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Using Bayesian Networks to link Environmental Flows to Ecosystem Services in the Murray-Darling Basin, Australia

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Abstract: In water resources management and planning, it is important to understand both (1.) the linkages between environmental flows and ecosystem condition as well as (2.) the linkages between ecosystem condition and ecosystem services. Bayesian Networks (BNs) are an integration-based modeling tool that could be suitable for representing and quantifying these linkages. To evaluate this, we developed a BN, using the Murray-Darling Basin (Australia) as a case study. The Murray-Darling Basin has both agricultural and ecological values, and has more than a century of water resource development and planning. Recently, ecosystem services have been proposed as a means to progressing water resource planning methods in the basin, and a means to engaging stakeholders in the planning process. On the basis of existing Ecological Character Descriptions of the 16 Ramsar sites of the Murray-Darling Basin, complimented with expert knowledge, we developed four sub-networks: ecosystem condition; regulating services; provisioning services; and cultural services. Our preliminary results showed that Bayesian Networks are very useful as integration tool to visualize and quantify the linkages between environmental flows and ecosystem services. However, the complexity and size of the combined Bayesian Network might be problematic for stakeholder engagement and communication. Extensions of Bayesian Networks, such as Object-Oriented Bayesian Networks (OOBNs) and Dynamic Bayesian Network (DBNs) might be even more suitable in this problem field, especially for communicating the complexity and multi-dimensional nature of the problem to stakeholders.

***Keywords**:* Bayesian Networks; Environmental Flows; Ecosystem Services

1 INTRODUCTION

Environmental flows are defined as “quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems“(Brisbane Declaration 2007). This definition acknowledges the environment as legitimate water user by itself but it also emphasizes that human well-being depends on goods and services of healthy ecosystems. Much of the environmental flow research focuses on the linkages between environmental flows and ecosystem condition, e.g. environmental flow requirements and ecological responses to environmental flows (Arthington et al. 2006, Poff and Zimmerman 2010, Poff et al. 2010, Pahl-Wostl et al. 2013). One approach that could be suitable to analyze the linkages between ecosystem condition and human well-being is the concept of ecosystem services (ESS).

1.1 Ecosystem Services

ESS are broadly defined as “benefits that people obtain from ecosystems” (MEA 2005). ESS can be grouped into provisioning, regulating, cultural, and supporting services. Provisioning services are benefits from the provision of natural resources, such as food, freshwater and timber. Regulating services are benefits from the regulation of ecosystem processes, such as maintenance of hydrological regimes or regulation of local climate. Cultural services are recreational and spiritual benefits of intact ecosystems. Supporting services, such as nutrient cycling and soil formation, are necessary for the provision of all other ecosystem services. The Economics of Ecosystems and Biodiversity (TEEB) for water and wetlands report recently highlighted the importance of wetland and water-related ESS for society and economy. The report stipulated that water-related ESS should become an integral part of water resource management (Russi et al. 2013).

1.2 Environmental Flow Management in the Murray-Darling Basin

The Murray-Darling Basin Authority (MDBA), established by the *Water Act 2007*, is responsible for Basin-wide water resources management and planning. With regard to managing environmental flows, the MDBA needs (1) to identify the environmental flow requirements of the Basin, and (2) to set sustainable diversion limits for the amount of water that can be taken for industry, agriculture and other consumptive water uses accordingly (MDBA 2011). Environmentally sustainable levels of take (ESLT) should leave enough water to the environment to sustain ecosystems and to ensure the provision of ecosystem services. The *Basin Plan 2012* has been passed to establish and legally enforce these environmentally sustainable levels of take for each catchment and the whole Basin. The Basin Plan also aims at giving effect to international agreements such as the Convention on Wetlands or Ramsar Convention (1971). This treaty calls for a “wise use” of all wetlands and requests the member countries to maintain the “ecological character” of Wetlands of International Importance, so-called Ramsar sites. By now, the definitions used for “wise use” and “ecological character” have been aligned with the more widely used terms of the ESS concept (Ramsar 2005). Therefore, the ESS concept is widely used in Australia to manage environmental flows and to implement the Ramsar Convention. To represent and quantify linkages between environmental flows, ecosystem condition, and ESS, we made use of so-called Ecological Character Descriptions of the Ramsar sites in the Murray-Darling Basin. As these linkages are highly uncertain and difficult to quantify (Pahl-Wostl et al. 2013), we decided to use Bayesian Networks, a probabilistic modeling tool, to explicitly express this uncertainty.

