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River restoration using simple decision support tools in the Lower Snowy River

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Abstract: Humans have extensively modified rivers throughout Australia. Such modifications can be direct, via changes to the natural flow regime, or indirect, such as removal of vegetation in the catchment, altering river geomorphology and changing sediment delivery to rivers. Past and ongoing human interventions have drastically changed the hydrology and geomorphology of the Snowy River, which has had a profound effect on the ecology of the system. Due to impoundments and water extraction, the Lower Snowy has seen a reduction of flows in the order of 55% (James 1989). However, environmental flows were introduced into the river in New South Wales at Jindabyne Dam in 2002. In the upper section, much attention has been given to the restoration of flows. In the Lower section, the Snowy has seen significant changes in geomorphology due to catchment and hydrology changes.

Community concern at the observed environmental degradation resulted in the development of the Snowy Rehabilitation Project, a cooperative project involving Victorian state and regional bodies. One major outcome of this project was funding for rehabilitation works in the Lower Snowy. As a result, much effort was put into modelling work. The focus of this was on better understanding the behaviour of sediments within the river and defining the needs for restoring ecological functions, with a primary focus on providing fish passage. This type of information was intended to develop a way forward for rehabilitation works in the Lower Snowy. It is important to note that this section of the Snowy is surrounded by privately owned agricultural land. Any rehabilitation works also needs to consider how proposed changes in river behaviour will impact on surrounding land.

From this work, a simple decision support system (DSS) was built. The DSS was designed to use modelled information and to assist in decision-making processes by linking management activities (or interventions) to outcomes. The tool uses a 'risk' approach to acknowledge the uncertainties that exist in our knowledge, including models, and the inherent variability of this natural system. The DSS ('The Snowy tool') user is the Victorian East Gippsland Catchment Management Authority (CMA).

The purpose of the Snowy tool is to 'provide an assessment of the cumulative outcomes and risks due to different levels of management intervention'. The rehabilitation activities of interest are: riparian vegetation management; management of vegetation on in-channel benches; and installation of large wood in channel. The model aims to predict the likely outcomes of interventions to: scour holes for fish habitat and migration; occurrence of overbank inundation; avulsion likelihood; and bench and bank stability.

The Snowy tool is a probabilistic model (Bayesian network) that incorporates data from the hydraulic model, HEC-RAS, as well as expert opinion, and a set of ecological response models developed previously. The model was evaluated within an expert workshop. The tool highlighted flaws in past studies, and could only partially address the needs of the decision-makers. The outcome of the project stresses the need for decision-making tools to be designed early in the project development, in order to better guide process modelling and data collection exercises. Without being designed upfront, much of the data collected can be well intentioned but poorly targeted at addressing the key needs for the river system.

Keywords: *River restoration, Snowy River, Bayesian networks*

1. INTRODUCTION

The Snowy River Rehabilitation Project: Plan of Works developed by the Victorian Department of Sustainability and Environment is an integrated program of rehabilitation works (DSE, 2004), which is being undertaken in 3 phases:

Phase 1: Development of an ecological response framework and ecological response models for a subset of outcomes, activities and reaches on the Lower Snowy River.

Phase 2: Development of a simplistic tool for the subset of outcomes, activities and reaches, including the implementation of the ecological response models developed in phase 1.

Phase 3: Development and application of the tool for all outcomes, activities, reaches and timeframes.

This paper details the development of a simple decision support tool for the Lower Snowy River undertaken in Phase 2, referred to in this paper as the 'Snowy tool'. The Snowy tool is designed to be used as a decision support tool for rehabilitation works in the Lower Snowy River. The Snowy tool was designed to be a series of sub-models that were linked within an integrated model. The integrated model was to be used to examine a subset of outcomes for a set of defined management (intervention) activities. The models were partially developed using index-based models in a preceding report (Phase 1 report, Borg and Argent, 2008), however much refinement of the Phase 1 models was necessary for Phase 2.

