepared (Ding et al., 2010; Hayes et al., 2004; Mysiak and Markandya, 2009; Rose, 2004).

Evaluation of drought may reveal ecosystem sensitivities and thresholds: tipping points between two stable ecosystem states (Salt and Walker, 2006); and cascading or cumulative effects that may occur with ecosystem degradation (Kinzig et al., 2006). In addition to ecosystem thresholds, historical analysis of drought may reveal socioeconomic and political tipping points. A socioeconomic tipping point may be reached when, for example, agricultural losses result in crop insurance claims or prompt a community to lobby political representatives for support. A political tipping point may be associated with a biophysically-based trigger for policy response, for instance a water quality threshold. Better understanding of, and managing for, ecological thresholds and socioeconomic and political tipping points can provide water resource policy makers and managers with new information to avoid costly ecosystem degradation and tipping points.

Despite the importance of information on thresholds and tipping points, standard methodologies for estimating drought-induced hydrological ecosystem service losses are rare (Hayes et al., 2004). Considering the relatively lengthy duration of droughts, the slow pace at which they proceed and their spatial extent, quantification of associated economic

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impacts is complex (Ding et al., 2010). Furthermore, droughts differ from other natural hazards in that they often lack conspicuous disaster impacts (Hayes et al., 2004). However, in fully-allocated river basins such as the Murray–Darling, there can be observable drought-related ecosystem degradation (Crossman et al., 2011; Kingsford et al., 2011).

In this paper, we develop an approach to cataloguing and estimating the hydrological ecosystem services losses associated with drought. We demonstrate this approach using an ecosystem service framework combined with evaluation of thresholds and tipping points in the South Australian Murray–Darling Basin (SA-MDB). The case study provides specific estimates of ecosystem service losses, ecological thresholds and socioeconomic and political tipping points, which can inform water, drought preparedness and mitigation policy in the SA-MDB. In particular we focus on retrospective assessment of ecosystem service losses that are revealed through directly observable defensive, mitigation, rehabilitation expenditures and damage costs. The approach can be applied more generally where there is information on these costs.

In the case study we find that the approach developed provides a useful organizing principle for cataloguing and quantifying the economic impacts of hydrologic ecosystem service losses associated with drought as well as the identification of ecological thresholds and socioeconomic and political tipping points that trigger a societal response. The estimates generated here should be interpreted carefully, however, since they are not measures of economic welfare rather they are an estimate of the costs of drought-induced hydrological ecosystem service losses. Still, we find that studying the magnitude and timing of such costs retrospectively has the advantage of revealing place-specific thresholds and tipping points that may not otherwise be evident.

Following the introduction, a brief description of the study area is provided. Next, the methods section presents the conceptual underpinnings of ecosystem service analysis, the typology used to classify drought impacted ecosystem services, and the approach to estimating the costs incurred as a result of ecosystem service losses. The fourth section provides estimates of expenditure by ecosystem service type. In the discussion section we highlight the strengths and limitations of the approach. The paper concludes with some lessons learned in the application of the approach to the case study of the SA-MDB.

2. Study Area

Our study is focussed on the South Australian portion of the Murray–Darling Basin (Fig. 1), the outflow sub-catchment of the Murray–Darling Basin (MDB). The MDB occupies one seventh of the Australian continent and is multi-jurisdictional with portions of the watershed in the States of South Australia, Victoria, New South Wales, and Queensland, as well as the Australian Capital Territory. The country's longest rivers are located in the basin, namely the Darling, the Murray and the Murrumbidgee Rivers, and 2.1 million people (10% of the Australian population) reside in the MDB.

Both dry land and irrigated agriculture are economically important activities, accounting for 10% of employment in the MDB. The MDB contains 65% of Australia's irrigated agricultural land (ABS, 2008). Perennial and annual horticulture and rice are important irrigated crops in the southern basin (MDBA, 2010a). Irrigated agriculture's share of total consumptive water use in the MDB was 83% in 2004–05. The MDB also has important social (Bark, 2011; Bryan et al., 2011), cultural and indigenous (Jackson et al., 2010; Weir, 2009) and environmental values (Hatton MacDonald et al., 2011; Tapsuwan et al., 2012).

Since the 1930s, the volume of water extracted from the basin increased from 3000 gigalitres (GL) to 11000 GL in the 1990s (MDBA, 2010a). This growth in consumptive demand coincided with a time of high average inflows. The most recent drought, the Millennium Drought, was the most severe drought in recorded history (Potter et al., 2010), with water availability in the southern basin reduced to less than 40% of the long-term average by 2006–07 (MDBA, 2010a). As the drought deepened, storages were drawn down, irrigation water allocations declined to record lows (Kirby, 2011) and States temporarily suspended their water sharing plans (NWC, 2009).

