Systematic planning for river rehabilitation: integrating multiple ecological and economic objectives in complex decisions.

Virgilio Hermoso ^{1,2,3}, Francis Pantus ^{1,3}, Jon Olley ^{1,3}, Simon Linke ^{1,2,3}, James Mugodo ³ and Patrick Lea ³.

¹ Australian Rivers Institute. Griffith University, Nathan Campus. Kessels Rd, 4111 Queensland. Australia.

² The Ecology Centre, School of Biological Sciences, University Queensland, St Lucia, 4168 Queensland, Australia.

³ eWater Cooperative Research Centre, The University of Melbourne. Parkville, 3010 Victoria, Australia.

Corresponding author: Virgilio Hermoso

email: virgilio.hermoso@gmail.com

Tlf: (61) 04 37218750

Running head: Freshwater systematic rehabilitation planning

Summary

1. Due to intensive human use freshwaters are among the most seriously threatened and modified environments on the planet. Their poor condition and the risk to services that humans need from these ecosystems make their rehabilitation a priority. However, many previous studies have reported the poor performance of many rehabilitation activities.

2. Here, we analyse reasons for this poor performance, focusing on the planning of rehabilitation activities, and propose a new approach.

3. We argue that the failure to include driving factors at a scale adequate to capture the ecological processes involved, together with an insufficient incorporation of socio-economic aspects, are key factors leading the poor performance of many rehabilitation activities.

4. We propose a new approach “Systematic rehabilitation planning” that brings together advances made in conservation planning (cost-effectiveness analysis) and ecosystem science (understanding the complexity of ecosystem processes). This enables planning to be done at the catchment scale, and the tradeoffs between various rehabilitation actions to be integrated and prioritized.

5. Finally, it is important given the constraints imposed by a lack of knowledge, that the planning process is part of an adaptive cycle where it can benefit from and consolidate the experience gained during the implementation and monitoring stages.

Keywords: Adaptive management, cost, efficacy, efficiency, integration, monitoring, multi-objective.

Introduction

Freshwaters are among the most seriously threatened and modified environments on the planet, due to intensive human use (Sala *et al.*, 2000). These systems have been crucial for human development (Malmqvist & Rundle, 2002). Human use has altered the ecology of freshwaters through habitat destruction and fragmentation, physical and chemical alterations, and the introduction of exotic species or overexploitation of freshwater resources (Collares-Pereira & Cowx, 2004). Changes in the catchments have also had significant impacts on freshwater ecosystems. Deforestation and agricultural development in many regions has significantly altered both flow and sediment regimes (Kreutzweiser *et al.*, 2005; Jordan, 2006). In some cases the degradation is so severe that it conflicts with further human use (eg Srinivasan & Reddy, 2009). The situation is expected to worsen in the next decades due to the combined effects of human population growth and climate change (Bates *et al.*, 2008).

In response to both the poor conservation status and increasing resource pressure rehabilitation projects are being implemented throughout the world (Roni, Hanson & Beechie, 2008). It is estimated that more than US\$ 1 billion is spent annually on rehabilitation projects in the USA alone, and the number of projects has increased exponentially in the last decade (Bernhardt *et al.*, 2005). Similar patterns have been reported in other areas (e.g. Verdonschot & Nijboer, 2002; Giller, 2005). Despite the high number of rehabilitation projects being implemented the rate of success is low (Alexander & Allan, 2007). Here, we analyse the main reported causes for the failure or poor efficiency of many rehabilitation projects, and propose a new approach to improve their success. In this paper we focus on the project planning process rather than comparing the efficiency of different rehabilitation techniques. The latter should be addressed once information on the efficacy of rehabilitation techniques has been systematically reviewed.

Why is rehabilitation planning needed?

Despite the considerable resources that are allocated to improving the condition of aquatic ecosystems, they are small compared to the scale of the problem (Prosser *et al.*, 2001). There is a need to make the most efficient use of the resources devoted to rehabilitation. A rehabilitation plan must specify what set of actions are needed and where they must be implemented; constrained by the available budget. Resources need to be targeted to specific actions and places that are expected to produce the maximum benefit.