1.1. The Snowy River

The Snowy River originates in the slopes of Mount Kosciusko in New South Wales flowing through to the Gippsland coast in Victoria. The river is over 500 kilometres in length, and crosses a broad range of landscapes including alpine meadows, snowgum woodlands, grassland plains, mountain forest, riparian forest, rainforest, floodplain agricultural land and coastal wetlands. The total catchment area is 15,860 km^2, of which 6,470 km^2 occurs in Victoria. The Victorian length of the river has heritage status because of its significant biological, geological, cultural, scenic and recreational values.

The construction of the Snowy Mountains Hydro-electric scheme took place in the 1960s. The scheme, along with past land management practices, has significantly altered the Snowy River's hydrology and ecology. After the commissioning of the scheme, natural flows to the upper Snowy were less than 1%. Including tributary inflows, the Lower Snowy had a reduction of flows in the order of 55% (James 1989). In 2002 the flows in the Upper Snowy were increased from 1% to 4% of natural (pre-dam) flows, however targets have been set for 15% by 2009 and 21% by 2012, though it is uncertain as to whether these targets will be met.

In Victoria, the reduction in natural river flows and the effect throughout the catchment of other human activities (such as removal of in-stream large woody debris, modification of riparian vegetation, modification to natural flood flow paths and channel levees, land clearing and land management practices) has had a significant adverse impact on the ecological condition of the Snowy River. Today, the Lower Snowy River is also characterised by large in-stream benches which have established vegetation. Vegetation management on the benches is important as, if it were to become unstable, large amounts of sediment would be mobilised in-stream. Mobile sediment 'slugs' have substantial impacts on aquatic communities through loss of habitat and migration routes (Bond and Lake 2003).

In 2001, the Victorian Government committed to undertaking a long term program of rehabilitation works on the Snowy River within Victoria. The objective of the works was to improve the ecological health of the Snowy River through implementation of in-stream, riparian and catchment works that complement the benefits of increased environmental flow releases. The Snowy tool is designed to be used as a decision support tool to inform rehabilitation works in selected reaches of the Lower Snowy River.

The Snowy tool has been created using the modelling approach, Bayesian networks. The selection of modelling platforms was undertaken in the first phase of the Snowy Rehabilitation Project (Phase 1 report, Borg 2008), in which Bayesian networks were deemed to be the most appropriate. The networks are scenario-based, providing an assessment of the cumulative outcomes within the river due to different management interventions. The project is concerned with predicting responses to the following interventions:

- riparian vegetation management (including changes to bed, bench and bank vegetation);
- management of vegetation on in-channel benches; and
- large wood installation (some form of in-stream structure).

2. MODEL DEVELOPMENT

Using preceding investigations, and in consultation with the end users, the model scope was defined, prototypes developed, reviewed and revised. The models aim to predict the likely outcomes of interventions to: scour holes for fish habitat and migration; occurrence of overbank inundation; avulsion likelihood; and bench and bank stability. The linkages between interventions and outcomes were based on response relationships derived in Phase 1 of the project (Borg and Argent 2008). These relationships were combined with other knowledge sources to derive Bayesian networks, which were developed in the modelling environment Netica (Norsys 2008).

2.1. Modelling Platform

Based on a review by Borg and Argent (2008) the most appropriate form for the Snowy tool was a Bayesian network. Bayesian networks are defined as graphical models consisting of a set of interconnected nodes and arcs (or arrows) incorporated with probability tables. Their selection was based on their ability to incorporate data from a range of sources (including other models and expert information). As they are probabilistic, they explicitly deal with uncertainties and can be used to graphically represent the likely outcome of interventions given a set of defined outcomes. By applying Bayes' theorem, Bayesian networks are inherently adaptable, allowing new information to be incorporated with relative ease. In natural resource management, Bayesian networks are increasingly becoming a modelling platform of choice. For a description of BNs and their use in natural resource management, see (Marcot 2006). For a description on how to construct a Bayesian network, see (Pollino et al. 2007).