Long-term over-allocation of water resources combined with inadequate adaptive drought management practices resulted in cascading spatial and temporal freshwater ecosystem degradation (Chiew et al., 2010; CISRO, 2012; Crossman et al., 2011; Kingsford et al., 2011). Examples of freshwater-dependent ecosystem degradation were standwide death of river red gums (MDBC, 2003), the formation of acid sulphate soils (Baldwin, 2011a), subsidence and river bank slumpage, hypersalinity in the lagoon complex situated at the terminus of the River Murray (Kingsford et al., 2011; Lester and Fairweather, 2011; Overton et al., 2010), and the siltation of the mouth of the River Murray (Webster, 2010).

Responding to the crisis, the Commonwealth and South Australian governments took defensive and mitigation measures as the Millennium Drought progressively deepened. These agencies commissioned studies on damage costs and preventative measures, and recorded expenditures. The declaration of riverbank collapse as a State hazard by the SA State Emergency Management Committee and the subsequent institution of South Australia's Riverbank Collapse Hazard Program is one such example.

3. Methods

The methods developed here involve three components. The conceptual framework underpinning the approach is the concept of ecosystem services cascades. The second component is the ecosystem service typology which enables the classification of ecosystem services. Third is the approach to estimating the costs incurred as a result of ecosystem service losses.

The concept of ecosystem service cascades (Fig. 2) was developed in Haines-Young and Potschin (2010) and modified in TEEB (2010). The core notion is that ecosystems and biodiversity are linked to human well-being and a cascade links the system components of the ecosystem service production chain. In this paradigm, structures and processes give rise to specific ecosystem functions which are physical, chemical or biological in nature (de Groot, 2010), and contribute to human well-being (Haines-Young and Potschin, 2010).

For example, a riparian ecosystem is an ecological structure. A key function of this system is the provision of shade to maintain a stable water temperature while one of the services this function provides is habitat for fish. The fish produced in this ecosystem provide recreation and food benefits to anglers. Governance arrangements influence how, when, and which fish may be harvested. These arrangements impact the management of the ecological system and therefore its functions. The ecosystem services framework relies on ecological, socio-cultural or economic metrics by which the impacts of ecosystem services on well-being are gauged. A distinction is made between the benefits of an ecosystem service and any monetary value placed on it. Ecosystem service benefits can be estimated by various environmental valuation techniques or may not involve the calculation of monetary value (Haines-Young and Potschin, 2009).

To enable classification and systematic analysis of ecosystem services, de Groot et al (2010) developed a typology which specifies the relationship between ecosystem structures, processes, functions, services and well-being.[1] This typology was later adapted by TEEB (2010) and is the classification system applied in this paper (Table 1). The first column of Table 1 presents the ecosystem processes which underpin the ecosystem services listed in column two. There are four main categories of ecosystem services: provisioning, regulating, habitat, and cultural and amenity services. Earlier typologies including that of the Millennium Ecosystem Assessment (2003) included supporting services, which

[1] See TEEB (2010) for a discussion of early developments in ecosystem services frameworks.