Rehabilitation planning: facts and challenges

Rehabilitation projects are generally not well documented, and it is often not easy to obtain basic information on project actions and outcomes (Bernhardt *et al.*, 2005); although only limited recovery of the ecosystem has been reported often (Alexander & Allan, 2007). There are many factors contributing to this ineffectiveness, but the failure to address the driving factors at an adequate scale has been highlighted as the main cause (Beechie *et al.*, 2010). For effective and efficient rehabilitation planning to occur, this and other issues (outlined below) need to be addressed.

The path of least resistance

In a recent review on rehabilitation projects in the USA, Alexander & Allan (2007) reported that the most common approach to prioritize rehabilitation sites was “available land opportunities”, so projects were mainly implemented in areas that were available because of land ownership opportunities (public land or land-owners willing to implement rehabilitation). This approach results in rehabilitation efforts being focused on areas that are neither the most in need of rehabilitation, nor those that will produce the maximum benefit to the whole system. For example, even though the most severe habitat and land-use changes are commonly on lowland floodplains and deltas, most rehabilitation actions are concentrated in headwater areas and small tributaries (Bernhardt *et al.*, 2005), where land is more likely to be in some form of public ownership or it has a lower productive potential. This type of approach has also been a

common practice in conservation planning where they have been criticised for their inefficiency and inability to protect biodiversity adequately (Pressey & Tully, 1994).

Systematic conservation planning (Margules & Pressey, 2000) addresses this problem from a holistic point of view, incorporating not only issues immediately related to the adequate representation of the target biodiversity, but also how to plan for conservation in an efficient way. To achieve this, systematic approaches integrate cost, and other spatial constraints, that help identify a minimum set of areas that represent adequately the target biodiversity and promote its long term persistence. Systematic planning is not exclusive to conservation and has been applied to other fields, such as the optimization of land uses and water allocation to maximize agricultural productivity (Nikkami, Elektorowicz & Mehuys, 2002; Riedel, 2003; Sadeghia, Jalili & Nikkamib, 2009). Xevi & Khan (2005) proposed a method to optimize the allocation of water quotas among different crops subjected to water limitations to maintain gross productivity targets under ecological and economic constraints in Australia. Randhir *et al.* (2001) developed a catchment-based prioritization model for water quality protection by managing land use. However, systematic planning is not broadly used in rehabilitation projects and just a few examples are available (eg Llewellyn *et al.*, 1995; Peters & Marmorek, 2001; Steel *et al.*, 2008).

Problems with planning and implementation scales.

Riverine ecosystems consist of a suite of hierarchically nested physical, chemical and biological processes operating at widely varying space and time scales. Success of rehabilitation is more likely when planned at large-scale than in small local-scale projects. However, the difficulty of planning over large areas has prevented the application of this type of approach (Lake, Bond & Reich, 2007). In freshwater systems, catchments have been recognized as the optimal planning scale (Kershner, 1997; Alexander & Allan, 2007). However, most stream rehabilitation projects are planned and implemented at smaller scales (Likens *et al.*, 2009),

involving localised interventions in stream channels, riparian zones and floodplains (Bond & Lake, 2003; Bernhardt *et al.*, 2005; Lake *et al.*, 2007). These efforts have suffered from a lack of ecological understanding of catchment processes (Beechie *et al.*, 2010). Often, rehabilitation projects seem to be implemented to address the symptoms of a single environmental concern at small local-scale, without appropriate effort to address larger-scale processes that may be responsible for the observed environmental degradation (Alexander & Allan, 2007). These local scale restoration efforts can result in more harm than good (Frissell & Nawa, 1992). Furthermore, the local-scale is not the most appropriate for considering processes and responses of rehabilitation actions, unless the problem being addressed has its origin at that scale (Beechie *et al.*, 2010).

When considering spatial scales in rehabilitation projects two issues are usually confounded: the scale of planning and the scale of implementation. To be successful a rehabilitation programme should be planned at the whole catchment scale, as we state above, but does not necessarily have to be implemented at that scale (e.g. rehabilitation of whole catchments). This way, catchment processes can be more efficiently incorporated in the plan while optimizing the number and spatial allocation of rehabilitation actions. However, the misconception that both the planning and the implementation scales have to be the same, and the lack of tools to address rehabilitation planning at the catchment scale, hindered progress to date.