The following section describes the scenarios, scales, additional hydraulic modelling and description of the sub-models within the Snowy tool.

2.2. Model Scales

The scale of interventions in the Lower Snowy required definition, where the spatial scale of interventions and time period for response were identified. The model needed to consider four reaches in the floodplain region of the Lower Snowy River, between Jarrahmond and Orbost (17.2 – 31.2km from the mouth of the Snowy). These reaches are:

- Reach 2: 26 – 31 km (Bete Bolong Levee)
- Reach 3: 25 – 26 km (Lynns Gulch)
- Reach 4: 22 – 25 km
- Reach 5: 15 – 22 km (Robinson's bank - Ashby and Watts Gulch)

The outcomes of interventions were considered for four reaches of the floodplain section of the Lower Snowy, over a ten-year planning horizon. A ten year period was considered a reasonable period for the local Catchment Management Authority (CMA) to work to. The flooding average recurrence intervals (ARIs) considered in the study were 1:1, 1:2, 1:5, 1:10, 1:50, and 1:100 year floods.

2.3. Additional physical modelling: Hydraulic modelling

To improve the representation of hydraulic behaviour in the Snowy tool, the need for further physical modelling was identified. Although the Snowy had been the focus of past hydraulic studies (e.g. (Sinclair Knight Merz 2005)), the management scenarios considered were regarded as either unrealistic or no longer relevant. Consequently, additional hydraulic modelling of the Lower Snowy was required to predict the likely changes in avulsion and overbank inundation given the management interventions defined in Section 1. This modelling was conducted using the Hydrologic Engineering Centre River Analysis System (HEC-RAS). The HEC-RAS model uses flow inputs to a river channel and predicts river hydraulics (e.g. sediment movement, overbank). The model was used to predict outcomes given different scenarios such as flow, sediment inputs, levee banks and installation of in-channel features (such as large wood), and these outputs were inputs for the models described in Section 3. The model was run for a set of ARIs described above and roughness measures (0.03, 0.05, 0.07, 0.09) on the bed and bank. The roughness measures act as surrogates, representing the amount of woody debris in a stream or the vegetation in channel and on the benches.

3. DESCRIPTION OF MODELS

As stated previously, this Phase 2 study was initiated to code index-based models, developed in Phase 1 (Borg 2008), as Bayesian networks. The index models related intervention activities to response, as informed by expert opinion and data. The index-based models informed the structure and relationship of the Bayesian networks. An expert workshop was conducted in Melbourne (October 2008) to review the Bayesian network prototypes. Workshop attendees included the Snowy Scientific panel, and representatives from CMA, Alluvium and the Department of Sustainability and Environment. Unfortunately, once codified, components of these models were considered to be of limited use as they were too subjective or considered an inadequate representation of the system complexity. Where possible, further efforts were undertaken to improve the models. A description of the Bayesian network models is given below.

3.1. Bench and Bank Stability

Vegetation on stream benches and banks has a number of roles, including maintaining biodiversity and effective stabilisation of sediments preventing erosion processes (Rutherfurd 2007; Borg 2008). Erosion is more likely to occur where removal of vegetation has occurred. Erosion can occur due to scour processes, which in the worst case scenario, can lead to bank slumping (Abernethy 1999). In order to limit scour, stream side and in channel vegetation can reduce local flow velocity and divert flow away from the bank, increasing stability and preventing the loss or failure of bench and banks (Abernethy 1999; Borg 2008).

Predicting the effectiveness of stabilisation of bench and the bank by vegetation is complicated by the range of potential erosion processes and the need for site specific and vegetation species-specific information (Abernethy 1999; Borg 2008). In the Snowy tool, an index-based approach, developed by Borg and Argent (2008) was used to model stability. The model has two outcomes: the bank stabilisation potential index and the bench stabilisation potential index.

