ARTICLE IN PRESS

Journal of Arid Environments xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

An ecosystem services and Bayesian modelling approach to assess the utility of water resource development in rangelands of north Australia

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ARTICLE INFO

Keywords:
Integrated assessment
irrigation development
food-water-environment nexus
land use change
aquatic ecology
Green Economy

ABSTRACT

Past water resource developments in dryland regions rarely estimated the full suite of environmental and social impacts arising from damming and diverting water for food production. Nowadays there is a greater focus on sustainable resource development which considers the economic, social and environmental costs and benefits. A challenge is to apply tools and methods which can capture the often disparate knowledge and data describing many costs and benefits. This paper describes a proof of concept application of a large Bayesian Decision Net to estimate the total utility of water resource development according to criteria of social, economic and environmental sustainability. We focus on two water-scarce catchments in remote northern Australia which are under investigation for development. The study catchments contain a diverse set of ecosystem services and socio-cultural values, including important Indigenous values and high value freshwater ecosystems. The Bayesian Decision Net was shown to have many properties that made it useful for performing a social, economic and environmental sustainability assessment, in particular its ease of construction; its ability to handle quantitative and qualitative data types; its preservation of system knowledge and; its ease of use in aiding decision making. From the perspective of the sustainability assessment in our case study, the total utility of water resource development for new irrigation is negative in both the studied catchments. The overall utility of water resource development could be positive if irrigation development is highly sensitive to the environment and there are very low environmental impacts, and much higher net economic returns to irrigators eventuate, possibly through higher commodity prices, lower capital costs of irrigation development or some combination of both.

1. Introduction

Despite the many economic benefits of opening up new areas for irrigation, past water resource developments have rarely estimated the full suite of environmental and social impacts arising from damming and diverting water for food production (Comprehensive Assessment of Water Management in Agriculture, 2007). The principals for sustainable development argue that resource development consider intergenerational impacts on the environment and society as well as the economy (UNEP, 2011). The economic, social and environmental components are inextricably linked and sustainable development should take an integrated approach to consider balancing impacts and benefits within these components (Hacking and Guthrie, 2008; Morrison-Saunders and Pope, 2013). While many tools have been developed for sustainability assessments (Ness et al., 2007; Singh et al., 2012), only relatively few take an integrated approach. Here we propose an integrated approach that uses the ecosystem services framework to organise components of a social, economic and environmental sustainability (SEES) assessment into the impacts of water resource development for scenaros of new irrigation. We apply a Bayesian Decision Network model to integrate the mix of qualitative and quantitative data inherent in sustainability assessments.

An assessment of the SEES impacts requires indicators describing environment and economy as well as broader social considerations. The concept of calculating impacts on economic, social and natural capital from corporate (or broader) activities is central to the idea of a Green Economy (Pearce et al., 1989; UNEP, 2011). The concept of a Green Economy is one which is resource and energy efficient, promotes human wellbeing (current and future generations) and social equity, and reduces environmental risks. The goal of a Green Economy is to provide greater protection for natural resources to ensure continued provision of ecosystem services (UNEP, 2011).

Transitioning to a Green Economy will require universal adoption of metrics of economic performance that take into account the scarcity and the condition of natural resources or natural capital (World Business Council for Sustainable Development, 2010). Green

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https://doi.org/10.1016/j.jaridenv.2018.02.007
Received 24 November 2016; Received in revised form 22 February 2018; Accepted 23 February 2018

Please cite this article as: Crossman, N.D., Journal of Arid Environments (2018), https://doi.org/10.1016/j.jaridenv.2018.02.007

accounting frameworks provide opportunities to incorporate sustainability criteria into common metrics of growth such as GDP. Recent developments include the UN Statistical Commission System of Environmental-Economic Accounting (SEEA) (United Nations Statistical Division, 2014), and the World Bank's Wealth Accounting and Valuation of Ecosystem Services (WAVES) partnership which aims to extend SEEA by applying ecosystem services and other natural resources accounting practices across case study countries (World Bank, 2012). The objective is to further develop green (i.e. SEES) accounting protocols and to incorporate these into national policy and development planning.

There are several challenges when conducting a robust SEES assessment. These include finding common units of measurement for the SEES components and appropriate modelling tools that bring together the many outputs and data types derived from complex SEES assessments. In greenfield development sites there can also be a lack of scientific knowledge about ecosystems and their biodiversity. Recent literature has pointed to Bayesian networks as a method for integrating non-commensurate data values and types derived from sustainability assessments (Chen and Pollino, 2012; Keshtkar et al., 2013; Landuyt et al., 2013; McVittie et al., 2015; Shaw et al., 2016).