Integration of ecosystem processes in planning

An additional common cause of the failure of rehabilitation work is due the underlying causes of the degradation not being addressed (Beechie & Bolton, 1999; Hillmann & Brierley, 2005; Beechie *et al.* 2008). Rehabilitation should be planned and implemented understanding the physical and ecological context of the processes that determine the current condition (Roni *et al.*, 2002; Alexander & Allan, 2007; Beechie *et al.*, 2010). In this way rehabilitation science

should be closely linked to ecosystem science, which aims to understand the drivers (human and non-human) that influence ecological patterns and processes (Likens *et al.*, 2009). Adaptive strategies that allow the incorporation of the knowledge gained from monitoring programmes and re-evaluation of the rehabilitation priorities based on this new knowledge (Fig. 1) can also greatly enhance the effectiveness of the project. There are numerous examples in the scientific literature reporting only limited recovery after rehabilitation due to the lack of consideration of ecosystem processes and failure to address the cause of the problem (Palmer, Menninger & Bernhardt, 2010). Parkyn *et al.* (2003) reported that a riparian re-vegetation project in New Zealand succeeded in improving water clarity and channel stability, but macroinvertebrate communities showed little response. Harrison *et al.* (2004) also found minor effect of in-stream rehabilitation structures on macroinvertebrate communities in the United Kingdom. Similar poor effect of in-stream structures on fish populations were highlighted by Pretty *et al.* (2003).

Previous attempts to incorporate ecological processes in rehabilitation planning have relied on predictive models that estimate the outcomes under different rehabilitation scenarios (Pieterse *et al.*, 2002; Reichert *et al.*, 2007; Steel *et al.*, 2008). Predictive models are based on the relationship between different components of the system and can be used to forecast the responses of an ecosystem to different rehabilitation actions. For example, a predictive model can be used to estimate the expected reduction of bank erosion after riparian revegetation. However, predictive models have not been adequately integrated into the decision-making process to facilitate the identification of rehabilitation priorities. Predictions obtained from different models (reflecting different rehabilitation strategies) are often directly presented to stakeholders in independent maps (see Baker *et al.*, 2004; Berger & Bolte, 2004; Hulse, Branscomb & Payne, 2004). Each map shows a future scenario under different rehabilitation priorities, usually focused on a single type of rehabilitation intervention, such as removal of barriers or eradication of invasive species. It is then a stakeholders' task to integrate different rehabilitation options to form the rehabilitation plan. Finding an optimal combination of multiple rehabilitation options in this way is a difficult task. To facilitate decision-making and

strengthen the whole planning process, these different scenarios should be integrated before being offered to stakeholders (e.g., a map with benefits expected if three different rehabilitation actions were implemented in a certain area). Given the weaknesses of the methods in use, which fail to provide integrated recommendations, and the limitation of more complex approaches to deal with rehabilitation issues (see Stewar-Koster *et al.*, 2010), new methods and tools are urgently required.

Inefficient incorporation of social and economic issues

The conflict between ecological benefits and socio-economic costs is an important constraint (rehabilitation comes at a considerable expense – socially and economically) that may hinder the success of a rehabilitation project. Given the limited budgets for rehabilitation activities, the consideration of social, economic and land use constraints are an important issue when establishing rehabilitation priorities (Palmer *et al.*, 2005; Craig *et al.*, 2008; Beechie *et al.*, 2008). A number of different methods have been proposed for incorporating social and economic costs into rehabilitation planning. Qureshi & Harrison (2001) dealt with conflicts in social and economic costs of riparian re-vegetation projects using a multi-criteria analysis tool (MCA). They claimed this to be appropriate for evaluating alternative riparian re-vegetation options, and for accommodating the conflicting views of various stakeholder groups. Using this method, they ranked different re-vegetation scenarios according to the preferences of each social group. Qureshi & Harrison (2001) suggested that this information could then be used to implement rehabilitation actions on those areas where socio-economic conflicts were low. However, MCAs fail to integrate multiple preferences from different social groups. In the end, stakeholders have to make their decisions based on a set of unconnected scenarios or priorities as explained in the previous section. In a recent study, Steel *et al.* (2008) incorporated estimates of the economic costs of different rehabilitation strategies for enhancing populations of Pacific salmon in a catchment in south-western USA. They identified six rehabilitation strategies,