The bank and bench indices are based on existing vegetation (EV) type; the proposed vegetation (PV) type; the vegetation establishment time (ET); and a hydrological component that accounts for the occurrence of a large, catastrophic flood (CF), shown in Equation 1. The index can vary over time (where time=i, from i=1 year to i=6-10 years, based on a 10 year planning horizon) (Borg 2008). The interaction of the factors is calculated using the formula:

$$\text{Bank stabilising potential index}_{\,time=i} = [EV + ((PV - EV) \times ET_{\,time=i})] \times CF \qquad \text{Eq. 1}$$

The bench stabilising potential index is a separate formula, but with the same construction as Eq. 1, where inputs relate to vegetation on the bench. The purpose of having separate outcomes is to represent different management interventions that may be implemented for each.

The effectiveness of stabilisation is dependent on vegetation type. Four different vegetation types, with their index values indicated brackets are considered in the model: no vegetation (0); grass (0.25); willows (1); and riparian rainforest (1) (Borg 2008). The bank stabilising potential of willows has been deemed to be similar to riparian rainforest, reflecting on work from Bailey and Rutherford 2004 (as cited in Borg (2008)).

Establishment time (ET) considers the stabilisation potential based on period of establishment time. In the model, it is assumed that a six-year-old restored riparian forest has the same bank erosion control as established willows (Rutherfurd 2007). The benefit of having native vegetation for biodiversity purposes is not considered. As defined by Borg and Argent (2008), the vegetation establishment time and the proportional change in stabilisation potential are: 0 years = 0, 1 year = 0.3, 2 years = 0.6, 3 years = 0.7.

The catastrophic flood factor (CF) recognises that vegetation can control bank erosion under a number of flow circumstances, but is ineffective at larger or catastrophic flows. Erskine and Saynor (1996) define a catastrophic flood as having a peak discharge of at least 10 times the magnitude of the mean annual flood. As bank vegetation is completely ineffective for erosion control when a catastrophic flood occurs, if it occurs the CF factor is 0, and if not it has been given the value of 1.

Density and type of riparian cover strongly influence all aspects of riverbank erosion. In this sub-model (Figure 1), we can examine the interactions between existing and proposed vegetation types, and its influence on either bank or bench stability, as influenced by flow.