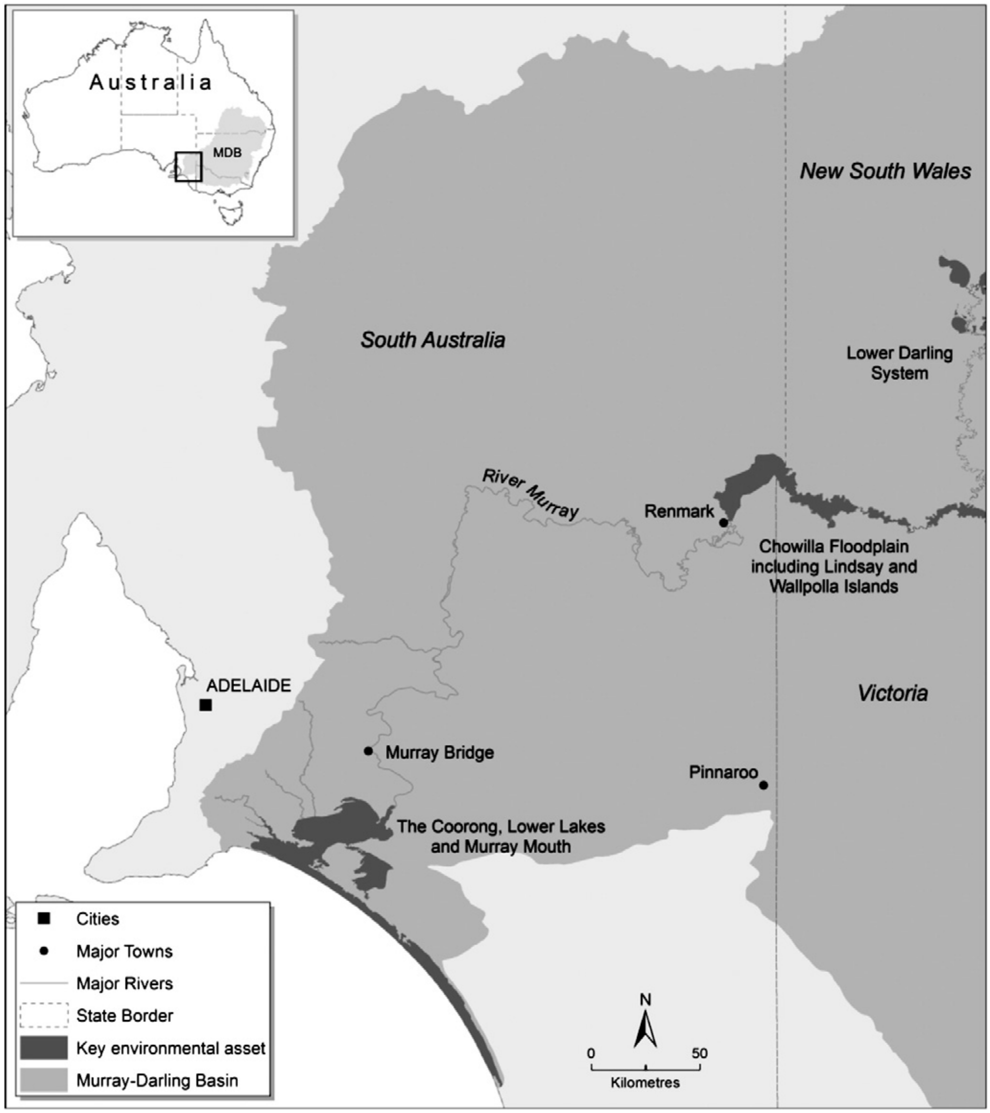

Fig. 1. The South Australian Murray–Darling Basin.

were a class of processes such as soil formation and nutrient cycling. This class was found to be problematic as it presented the risk of double counting (Boyd and Banzhaf, 2007; Fisher and Turner, 2008; Hein et al., 2006; Wallace, 2008). The third column lists possible ecosystem service valuation techniques (Farber et al., 2006). Cost-based methods, namely defensive expenditure, mitigation expenditure and damage cost methods were applied in the case study. The final column indicates which ecosystem services were estimated with cost-based methods and which services would require other valuation techniques for their estimation. As noted in the introduction, limiting analysis to cost-based estimates of ecosystem service values with a retrospective view has some advantages, particularly in identifying ecological and political tipping points. However, the approach also has some limitations in that some relevant stated preference study estimates of consumer surplus loss are not taken into account; some perspectives on approaches to addressing this limitation are provided in the discussion below.

We define the boundaries of the ecosystems in our case study as freshwater hydrological ecosystems in the SA-MDB and the period of

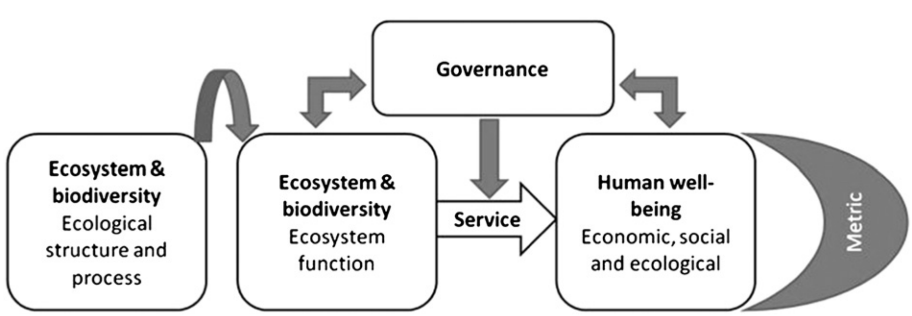

Fig. 2. Based on Haines-Young and Potschin, 2010.

Table 1
Hydrological ecosystem services estimated in the South Australian Murray–Darling Basin.