including spending the entire budget on barrier removal, or riparian protection only or on a suite of mixed options. For each of the strategies they allocated rehabilitation actions until the budget was used, and then predicted the benefit that each of the six strategies would bring in terms of improved habitat quality. This approach is a substantial improvement on previous methods since it allows a comparison of costs and benefits for different each of the rehabilitation strategies. However, it is limited because of the small number of options that can be evaluated (typically <10) (Hulse, Branscomb & Payne, 2004; Baker *et al.* 2004). Moreover, as highlighted above, the integration of results from different strategies is also lacking.

There are examples of effective incorporation of cost in the planning process in other fields, such as systematic conservation planning, landscape rehabilitation projects (Espelta, Renata & Habrouk, 2003), land use optimization (Onal *et al.* 1998) or forest management (Ducheyne, Wulf & Baets,. 2004). There is also a growing knowledge about the costs of rehabilitating freshwater ecosystems (Nielsen-Pincus & Mosseley, 2010). Given these precedents in methods and information for freshwater projects, scientists/managers should be able to incorporate socio-economic considerations explicitly in freshwater rehabilitation planning.

Insufficient and/or inadequate monitoring.

In a review on over 37,000 river rehabilitation projects in the USA, Bernhardt *et al.* (2005) found it very difficult to get basic data on project actions and outcomes. They reported that only 10% of project records indicated that any form of assessment or monitoring occurred. The lack of adequate monitoring and reporting of project outputs explains the absence of major reviews on rehabilitation practices in freshwater systems (Roni, Hanson & Beechie, 2008). This is a common issue highlighted in many other studies (Verdonschot & Nijboer, 2002; Hillman & Brierly, 2005) and has direct implications on rehabilitation success, not only for the actual project being implemented, but for future projects. The lack of reliable information (from

previous experience) on success or failure of previous rehabilitation practices does not help avoid costly errors and pose a serious constrain when setting rehabilitation priorities (Fig. 1). In this sense, monitoring should play key role in future decision-making processes or in the adaptive management of projects already implemented to overcome constraints imposed by lack of knowledge and advise on best practices (“learning” and “adjust” in Fig. 1) (Hanley & Power, 1996; Downs & Kondolf, 2002). However, the ability to design and conduct evaluation studies with sufficient statistical power is frequently beyond the capability of most practitioners, due to the long period of monitoring needed to confirm a response (Roni *et al.*, 2005) or number of replicates needed to gain sufficient statistical power. It would be unrealistic in terms of cost to force every rehabilitation project to implement an exhaustive and extensive monitoring programme. Nevertheless, some standardized procedures that allow rehabilitation practitioners to evaluate the effectiveness of programmes should always be developed as best practice (Palmer *et al.*, 2005).

Systematic rehabilitation planning: a new decision support system for river rehabilitation.

Systematic rehabilitation planning has its foundations in ecosystem processes and socio-economic constraints. By addressing these two aspects we ensure that the rehabilitation project will not only improve the symptoms but will also address the driving factors responsible for the degradation in the most cost-effective way. Firstly, rehabilitation planning must identify the driver(s) of the problem being targeted, and incorporate the best available information on the ecological processes involved in the degradation. This can be done, for example, by using statistical models that estimate the effect of each rehabilitation action on the pursued objectives (e.g. river bank erosion models). Secondly, socio-economic constraints must lead to the identification of the most efficient set of rehabilitation actions for achieving the rehabilitation goals. These must include not only cost of rehabilitation but also social aspects, such as the

implications of rehabilitation actions on local economies (the so called opportunity cost in conservation planning), and landowner willingness to collaborate. If correctly addressed, all these issues will help deliver more realistic and efficient rehabilitation plans and aid their implementation (Barmuta *et al.*, 2011).