1.3 Bayesian Networks (BNs)

Bayesian Networks (BNs) are an integration-based modeling tool which is increasingly used to model ecosystem services (Landuyt et al 2013). In BNs, causal relations between variables or “nodes” are visualized with directed links and quantified with so-called conditional probability tables (CPTs). A wide-range of input data, including expert knowledge, can be used to derive these CPTs. BNs are suitable to engage stakeholders and to support decision-making under uncertainty (Varis et al. 2011, Carmona et al. 2013). Most BN applications look at one or two ESS only (Landuyt et al 2013). In our case study, we aimed at modeling all ESS that result from environmental flows simultaneously. To evaluate the applicability of BNs for this purpose, we developed a BN using the Murray-Darling Basin (Australia) as a case study. Based on existing Ecological Character Descriptions of the 16 Ramsar sites of the Murray-Darling Basin, complimented with expert knowledge, we developed four sub-networks.

In section 2, we provide an overview of ESS in the Murray-Darling Basin. In section 3, we present three sub-networks on ecosystem condition, provisioning services, and regulating services. In section 4, we discuss our preliminary results and draw some conclusions.

2 ESS IN THE MURRAY-DARLING BASIN

In 2012, the MDBA commissioned a research project on ecological and economic benefits of environmental flows in the Murray-Darling Basin (CSIRO 2012). The CSIRO Multiple Benefits of the Basin Plan Project identified and quantified ESS expected to arise from recovering more water for the environment in the Basin. The project focused on 10 very broad provisioning, regulating and cultural services from the Millennium Ecosystem Assessment. However, the Murray-Darling Basin provides a much higher number of Basin-specific ESS.

We used Ecological Character Descriptions (ECDs) of the Ramsar sites to get a more holistic view on Basin-specific ESS. As the "ecological character" of Ramsar sites is defined as "the combination of ecosystem components, processes and services that characterize the wetland at any given point of time" (Ramsar 2005), their ECDs provide a good overview of water-related and wetland ESS in the Murray-Darling Basin. We summarized all ESS mentioned in 10 ECDs of which we included 35 Basin-specific ESS in our BN. Most provisioning and regulating services, such as fresh water supply or sediment trapping, are most likely provided by all Ramsar sites but not mentioned in all ECDs. Only few provisioning and regulating services, such as salt harvesting and salinity water disposal, only exist in single Ramsar sites (Table 1).

Table 1: Selection of provisioning and regulating services in 10 Ramsar sites of the Murray-Darling Basin.

	R1[1]	R2[2]	R3[3]	R4[4]	R5[5]	R6[6]	R7[7]	R8[8]	R9[9]	R10[10]
Provisioning services										
Apiculture		x							x	
Fresh water supply			x	x	x	x	x	x	x	x
Fresh water storage (emergency stock)						x	x	x		
Timber production		x								
Firewood collecting		x								
Cattle grazing		x	x				x		x	x
Salt harvesting							x			
Biochemical products & genetic resources				(x)				(x)		
Regulating services										
Groundwater recharge		x					x			
Maintenance of hydrological regimes (incl. flood control)	x	x	x	x	x	x	x	x	x	x
Regulation of water temperature			x							
Maintenance of local climate				x				x		
Carbon sequestration	x	x	x	x	x					x
Sediment trapping/retention			x	x		x		x		x
Salinity water disposal							x			x
Biological control of pests and diseases				x				x		

[1]Banrock Station Wetland Complex (Butcher et al. 2009), [2]Barmah Forest (Hale and Butcher 2011), [3]Blue Lake (DECC NSW 2008), [4]Currawinya Lakes (Fisk 2009), [5]Ginini Flats Wetland Complex (Wild et al. 2010), [6]Hattah-Kulkyne Lakes (DSE Victoria 2010a), [7]Kerang Wetlands (DSE Victoria 2010b), [8]Macquarie Marshes (OEH NSW 2012), [9]Paroo River Wetlands (Kingsford and Lee 2010), [10]Riverland (Newall et al. 2007)

3 BNs ON ESS OF ENVIRONMENTAL FLOWS

A healthy ecosystem condition is the starting point for the provision of ESS. Therefore, we first developed a BN on the impact of changing water availability on the ecosystem condition (Figure 1). All BNs in this paper were generated using Netica™ Version 4.6 (Norsys, http://www.norsys.com).