Ecosystem process	Ecosystem service	Valuation approach	Estimated
	Provisioning services		
In-channel flows (for irrigation)	Food	MP	✓
Turbidity mitigation	Water	MP	✓
Photosynthesis	Raw materials	MP	
Primary productivity	Genetic resources	AC, MP, RC	
	Regulating services		
Sink for pollutants and carbon	Air quality and climate regulation	SP	
Slow of surface flow in floods	Moderation of extreme events	AC, RC	✓
Water infiltration and percolation	Regulation of water flow	AC, RC	✓
Decomposition and microbial respiration	Waste treatment	RC, AC	
Sediment stabilisation	Erosion prevention	AC, RC	✓
Soil formation, mineral weathering, bioturbation	Soil fertility and nutrient cycling	AC, SP	
Plant flowering and fertilisation	Pollination	RC, AC	
Predator - prey interactions	Biological control	AC	
	Habitat services		
Floodplain inundation and in-channel freshes	Maintenance of life cycles	AC, RC	✓
Ecosystem disturbance regime	Maintenance of genetic diversity	AC, RC	
Biotic – abiotic interactions	*Cultural and aesthetic services*	SP	
	Aesthetics; spiritual and cognitive development		
In-channel flows	Recreation and tourism	SP	✓

Table based on TEEB (2010) and Plant et al. (2012). Valuation approach based on Farber et al. (2006) where AC is avoided cost, RC is replacement cost, MP is market price, TC is travel cost and SP is stated preference.

analysis is the duration of the Millennium Drought (1997–2010). The costs associated with ecosystem services losses assessed were those which triggered a socioeconomic or political tipping point resulting in a known expenditure or economic loss. The breadth of the ecosystem service losses estimated was bound by the data available on defensive expenditures to protect from further ecosystem loss, and mitigation expenditures and damage costs.

The literature, primarily in the form of government reports, was consulted to document the range of expenditures or costs associated with ecosystem service losses during the drought. To triangulate the initial findings, the key informant approach was applied. We undertook semi-structured in-person and telephone interviews with representatives from the South Australian Government and industry. We interviewed staff from the Department for Water, the Department for Environment and Natural Resources, and the Department for Transport, Energy and Infrastructure, the South Australia Tourism Commission and the Department of Primary Industries and Resources of South Australia. The industry group we consulted was the South Australian Boating Industry. A number of datasets were obtained from the Federal Government's Department of Resources, Energy and Tourism, the Australian Bureau of Statistics, and Tourism Research Australia.

In some cases, the Commonwealth purchased water to maintain ecosystem service supply. To estimate the value of the water purchased, knowing the volume of water purchased, we estimated the price of water following Brennan's (2006) econometric estimation approach. Using rainfall and water allocation data for 1998 to 2004, Eq. (1) demonstrates this relationship where A is water allocation as a proportion of entitlement and R is total seasonal rainfall.

$$Ln\ Price = 7.484 - 1.30806\ A - 0.00718R \tag{1}$$

Salinity damage costs for domestic and industrial users were calculated based on the econometric specification developed in GHD (1999) and adapted in RMGC (2009). Data on salinity loads were obtained from MDBA (2010b). The model specification for household salinity damage costs is as follows:

$$HHDC = 0.2458T + 135 \tag{2}$$

where $HHDC$ is household salinity damage cost in dollars per household per year, T is the total dissolved solids in milligrams per litre.

Industrial salinity damage cost was estimated as:

$$IDC = 0.00063T + 0.35 \tag{3}$$

where IDC is industrial salinity damage cost in dollars per kilolitres per year.

The 3500 GL reduction in water diversions was chosen as the intermediate reduction proposed by the MDBA (2010a) in the Guide to the Proposed Basin Plan which aims to restore the ecological health of the MDB. Since the Proposed Basin Plan was released, a Revised Basin Plan proposes water diversions be reduced by 2750 GL/yr on average (MDBA, 2012).

Finally, the estimates of ecosystem service losses were aggregated. It should be emphasised that our ecosystem service losses estimates are not equivalent to the Total Economic Value of hydrological ecosystem services in the SA-MDB as many ecosystem services losses were not estimated, rather we provide an estimate of specific ecosystem services losses, based on defensive and mitigation expenses triggered by the breach of a socio-economic or political tipping point.

4. Results

The cost-based data provide guidance on which ecosystem services lost or degraded by drought were valued by communities and government and triggered defensive expenses, mitigation expenses and damage costs. The results presented here are compared to a baseline of non-drought periods. Figures reported are estimates of expenditures incurred in response to drought and did not include routine or reoccurring natural resource management expenditures.