Following the arguments above, we propose two basic improvements to current decision support systems under a systematic planning framework. Firstly, planning methods must facilitate the decision-making of stakeholders by providing them with integrated solutions, where ecosystem processes have been incorporated, across multiple rehabilitation actions (Fig. 2). Rather than showing different rehabilitation scenarios for each management action, these should be offered already combined to stakeholders. This can be done by seeking the best combination of management actions that achieve the rehabilitation goals at the minimum cost (Fig. 3). This complex task is currently addressed in conservation planning by using optimization methods, such as meta-heuristic algorithms (Possingham *et al.*, 2000). Optimization algorithms increase the number of scenarios that can be evaluated. Instead of prospecting just a few scenarios for each rehabilitation action independently, optimization algorithms can evaluate many different combinations of rehabilitation actions in a few minutes. This also implies a substantial difference in the way systematic planning involves stakeholders in the identification of rehabilitation priorities. In traditional methods, stakeholders have to determine which actions to implement, combining options from different rehabilitation maps containing predictions from different scenarios. Optimization methods can combine those actions and offer stakeholders different integrated rehabilitation scenarios (the stakeholder does not have to find the best combination) for a certain rehabilitation priority (Fig. 3).

Secondly, given the complexity of rehabilitation projects, future decision support systems for rehabilitation planning must be able to cope with more than one objective at the time. The main difference when planning for several objectives with respect to a single objective problem is that in the latter there is only one global optimum, while in multi-objective optimization there is no single optimal solution. Multiple-objectives usually conflict so that improvement in one is

11

usually achieved at the expense of the others. This implies a drastic change to the optimization philosophy since, instead of searching for a global optimum, multi-objective methods focus on showing the best *trade-off* between a set of competing objectives. In other words, they try to find that set of solutions that maximizes the gain in one objective while minimizing the decline in the others (so called ‘non-dominated’ solutions). These solutions form a *Pareto-optima* (Czyzak & Jaszkiewicz, 1998), which can be easily checked and evaluated (Fig. 3). The use of Pareto graphs would facilitate the decision-making process, since they clearly show the gains and losses in the objectives pursued and allow stakeholders to evaluate the implication of their preferences on all the objectives in an integrated way. Multi-objective optimization methods have been applied to diverse environmental problems, such as the optimization of spatial forest management (Ducheyne, Wulf & Baets, 2004) or optimal water allocation problems (Xevi & Khan, 2005). However, they have never been implemented in freshwater rehabilitation planning.

Conclusion

Rehabilitation resources are limited and need to be targeted to specific actions and places that are expected to produce the maximum benefit. A rehabilitation plan must specify what set of actions are needed and where they must be implemented; constrained by the available budget. Systematic rehabilitation planning is a new planning approach that brings together advances made in conservation planning (cost-effectiveness analysis) and ecosystem science (understanding the complexity of ecosystem processes). It is a process-based method which enables planning to be done at the catchment scale, the tradeoffs (ecological, social and economic) between various rehabilitation actions to be integrated, and thousands of different planning scenarios to be considered in parallel. The inclusion of both ecosystem processes and socio-economic issues should facilitate the decision-making in rehabilitation planning and improve the cost-effectiveness of rehabilitation projects. It is important that this planning

process, like all others, should be part of an adaptive cycle. It can then benefit from and consolidate the experience gained from the implementation and monitoring of the rehabilitation activities. Given the potential benefits that the implementation of systematic planning in rehabilitation projects would bring we encourage further research on this topic to develop the methods and tools necessary to put the ideas we present here into practice.

Acknowledgments

The authors would like to thank SEQ Healthy Waterways Partnership and the eWater Cooperative Research Centre for financial support of this work, and two anonymous reviewers for their comments on an earlier version of this manuscript. We also thank A. Hildrew and an anonymous reviewer for their helpful comments on an early version of this manuscript.