From bottom to top, the BN says that whether the ecosystem is in a poor or healthy condition depends on whether the structural and functional components of the ecosystem are poor or healthy. Function components, such as nutrient cycling and organic carbon cycling, belong to supporting services. Structure components, such as biodiversity, are sometimes referred to as habitat services (CSIRO 2012). Whether these components are in a healthy or poor state depends on how much water is available and the duration of this water availability. We included this time dimension as the impact of low or high water availability is very different whether it only takes one year or up to 5 or ten years. The water availability is influenced by annual water supply, environmental flows and the duration. This way, the BN highlights what difference environmental flows can make if the annual water supply was low for a certain period of time.

To show how supporting services and a healthy ecosystem condition are prerequisites for the provision of all other ESS, we used our sub-network on ecosystem condition as input for the sub-networks on provisioning, regulating, and cultural services.

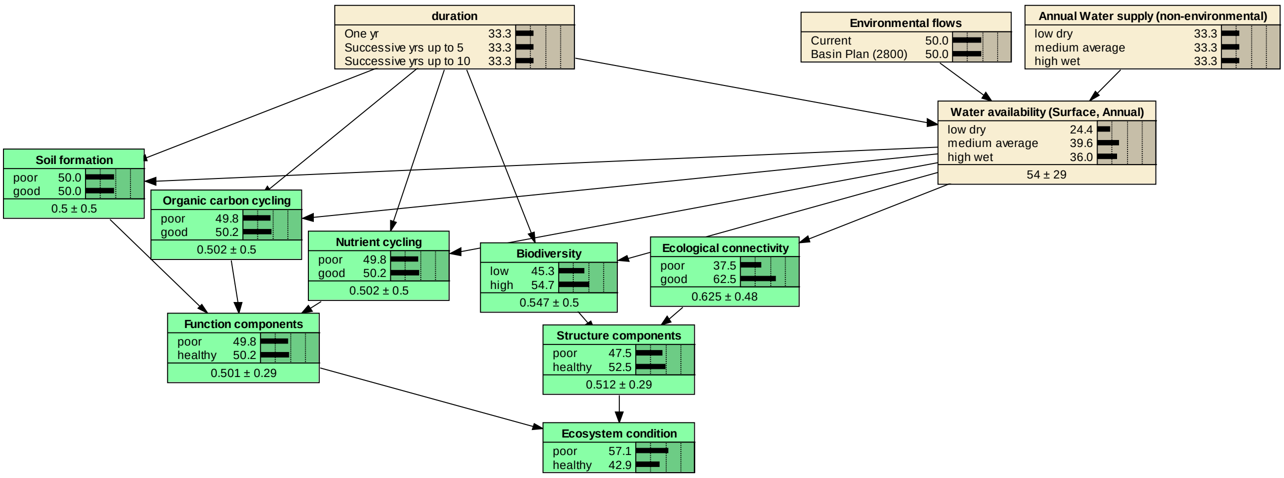

Figure 1: Sub-network on ecosystem condition.

The sub-network on provisioning services (Figure 2) indicates that some ESS, such as fresh water supply and fresh water storage, mainly depend on water availability; whereas other ESS, such as cattle grazing and apiculture, mainly depend on a healthy ecosystem condition. The node "Ramsar sites" is only connected to site-specific ESS. ESS that only apply to few Ramsar sites, e.g. cattle grazing and salt harvesting (Table 1) are site-specific and therefore connected to "Ramsar sites"; ESS that should apply to all Ramsar sites, e.g. fresh water supply and fresh water storage apply, are not connected to "Ramsar sites". This way, we reduced the number of links. Some ECDs mentioned potential ESS, such as biochemical products & genetic resources for medicine (Table 1). To capture this, we added a node for "Biochemical & genetic resources", but have not connected this as there was no information to populate it. As Ramsar sites are usually not used for irrigated agriculture, we only included cattle grazing in the network on provisioning services. However, increasing environmental flows in the Murray-Darling Basin would require a shift from irrigated agricultural production towards dryland agricultural production in the long-term (CSIRO 2012). The output variables at the bottom of each sub-network, here "Provisioning services", use a simple equation in Netica to equally weight the influence of the incoming parent nodes. This way, our BNs treat all ESS as equally important. The sub-network on regulating services (Figure 3) indicates that most regulating services depend on a healthy ecosystem condition, whereas only groundwater recharge is dependent on water availability. The combined BN on ecosystem condition, provisioning, regulating, and cultural services is able to show the impact of water availability on ecosystem condition and all ESS simultaneously. It presents how environmental flows can help to sustain a healthy ecosystem condition and to provide ESS.