Table 2 breaks down expenditures or damage losses by ecosystem service. In this case study, the Government, communities and individuals incurred expenditures of nearly $810 million. The majority of the expenditures to remediate ecosystem service losses were for provisioning and regulating ecosystem services. All ecosystem services are vulnerable during extended drought however the risk of system collapse provided added motivation for defensive expenditures.

4.1. Provisioning Ecosystem Services

Communities located in the southern SA-MDB were highly dependent on water sourced from the Lower Lakes and the River Murray for livestock, dairying and irrigated agriculture as well as for urban and

Table 2
Mitigation, replacement and adaptation costs, SAMDB and Lower Lakes (1999 to 2011).

Ecosystem function	Service	Expenditure or estimated loss	Millions of AU$ (2010 base)	Period	Data source
Provisioning	Rural and agricultural water supply	Investment in integrated pipeline system for livestock and domestic uses	120.0	2009	Department of Sustainability, Environment, Water, Population and Communities
	Water supply	Water purchased for critical human needs	88.6	2007–2010	DFW (2011b) and author's calculations
	Food production	Water purchased for perennial plantings	32.4	2001–2010	DFW (2011b) and author's calculations
	Food production	Dairying	50.7	2002–2007	DEH (2009)
Subtotal			*291.7*		
Regulating	Water regulation	Repairs to bridges, ferry landings, pipelines and emergency levee repairs	2.4	2006–2010	DFW (2010a)
	Soil retention	Riverbank collapse including property damage	12.8	2009–2011	DFW (2010b)
	Water regulation	Lost expenditure from irrigation upgrades and laser levelling	82.0	2005–2009	DFW (2010a) and Kingsford et al. (2011)
	Biological/water/waste	Salinity damage cost	82.9	1999–2011	Author's own calculations based on GHD (1999) and MDBA (2010b)
Subtotal			*180.1*		
Habitat	Biological regulation	Dredging the mouth of the Murray River	40.0	2002–2010	DFW (2011a)
	Biological regulation	Acid sulphate soil and revegetation works	20.0	2008–2010	Department for Environment and Heritage (2010), Kingsford et al. (2011)
	Biological regulation	Water pumping (Lake Albert to Alexandrina)	14.0	2009–2010	Kingsford et al. (2011)
	Biological regulation	Weirs to prevent acidification	40.0	2007–2009	Kingsford et al. (2011)
	Biological regulation	Environmental water reserve purchase	49.1	2009	DFW (2011b)
Subtotal			*163.1*		
Cultural	Recreation	Tourism	174.8	1999–2011	Sobels (2011) and DRET (2010)
Subtotal			*174.8*		
Total			809.7		

country-town water supplies. Low flows in the River Murray and reduced lake levels affected physical access to water; irrigation water supply from the Lakes was temporarily suspended in 2007. Reduced flows also affected water quality and safe drinking water standards were breached. The Commonwealth Government's response to this significant challenge was two-fold.

First, under the Commonwealth Government *Water for the Future* Sustainable Rural Water Use and Infrastructure program, a $120 million State Priority Project[2] was financed (Department of Sustainability, Environment, Water, Population and Communities, 2010; Table 2). Through the State Priority Project, investment was made in integrated pipelines for irrigation, livestock, domestic and potable uses in the Lower Lakes region. This replacement expenditure was a one-time expense enabling communities to access alternative water supplies. A second response was for the South Australian Government to purchase water allocations from the water market to meet critical human water needs: between 2007 and 2010, the South Australian Government purchased 167 GL (DFW, 2011b) estimated to cost $88.6 million. Between 2001 and 2010, the South Australian Government purchased an additional 61 GL of water as part of the Critical Water Allocations initiative (DFW, 2011b) to protect riparian habitat; the estimated cost of this water was $32.4 million.

Economic impacts of the drought on the agricultural sector are difficult to isolate given a high level of adaptation in the industry and fluctuations in world commodity prices, such as the cereal price spike that occurred in 2006–07. There is some evidence that agricultural property values declined during the drought by up to 15% (Egan Edge, 2008). Although not included in the results reported here, Wittwer and Griffith (2011) estimated the loss of agricultural provisioning services. They estimated that for the South Australian portion of the MDB, drought impacts on irrigated agriculture's contribution to the regional economy declined by 1.9% while gross regional product for the southern MDB fell by 5.7% in 2007–08 relative to a no drought baseline. Specific drought-related losses in the SA dairy industry between 2002 and 2007 were estimated at $50.7 million (DEH, 2009) and are included in Table 2. Overall, provisioning ecosystem service mitigation expenditures and losses were estimated at $291.7 million.