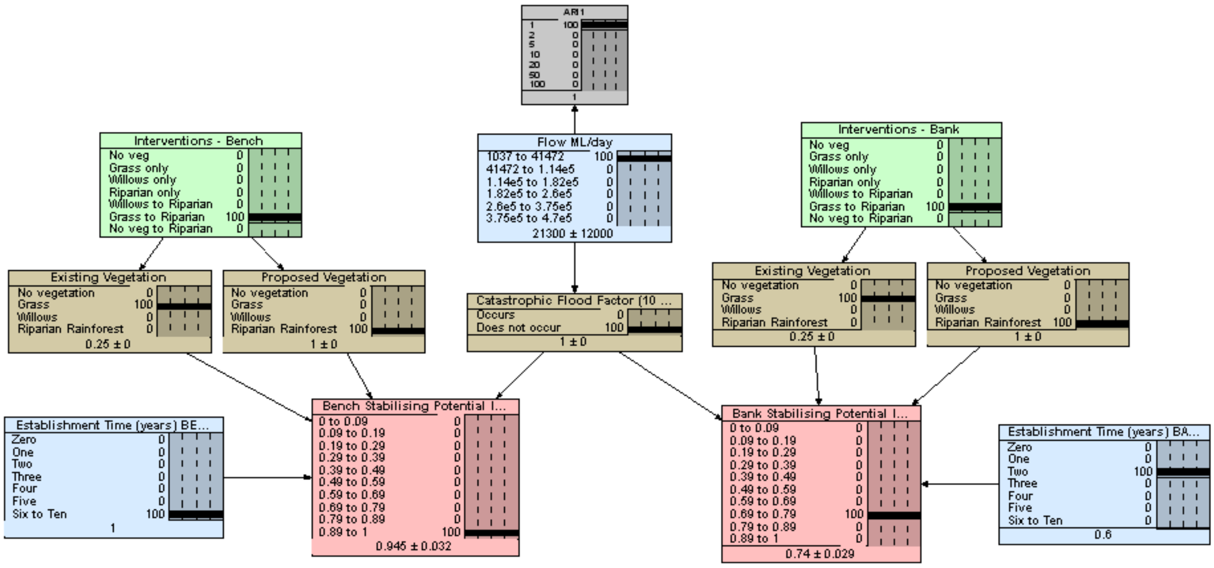

Figure 1. Scenario of Bench and Bank Stability

To demonstrate the use of the bench and bank stability model, the scenario tested for the bench (left hand side) is 'Existing vegetation = Grass" and "Proposed vegetation = Riparian Rainforest", with the vegetation establishment time being set to six to ten years. For the bank (right hand side) existing and proposed vegetation are the same as for the bench, but with an establishment time of only two years. For details on the model scenario and outcomes see Table 1.

Table 1. Bench and Bank Stability model scenario and outcomes

User Input	Model change/output	Explanation
Average Recurrence Interval input = 1	Catastrophic Flood Factor = 'Does not occur'	1 in 1 year flood is not considered catastrophic
Interventions – Bench = Grass to Riparian	Existing vegetation = Grass, Proposed vegetation = Riparian	Management intervention: native riparian vegetation is planted in an area where there was previously just grass
Establishment Time - bench = 6 to 10 years		The effectiveness of riparian vegetation is tested at 6 years post planting
Bench Stabilising Potential Index	**p = 0.89 to 1**	**Tested scenario outcome: proposed intervention is highly effective in stabilising the bench.**
Interventions – Bank = Grass to Riparian	Existing vegetation = Grass, Proposed vegetation = Riparian	There will be a management intervention, where Riparian vegetation will be planted where there was previously only Grass
Establishment Time - bank = 2 years		The effectiveness of riparian vegetation is tested at 2 years post planting
Bank Stabilising Potential Index	**p = 0.69 to 0.79**	**Tested scenario outcome: proposed intervention is effective in stabilising the bank.**

In a comparative scenario, where grass is maintained on the benches and no bank vegetation is present, the bench stabilising potential is low (p(Bench Stabilising Potential Index) = 0.19 to 0.29) and the bank stabilising potential index is very low (p(Bank Stabilising Potential Index) = 0 to 0.19). The 'grass only' bench scenario has a relatively low bench stabilisation potential, and no prospects for increased stabilisation as there is no change between existing and proposed vegetation. The 'no vegetation' bank scenario has the lowest bank stabilising potential.

In summary the model outputs show there is a greater stabilising potential from willows and riparian vegetation than grass or no vegetation (Rutherfurd 2007; Borg 2008), and greater stabilisation potential the longer the vegetation is allowed to establish (up to 6 years).

3.2. Avulsion Likelihood and Overbank Inundation Model

Avulsion likelihood and overbank inundation were combined into one sub-model, as they are influenced by the same drivers. However, they remain independent outcomes.

Avulsion Likelihood

Avulsion is the natural process, where flow is diverted out of an established river channel into a new permanent course on the adjacent floodplain. Smith (1978) describes two necessary conditions for avulsion:

1. A long-term 'set-up' in which the channel gradually increases its susceptibility to avulsion; and
2. A short-term 'trigger' event which initiates the flow diversion.

Using information from an expert panel, the gulches in the river were defined as susceptible points for avulsion. The model incorporates spatial components to take into consideration the increased susceptibility of these reaches. The user can test the likelihood of avulsion to flood events, given different management interventions. Thus, the approach adopted was to develop an avulsion likelihood index-based on:

1. the presence or absence of factors that predispose a system to avulsion; and
2. the occurrence of a flood event that exceeds a certain threshold (Borg 2008)

The avulsion likelihood index is made up of the following factors: sediment (representing mobilisation of material from upstream); vulnerability of reach avulsion; and stream power and duration of flow.