References

- Alam, K. (2008) Cost-Benefit Analysis of Restoring Buriganga River, Bangladesh. *International. Journal of Water Resources Development*, **24**, 593-607.
- Alexander, G.G. & Allan, J. D. (2007) Ecological success in stream restoration: case studies from the Midwestern United States. *Environmental Management*, **40**, 245-255.
- Baker, J., Hulse, D. W., Gregory, S. V., Van sickle, J., Berger, P. A., Dole, D. & Schumaker, N. H. (2004) Alternative futures for the Willamette River basin, Oregon. *Ecological Applications*, **14**, 313-324.
- Bates, B.C., Kundzewicz, Z.W., Wu, S. & Palutikof, J.P. (2008) *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. IPCC Secretariat, Geneva.
- Barmuta, L.A., Linke, S. & Turak, E. (2011) Bridging the gap between “planning” and “doing” for biodiversity conservation in freshwaters. *Freshwater Biology*, **56**, 180-195.
- Beechie, T.J. & Bolton, S. (1999) An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. *Fisheries*, **24**, 6-15.
- Beechie, T.J., Pess, G., Roni, P. & Giannico, G. (2008) Setting River Restoration Priorities: a Review of Approaches and a General Protocol for Identifying and Prioritizing Actions. *North American Journal of Fisheries Management*, **28**, 891-905.
- Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., Roni, P. & Pollock, M. M. (2010) Process-based Principles for Restoring River Ecosystems. *BioScience*, **60**, 209-222.
- Berger, A. & Bolte, J. P. (2004) Evaluating the impact of policy options on agricultural landscapes: an alternative-futures approach. *Ecological Applications*, **14**, 342-354.
- Bernhardt, E.S., Palmer, M.A., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, B., Katz, S., Kondolf, G.M., Lake, S., Lave, R., Meyer, J. L., O'Donnell, T.

- K., Pagano, L., Powell, B., Sudduth, E. (2005) Synthesizing U.S. River Restoration Efforts. *Science*, **308**, 636-637.
- Bond N.R. & Lake P.S. (2003) Local habitat restoration in streams: constraints on the effectiveness of restoration for stream biota. *Ecological Management and Restoration*, **4**, 193-198.
- Collares-Pereira, M.J. & Cowx, I. G. (2004) The role of catchment scale environmental management in freshwater fish conservation. *Fisheries Management and Ecology*, **11**, 303-312.
- Craig, L.S., Palmer, M.A., Richardson, D.C., Filoso, S., Bernhardt, E.S., Bledsoe, B.P., Doyle, M.W., Groffman, P.M., Hassett, B.A., Kaushal, S.S., Mayer, P.M., Smith, S.M. & Wilcock, P.R. (2008) Stream restoration strategies for reducing river nitrogen loads. *Frontiers in the Ecology and the Environment*, **6**, 529-538.
- Czyzak, P. & Jaskiewicz, A. (1998) "Pareto Simulated Annealing—A Metaheuristic Technique for Multiple-Objective Combinatorial Optimization. *Journal of Multi-Criteria Decision Analysis*, **6**, 34–47.
- Downs, P.W. & Kondolf, G.M. 2002: Post-project appraisals in adaptive management of river channel restoration. *Environmental Management* **29**, 477–96.
- Ducheyne, E.I., de Wulf, R.R. & de Baets, B. (2004) Single versus multiple objective genetic algorithms for solving the even-flow forest management problem. *Forest Ecology and Management*, **201**, 259–273.
- Espelta, J.M., Retana, J. & Habrouk, A. (2003) An economic and ecological multi-criteria evaluation of reforestation methods to recover burned *Pinus nigra* forests in NE Spain. *Forest Ecology and Management*, **180**, 185–198.
- Frissell, C.A. & Nawa, R. K. (1992) Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. *North American Journal of Fisheries Management*, **12**, 182-197.