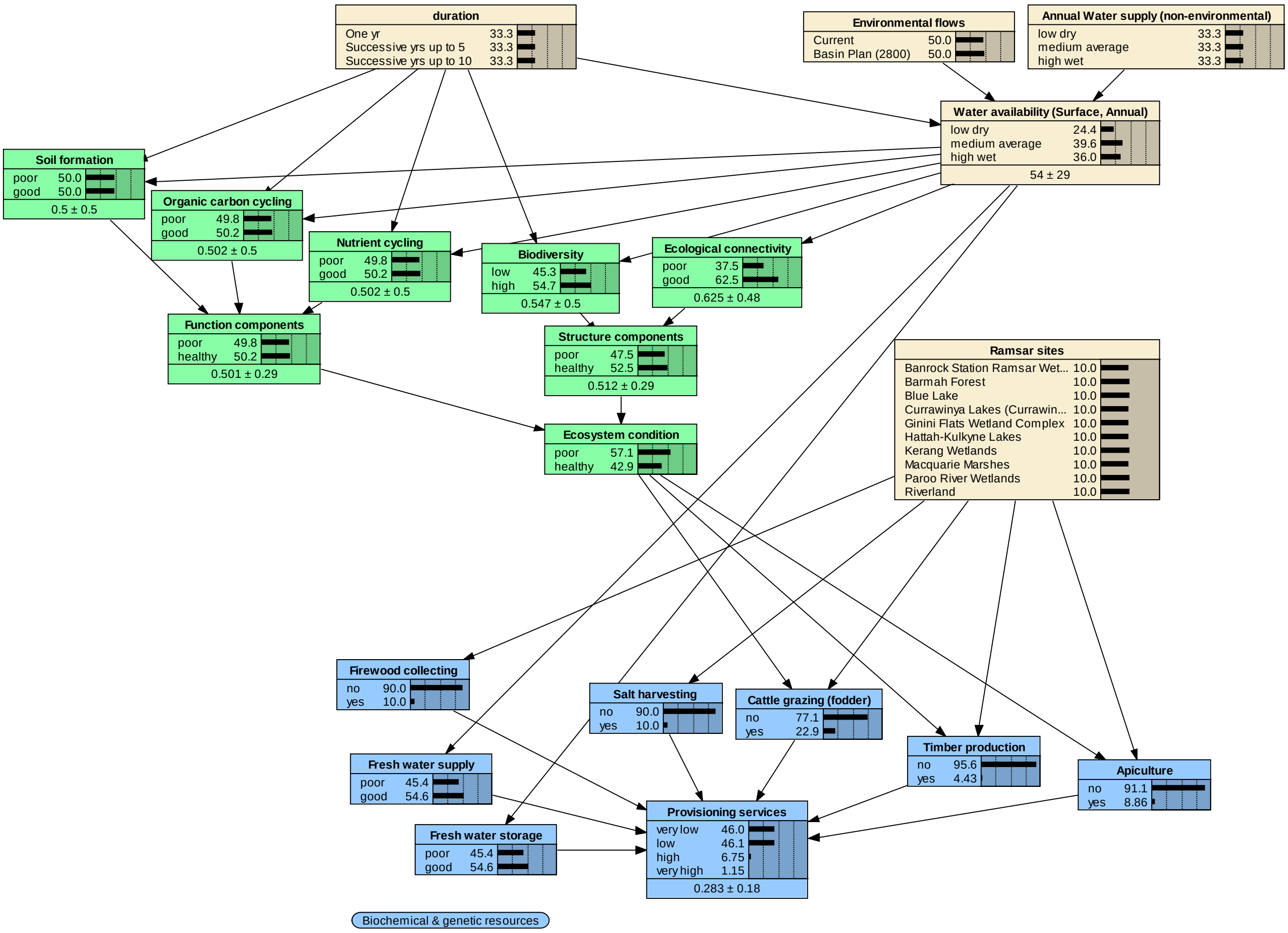

Figure 2: Sub-network on provisioning services.