Scenarios were tested to assess the outcomes of interventions: large wood installation and vegetation management. As expected, large wood in-stream increases channel resistance because large woody debris has the potential to increase the likelihood of channel avulsion via increased stream power. Increased sand movement, as influenced by bench stability and vegetation management, can also increase the likelihood of avulsion occurring by blocking gulches.

Overbank Inundation

The occurrence of overbank inundation is influenced by the channel capacity and the channel resistance. Many aspects contribute to channel resistance, including: substrate type; the cross sectional variation; the types, density and extent of vegetation on the banks; obstructions in the channel; and the degree of channel meandering (Borg 2008).

The occurrence of overbank inundation is predicted using modelled data from the hydraulic model HEC-RAS, where the roughness inputs are used for representing vegetation or wood on the bench and in channel (described in Section 2.3). The Snowy tool uses the hydraulic model outputs to represent overbank inundation, predicting the likelihood of inundation occurring and the height of inundation. The HEC-RAS modelling was completed using the average bank height for each reach, as it was deemed a sufficient representation for the model (pers comm. Keller 2008). The HEC-RAS model does not consider connectivity between reaches. Therefore, if an overbank event occurs at an upper reach, this does not flow down to the following reaches. This is an important limitation that could be overcome with further HEC-RAS model investigations and local survey information.

In the Snowy tool, intervention scenarios include large wood installation and vegetation management. The model indicates that where large woody debris is placed in streams and where vegetation is maintained on benches in the river, the incidence of overbank inundation is likely to increase at ARI $\geq$ 2 years, particularly in two of the reaches.

3.3. Formation of Scour holes

Scour holes occur where the removal of individual sediment particles or aggregates occurs by flow (Abernethy 1999). The maintenance and generation of scour holes are important in sedimented rivers for facilitating ecological processes, such as fish migration. A sand slug can dramatically modify channel geometry and cause significant habitat modification in streams by burying woody debris and reducing channel volume, water depth and channel complexity (Bond and Lake 2003). In the Snowy system, scour hole formation has been reduced by removal of woody debris. The reintroduction of woody debris is critical for promoting scour hole formation. These holes need to be appropriately spaced for effective fish migration.

Predicting scour hole formation is complicated by the sediment type, channel configuration, flow regime, and delivery of sediment from reaches further up the river. Despite several years of investigations in the Lower Snowy River, no models for scour prediction have been developed, despite the critical importance of establishing fish migration in the system (Department of Sustainability & Environment 2004). Consequently, only a simple model was developed for scour, using data from an earlier modelling study (Sinclair Knight Merz 2005) and expert opinion.

In the Snowy tool, scenarios were tested for large wood installation and mobilisation of upstream reaches. Although high flows ($\geq$ 10300 ML/day) are likely to promote localised scour hole formation, the sand mobilised from upper reaches is likely to negate any improvements in fish habitat.

4. DISCUSSION

To rehabilitate the Lower Snowy River, the dynamic features of the system need to be returned, but the system is going to need a prolonged time to recover to an ecologically 'healthy' state. The installation of large woody debris would provide passage for native fish, which are known to respond strongly to local habitat manipulations that increase the availability of deeper, slow flowing water (Bond and Lake 2003). However, the build up of sediment in the channel due to increased sedimentation rates as a consequence of a reduction in natural flows has lead to the establishment of vegetation on in-stream benches. Any actions that destabilise benches are likely to mobilise large amounts of sediments to downstream reaches. Large woody debris would become vulnerable to mobilisation of large amounts of sediment.

The sub-models developed in this project are highly subjective, based on limited information and, given the different scales, flow regimes and types of interventions tested in physical modelling studies, the sub-models were unable to be integrated. This highlights the limitations of developing a tool for management when the knowledge of the system and its behaviour is poor. It also highlights that the studies initiated over the Snowy Rehabilitation program have not been well integrated or executed, with little integration in activities upfront. Consequently, the Snowy Tool has been implemented by the CMA as part of an adaptive management program; with the model being updated as rehabilitation works are undertaken.

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