- Giller, P.S. (2005) River restoration: seeking ecological standards. Editor's introduction. *Journal of Applied Ecology*, **42**, 201-207.
- Hanley, A. & Power, R.L. (1996) Adaptive management for sound ecosystem management. *Environmental Management*, **20**, 879-86.
- Harrison S.S.C., Pretty J.L., Shepherd D., Hildrew A.G., Smith C. & Hey R.D. (2004) The effect of instream rehabilitation structures on macroinvertebrates in lowland rivers. *Journal of Applied Ecology*, **41**, 1140-1154.
- Hillman, M. & Brierley, G. (2005) A critical review of catchment-scale stream rehabilitation programmes. *Progress in Physical Geography*, **29**, 50-76.
- Hulse, D. H., Branscomb, A. & Payne, S. G. (2004) Envisioning alternatives: using citizen guidance to map future land and water use. *Ecological Applications*, **14**, 325-341.
- Kershner, J.L. (1997) Setting riparian/ aquatic restoration objectives within a watershed context. *Restoration Ecology*, **45**, 15-24.
- Lake, P.S. (2001) On the maturing of restoration: linking ecological research and restoration. *Ecological Management & Restoration*, **2**, 110-115.
- Lake, P. S., Bond, N. & Reich, P. (2007) Linking ecological theory with stream restoration. *Freshwater Biology*, **52**, 597-615.
- Likens, G.E., Walker, K.F., Davies, P.E., Brookes, J., Olley, J., Young, W.J., Thoms, M.C., Lake, P.S., Gawne, B., Davis, J., Arthington, A.H., Thompson, R. & Oliver, R.L. (2009) Ecosystem science: toward a new paradigm for managing Australia's inland aquatic ecosystems. *Marine and Freshwater Research*, **60**, 271-279.
- Llewellyn, D.W., Schaffer, G.P., Craing, N.J., Creasman, L., Pashley, D., Swan, M. & Brown, C.. (1995) A decision support system for prioritizing restoration sites on the Mississippi River alluvial plain. *Conservation Biology*, **10**, 1446-1455.

- Malmqvist, B. & Rundle, S.R. (2002) Threats to the running water ecosystems of the world. *Environmental Conservation*, **29**, 134-153.
- Margules, C.R. & Pressey, R.L. (2000) Systematic conservation planning. *Nature*, **405**, 243-253.
- Nielsen-Pincus, M. & Mosseley, C. 2010. "Economic and employment impacts of forest and watershed restoration in Oregon." Working Paper No. 24. *Ecosystem Workforce Program, Institute for A Sustainable Environment*, University of Oregon, Eugene.
Available at <http://ewp.uoregon.edu/sites/ewp.uoregon.edu/files/downloads/WP24.pdf>
- Nikkami, D., Elektorowicz, M. & Mehuys, G.R. (2002) Optimizing the management of soil erosion. *Water Quality Research Journal in Canada*, **37**, 577-586.
- Onal, H., Algozin, K.A., Isik, M. & Hornbaker, R.H. (1998) Economically efficient watershed management with environmental impact and income distribution goals. *Journal of Environmental Management*, **53**, 241-253.
- Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C. N., Follstad Shah, J., Galat, D. L., Loss, S. G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L., O'donnell, T.K., Pagano, L. & Sudduth, E. (2005) Standards for ecologically successful river restoration. *Journal of Applied Ecology*, **42**, 208-217.
- Palmer, M. A., Menninger, H. L. & Bernhardt, E. (2010) River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? *Freshwater Biology*, **55**, 205-222.
- Parkyn S.M., Davies-Colley R.J., Halliday N.J., Costley K.J. & Croker, G.F. (2003) Planted riparian buffer zones in New Zealand: do they live up to expectations? *Restoration Ecology*, **11**, 436-447.
- Peters, C.N. & Marmorek, D. R. (2001) Application of decision analysis to evaluate recovery actions for threatened Snake River spring and summer Chinook salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences*, **58**, 2431-2446.