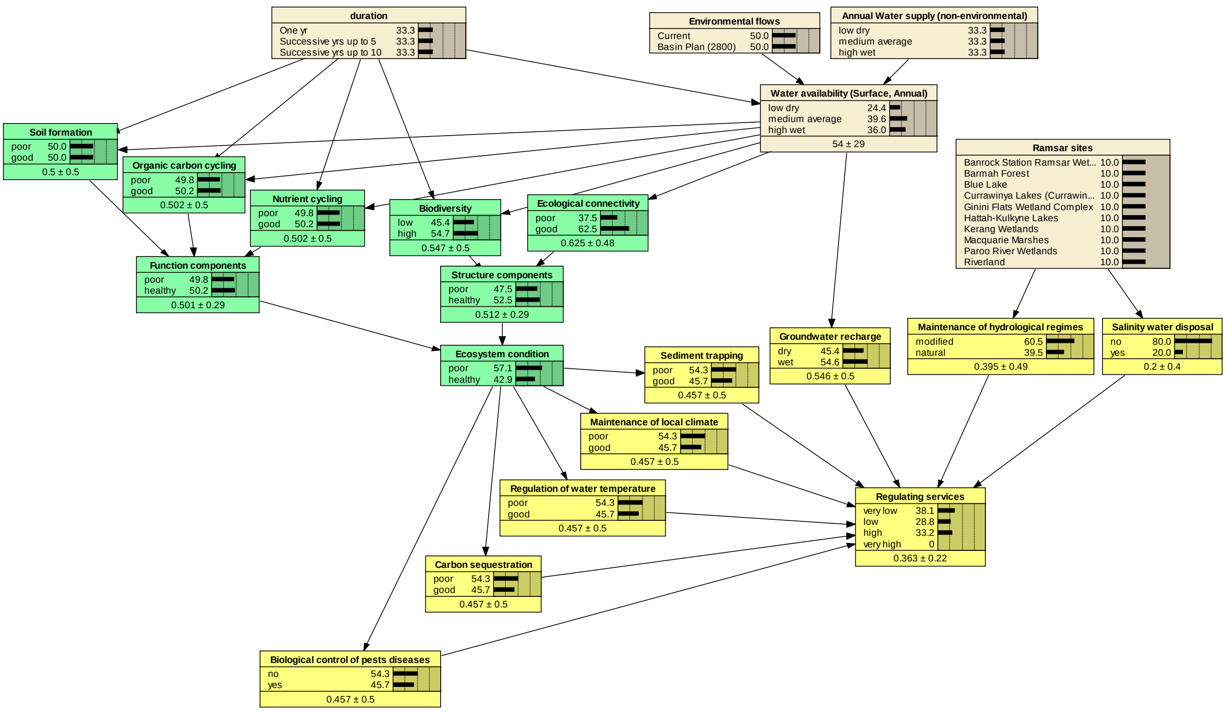

Figure 3: Sub-network on regulating services.

4 DISCUSSION AND CONCLUSION

Our preliminary results showed that Bayesian Networks are very useful as integration tool to visualize and quantify the linkages between environmental flows, ecosystem condition, and ecosystem services. BNs are especially useful if linkages are uncertain or if only expert knowledge can serve as input data. However, the size of the combined BN might be problematic for communicating the complexity and multi-dimensional nature of the problem to stakeholders. Object-Oriented Bayesian Networks (OOBNs), a BN extension with a nested structure, might help to overcome this weakness. Another challenge in modeling ESS of environmental flows is the representation of time. As the impact of water availability and environmental flows on ecosystem condition and ESS varies with different durations, Dynamic Bayesian Network (DBNs) might be even more suitable in this problem field.

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