4.2. Regulating Ecosystem Services

Numerous costs to governments, utilities, communities and individuals arose from the loss or degradation of regulating hydrological ecosystem services. These services were related to maintenance of adequate in-channel base flows as well as low inflows more generally. Consequences of inadequate base flows included floodplain and riverbank recession, consolidation, desiccation, cracking, slumping and in some cases, total riverbank collapse while reduced river flows increased salinity and associated treatment costs.

Subsidence of floodplain soils required emergency levee repairs costing $1.38 million, and with further subsidence and cracking, an additional $30 million in levee repairs is expected (DFW, 2010a), but not included in this estimation. Adaptive measures to modify bridges, ferry landings and pipelines to low-flow conditions were estimated to exceed $1 million (DFW, 2010a).

A localised hazard, particularly below Lock One on the River Murray, was riverbank slumping and collapse (DFW, 2010b) resulting in extensive road and other infrastructure damage. To monitor and mitigate this hazard, the Department for Water instituted the Riverbank Collapse Hazard Program at an expense of $3 million over a two year period. Additional costs associated with localised riverbank collapse monitoring and mitigation were absorbed by private landowners, developers, the Department for the Environment and Natural Resources and local Councils, costing an estimated $1 million. Public and private property damage costs from riverbank collapse were estimated at $8.8 million (DFW, 2010a). Further research could estimate costs associated with forgone development since some areas adjacent to the River Murray were quarantined from development due to a high risk of riverbank collapse. There is some evidence that these costs are considerable, for instance a real estate developer was required to return over $3.8 million in investment to clients who purchased lots in areas of enhanced risk (Sobels, 2011).

Another suite of costs are associated with lost efficiencies. Over $60 million of investment in laser levelling of farm plots was unrecoverable as a result of floodplain consolidation and cracking

[2] See http://www.environment.gov.au/water/policy-programs/srwui/state-priority-projects/index.html

(Kingsford et al. 2011). In addition, as the downstream State, South Australia suffers the effects of low flows and salinity more acutely than upstream States. In response, South Australia has had a history of upgrading agricultural irrigation infrastructure and is one of the most efficient irrigation industries in the basin States (Government of South Australia, 2011). Salinity and other drought-related damages to this irrigation infrastructure were estimated at $22 million (DFW, 2010a). Higher concentrations of salts also damaged industrial and household infrastructure. Estimates of salinity costs in the drought were based on avoided costs and salinity levels during average flow, non drought years. Salinity damage costs were estimated at $60.9 million and $22.0 million for domestic and industrial users, respectively. Overall, expenditures to replace regulating services and mitigate further damages exceeded $180.1 million.

4.3. Habitat Ecosystem Services

The loss of habitat hydrologic ecosystem services entailed another suite of expenditures by the Commonwealth and South Australian Governments to mitigate further environmental decline. In 2002, flow from the River Murray to the ocean ceased and a sandbar formed at the Murray Mouth. Salinity in the southern Coorong Lagoon became hypersaline and the policy response was to dredge the Murray Mouth to re-establish connectivity between the Coorong and the Southern Ocean (Webster, 2010). Estuarine conditions could not be restored without a return of freshwater flows down the River Murray which occurred in 2010. This was the second occasion that the river mouth required dredging, the first occurring in 1981 (MDBC, 2005). The cost of dredging between 2002 and 2010 was conservatively estimated at $40 million (DFW, 2011a).

Low inflows resulted in low lake levels in the Lower Lakes (Lakes Alexandrina and Albert). This was a significant health and environmental concern as sulphidic lake bed sediments became exposed (Baldwin, 2011a). To mitigate the creation of acid sulphate soils, the South Australian government funded revegetation works around the Lower Lakes with aerial seeding of 4500 ha of exposed lakebeds, the barrage islands and other exposed areas around the Goolwa Channel. In 2010 alone, 300 tonnes of seed were sown on 5000 ha of exposed lakebed and an additional 1.1 million native seedlings were planted on 2300 ha. Revegetation works were funded by the government's $10 million Lower Lakes Bioremediation and Revegetation Project (Department for Environment and Heritage, 2010).