Bayesian networks can be used to integrate different forms of evidence, particularly in relating the potential outcomes of management interventions to a defined set of endpoints. They have become a modelling platform of choice in natural resource management contexts, including in ecosystem service assessments (Barton et al., 2008; Kragt et al., 2011; Landuyt et al., 2013; Tantipisanuh et al., 2014; McVittie et al., 2015). Recent studies have applied Bayesian networks to assess ecosystem service trade-offs between development and conservation in forested and mountainous landscapes (Grêt-Regamey et al., 2013; Gonzalez-Redin et al., 2016), and trade-offs between provisioning and bundles of other ecosystem services (Landuyt et al., 2016). The applications to water resource development and ecosystem service trade-offs appear to be less common, although examples exist where Bayesian networks have been used to support decision making and planning within the context of environmental versus agricultural water uses (Xue et al., 2017a, 2017b). The application of Bayesian approaches to water resource management was reviewed by Phan et al. (2016), who found that most applications were to support water sharing, water quality and in-stream ecology decisions within highly developed contexts. There appears to be a dearth of application to assess trade-off between water resource development and ecosystem services in greenfield sites.

Bayesian networks are favoured because they use graphical models of interconnected nodes and arcs (or arrows) and probabilities describing the relationships between them. Nodes represent discrete or continuous variables, while arcs represent causal relationships between variables. A Bayesian network graph structures a problem such that it is visually interpretable by stakeholders and decision-makers while serving as an efficient means for evaluating the probable outcomes of management decisions on selected variables (Chen and Pollino, 2012). A notable strength of Bayesian networks relative to other modelling platforms is their ability to investigate the impacts of multiple factors in complex environments, including integration problems (Ticehurst et al., 2007; Barton et al., 2008; Molina et al., 2010). They allow different types of information to be integrated into a single framework, and use probabilities to analyse multiple, complex scenarios. Bayesian networks' most evident limitations are their tendency to overemphasise expert opinion and the potential for large networks to become unmanageable (Uusitalo, 2007). Bayesian Decision Networks (BDNs) incorporate 'Decision' nodes, and 'Utility' nodes, where decision nodes represent two or more choices that a manager can take which can influence the values of other nodes. Utility nodes explicitly represent the value, either cost or benefit, of some outcome or decision state, within the network of each possible outcome state (Pollino and Henderson, 2010). The probabilities for each node, known formally as the Conditional Probability Table (CPT) for a node, contain entries for every possible combination of the states of the parent nodes.

The aim of this paper is to develop and apply a BDN model that integrates socio-economic assessments of the relative value and importance of ecosystem services with a number of analyses estimating biophysical changes possible following water resource development in far north Queensland, Australia. The sub-tropical study region contains remote and relatively undeveloped and unmodified river systems and therefore is under significant development pressure. Here a SEES assessment is defined as the overall utility of water resource development given the potential impacts to ecosystem services as well as potential benefits to society from development (e.g. regional economic growth, employment).

Our study uses a number of datasets, namely: i) expert knowledge on potential impacts to aquatic and terrestrial ecosystems and associated ecosystem services from water resource development, captured by surveying regional stakeholders; ii) unit economic values of ecosystem services supplied by land and water ecosystems derived from secondary literature and transferred to the study area, and; iii) modelled farm- and regional-scale socio-economic benefits of potential water development options derived from other parts of a larger study from where the work in this paper is drawn: the Flinders and Gilbert Agricultural Resource Assessment (Petheram et al., 2013b, c). We then build a BDN that integrates this data to estimate the utility of water resource development based on social, environmental and economic benefits and impacts. We then explore hypothetical scenarios that could increase the utility of water resource development.

The objectives of our BDN model are defined using utilities, expressed as the potential water resource development impacts (benefits or costs) across ecosystem service values, as well as ecological features and economic benefits. Using the causal structure of the BDN, we seek to quantify the impacts of water resource development scenarios to inform debate within the Flinders and Gilbert Catchments.

2. Methods

2.1. Study area

The Flinders and Gilbert catchments in far northern Queensland are the focus of this study. These catchments have been targeted for potential development of their water resources because they have very low levels of development due to their remoteness, and consequently, very low population densities. The 47,000 km^2 Gilbert catchment contains the Gilbert-Einasleigh river system (Fig. 1) and has the sixth-highest average discharge of any river in Australia. The 100,000 km^2 Flinders catchment (Fig. 1) contains the Flinders River, the longest river in Queensland and the sixth longest river in Australia. The Gilbert and Flinders catchments have a semi-arid tropical climate, with high monsoon variability and occasional severe cyclones. As a result, rainfall is highly seasonal, with 93% and 88% of rainfall occurring during the wet season (November to April inclusive) in the Gilbert and Flinders catchments, respectively. Spatially, mean annual rainfall varies from about 1050 mm on the coast in the north of the Gilbert catchment to about 650 mm in the south-east of the catchment, and from about 800 mm on the coast in the north of the Flinders catchment to about 350 mm in the south of the catchment (Petheram and Yang, 2013).

Typically the management of water resources and river ecosystems in northern Australia is focussed on development rather than adjustment (Jackson et al., 2008). But in recent years the community values associated with water resource development have changed and diversified, moving from a focus primarily on private economic benefit toward a focus on multiple public and private benefits. Jackson et al. (2008) demonstrate that unregulated river systems make an important contribution to human well-being and cultural identity. People have a strong attachment to rivers, and protection of ecological and aesthetic values now compete with resource development-focussed values. Local residents, recreational and commercial fishers, tourists and