In addition to revegetation works, the South Australian Government spent $10 million liming exposed lakebeds (Kingsford et al. 2011). To prevent further exposure of Lake Albert, in June 2009 and again in January 2010, $14 million were spent to pump water from Lake Alexandrina to Lake Albert. To contain acidification and its impacts on water quality, fisheries and natural habitats, two weirs were constructed, at a cost of $40 million (Kingsford et al. 2011).

Another expense to mitigate further loss of habitat ecosystem services was the purchase of 97.6 GL of water, estimated at $49.1 million, to serve as an environmental water reserve for the Lower Lakes (DFW, 2011b). The total drought-related costs associated with widespread acidification in the Lower Lakes, however, is unknown as some ecosystems have been pushed to new states of equilibria and in some cases, ecosystem damage may be irreversible. Furthermore, not quantified here are the monitoring, hazard assessment, transition and adaptive management costs that will be required now and in the future (Baldwin, 2011b). Overall, expenditures to restore or maintain habitat services were estimated at $163.1 million.

4.4. Cultural and Amenity Ecosystem Services

The Millennium Drought reduced the supply of cultural and amenity services due to low inflows, poor water quality, and people's perceptions of how the drought may have affected these services (DRET, 2010). For instance, numerous campsites were closed for remediation, while some mooring sites were rendered inaccessible. At one marina alone, 60 of its 64 boats were forced to relocate. Slipways and marinas also reportedly lost the opportunity to service around 1000 boats at a fee of $5500 per boat per year (Sobels, 2011). Reductions in tourism were estimated to have cost the South Australian River Murray houseboat fleet tens of millions of dollars. Overall, the direct and indirect tourism losses were estimated at $174.8 million for the period (DRET, 2010), while another source reported losses closer to $200 million per year (DEH, 2009).

4.5. Thresholds and Ecosystem Service Losses

In the process of cataloguing and estimating the costs of hydrological ecosystem service losses over the course of the Millennium Drought, insight was gained into thresholds. This threshold analysis aided the identification of ecosystem services that might otherwise have gone unnoticed, for instance regulating ecosystem services were revealed through river bank collapse emergency expenditures. We discuss two thresholds, a biophysical threshold, the disconnection of Lake Albert from Lake Alexandrina, and a hydrologic threshold, the low in-river channel water levels.

Between 1999 and 2007, the level of Lake Alexandrina was between 0.8 and 0.6 m Australian Height Datum (AHD). This level corresponds to the lake at close to full water supply with salinity between 400 and 2300 electrical conductivity units (EC). By 2008, the lake level had fallen to −0.4 m AHD and salinity reached 3250 EC in some areas. Lakes Alexandrina and Lake Albert also became disconnected, isolating fish communities. In 2009, the Lake reached −0.8 m AHD and the shores of Lakes Alexandrina and Albert retreated by up to 2 km. This lake level marked a critical ecosystem threshold where saturated sulphidic sediments were exposed and large areas of lake beds acidified upon drying, producing acid sulphate soils (Baldwin, 2011a). In addition to acidification, ongoing evaporative losses reduced dilution capacity and water quality, and critical salinity targets for safe drinking water (<800 EC) were breached. The salinity load in Lake Alexandrina exceeded the threshold for most freshwater fish species resulting in fish loss from the lake and tributary wetlands (Department for Environment and Heritage, 2010). The lakes were also no longer suitable for supplying drinking water or supporting recreation. In this example ecological, socioeconomic and political thresholds were progressively crossed with the continued degradation of the lakes' condition.

A second threshold was surpassed when the depth of in-river channel water dipped below a critical minimum level for riverbank stability (DFW, 2010a, 2010b). Riverbanks receded, desiccated, cracked and in the worst of scenarios, slumped and collapsed. Both public and private expenditures to prevent further losses began in 2010. The South Australia Riverbank Collapse Hazard Program was instituted to deal directly with these ecosystem service losses.

The analysis of actual mitigating, defensive expenditures and damage costs provided detailed information on biophysical thresholds, including hydrological and ecological, response thresholds in the MDB. We would not have been fully aware of many of these thresholds prior to the drought and cataloguing of these expenditures. Furthermore, the two thresholds discussed reveal different trigger mechanisms. The first triggered an emergency response and suite of expenditures to mitigate further acid sulphate soil formation (revegetation, liming and water purchases) and the provision of alternative water supplies. The second threshold involved a longer time lag between cause and consequence followed by a combination of emergency repairs to infrastructure and a longer-term monitoring program. Finally, we note that these thresholds were utilised in the CSIRO (2012) assessment of the Murray–Darling Basin Plan to model benefits of returning water to the river system as compared to the status quo management of the system.

5. Discussion

The cost-based approach developed here to estimate values for freshwater hydrological ecosystem service losses in drought is contingent on expenses that can be linked to an ecological, socioeconomic or political tipping point. State and national legislation for example can set off a legal trigger requiring the government to undertake defensive, replacement and mitigation expenditures. In our case study, the South Australian Safe Drinking Water Act 2011 and the Australian Drinking Water Guidelines (NHMRC, 2004) were examples of political tipping points that were breached.[3] International treaties, for example the Ramsar Convention (1971), may also pressure national governments to respond. In the Water Act of 2007, the legislation underpinning water reform in the MDB, the Australian government committed to protect the ecological character of Ramsar-listed wetlands. In our study area, The Coorong, Lake Alexandrina and Lake Albert are Ramsar sites. The degradation of the ecological character of these sites during the course of the drought prompted the South Australian and Commonwealth governments to invest in preventing further damage to these ecosystems.[4]

Our application of the ecosystem services approach proved to be a valuable organizing principle for thinking about the costs associated with drought. By carefully tracing expenditures and losses associated with the Millennium Drought in this framework, various hydrological ecosystem services that often go unnoticed were revealed, for example, habitat services through acid sulphate soil mitigation and regulatory services via their role in preventing riverbank and floodplain subsidence.

As with all valuation methods, there are a number of limitations in the application of cost-based measures of ecosystem service losses (Bockstael et al., 2000; Shabman and Batie, 1978; USNRC, 2005). The key limitation is that cost measures are not measures of economic welfare or indeed value. Depending on the shape of the supply and demand curves for ecosystem services, avoided costs are unlikely to be equivalent to changes in economic surplus between drought and pre-drought scenarios. Consequently, avoided cost measures are not measures of consumer or producer surplus grounded in an economic welfare maximisation framework and therefore must be applied judiciously and transparently in a cost–benefit framework. In spite of these caveats, cost-based measures can provide useful information for policymakers in planning budgets and mitigation responses to drought as we have demonstrated in the SA-MDB case study.

We note that not all ecosystem services are amenable to measurement with cost-based methods (Table 1) and that for those that are not, other methods may be more appropriate. A distinct advantage of cost-based estimates, however, is that they are based on actual expenditures by governments, utilities and individuals, and as we have seen, these expenditures are in many cases triggered by socioeconomic and political tipping points. The approach developed here may be adapted to other drought prone regions as most governments are required to register expenditure data availing these data to be readily and cost-effectively collected.

6. Conclusions

Employing cost-based valuation methods, this study estimated that the economic cost of hydrological ecosystem service losses in the SA-MDB during the Millennium Drought was nearly $810 million. We find that the majority of hydrological ecosystem losses were provisioning and regulating services, which as Farber et al. (2006) conclude, are among the most amenable to valuation with cost-based approaches. It should be noted that our ecosystem service losses estimates are not equivalent to the Total Economic Value of hydrological ecosystem services in the SA-MDB since the estimates presented here are of economic loss, not value. It should also be noted that we did not account for all ecosystem service losses that occurred during the drought. Instead, we provided an estimate of specific ecosystem services losses which triggered defensive or mitigation expenses through the breach of a socio-economic or political tipping point.

This analysis was based on readily available published reports, data, and key informant semi-structured in person and telephone interviews. There is significant scope for estimating additional categories of hydrological ecosystem services with some further data collection and economic modelling. The forgone land development value due to riverbank instability and other hazards is one such possibility. Increased water treatment costs and consumer surplus losses attributed to water restrictions could also be estimated.

One limitation of the cost-based valuation methods employed here is that they do not capture non-use values such as bequest and existence value, and values communities place on the aesthetics of a healthy system. Nonetheless, cost-based estimates of ecosystem service losses can inform the design of stated preference studies. The approach developed here to estimating ecosystem service losses due to drought revealed some services that may not have been considered without having first observed the Millennium Drought experience. With a greater understanding of the range of hydrological ecosystem services provided by river basins, more robust stated preference surveys may be designed, supplementing the background information presented to survey respondents and aiding in the formulation of the questions themselves, to include the multifaceted values of freshwater ecosystems.

The cataloguing of hydrological ecosystem services in an ecosystem services framework and the application of cost-based methods fills an important gap in the literature by providing a standardised and transferable approach to estimating hydrological ecosystem service losses resulting from drought. The case study application to the SA-MDB and the estimates generated here demonstrate the utility of the approach and its potential for informing water, drought preparedness and mitigation policy, and to contribute to more robust decision-making.

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