- Pieterse, N.M., Verkroost, A.W.M., Wassen, M., Olde Venterink, H. & Kwakernaak, C. (2002) A decision support system for restoration planning of stream valley ecosystems. *Landscape Ecology*, **17**, 69-81.
- Possingham, H.P., Ball, I.R. & Andelman, S. (2000) Mathematical methods for identifying representative reserve networks. *Quantitative Methods for Conservation Biology* (eds. S. Ferson & M. Burgman), pp. 291-305. Springer-Verlag, New York.
- Pressey, R.L. & Tully, S.L. (1994) The cost of ad hoc reservation: a case study in New South Wales. *Australian Journal of Ecology*, **19**, 375-384.
- Pretty, J.L., Harrison, S.S.C., Shepherd, D.J., Smith, C., Hildrew, A.G. & Hey, R.D. (2003) River rehabilitation and fish populations: assessing the benefit of instream structures. *Journal of Applied Ecology*, **40**, 251-265.
- Prosser, I.P., Rutherford, I.D., Olley, J.M., Young, W.J., Wallbrink, P.J. & Moran, C.J. (2001) Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. *Marine and Freshwater Research*, **52**, 81-99.
- Qureshi, M.E. & Harrison, S.R. (2001) A decision support process to compare Riparian *re-vegetation* options in Scheu Creek catchment in North Queensland. *Journal of Environmental Management*, **62**, 101-112.
- Randhir, T.O., O'Connor, R., Penner, P.R., Goodwin, D.W. (2001) A watershed-based land prioritization model for water supply protection. *Forest Ecology and Management*, **143**, 47-56.
- Reichert, P., Borsuk, M., Hostmann, M., Schweizer, S., Sporri, C., Tockner, K. & Truffer, B. (2007) Concepts of decision support for river rehabilitation. *Environmental Modelling and Software*, **22**, 188-201.
- Riedel, C. (2003) Optimizing land use planning for mountainous regions using LP and GIS towards sustainability. *Journal of Soil Conservation*, **34**, 121-124.

- Roni, P., Beechie, T.J., Bilby, R.E., Leonetti, F.E., Pollock, M.M. & Pess, G.R. (2002) A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. *North American Journal of Fisheries Management*, **22**, 1–20.
- Roni, P., Hanson, K. & Beechie, T. (2008) Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques. *North American Journal of Fisheries Management*, **28**, 856-890.
- Sadeghia, S.H.R., Jalili, Kh. & Nikkamib, D. (2009) Land use optimization in watershed scale. *Land Use Policy*, **26**, 186–193.
- Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, L., Sykes, M.T., Walker, B.H., Walker, M. & Wall, D.H. (2000) Biodiversity – global biodiversity scenarios for the year 2100. *Science*, **287**, 1770–1774.
- Steel, E.A., Fullerton, A., Caras, Y., Sheer M.B., Olson, P., Jensen, D., Burke, J., Maher, M. & McElhany, P. (2008) A spatially explicit decision support system for watershed-scale management of salmon. *Ecology and Society*, **13**, 50-81.
- Stewart-Koster, B., Bunn, S.E., Mackay, S.J., Poff, N.L., Naiman, R.J. & Lake, P.S. (2010) The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. *Freshwater Biology*, **55**, 243–260.
- Verdonschot, P.F.M. & Nijboer, R.C. (2002) Towards a decision support system for stream restoration in The Netherlands: an overview of restoration projects and future needs. *Hydrobiologia*, **478**, 131-148.
- Xevi, E. & Khan, S. (2005) A multi-objective optimisation approach to water management. *Journal of Environmental Management*, **77**, 269–277.

Figure 1. Conceptual scheme of rehabilitation programmes incorporating an adaptive management approach. Rehabilitation projects are conceived as leading a current degraded system to a desirable state through the implementation of rehabilitation actions. The effectiveness of these actions is monitored and assessed. The assessment is incorporated into a better understanding of the system (learning) and, if required, the plans and actions are adjusted. The process is constrained by socio-economic issues (e.g. budget limits) and knowledge limitations. Knowledge constraints can be overcome by incorporating the information gained during the monitoring, evaluation and learning phase into the planning process. In this way, the effectiveness of these actions can help correct initial misallocation of budget (adjust the current plan) and serve as an example for future plans (reduce knowledge constraints).

Figure 2. Prioritization scheme of multiple objectives in rehabilitation projects. The improvement in the current status of each action that is believed to be necessary is evaluated using predictive models or any other estimate of their effectiveness. This produces information on different rehabilitation scenarios and cost associated that need to be combined to set rehabilitation priorities. Systematic methods differentiate from traditional methods in the way this information is integrated. Traditional rehabilitation schemes provide several independent rehabilitation scenarios in different maps resulting from the implementation of a particular action each (e.g. dam removal, riparian re-vegetation) and then stakeholders have to combine them to find the best way to achieve the rehabilitation objectives. Systematic planning integrates all the considered actions, so synthetic solutions showing the best trade-offs between objectives are presented to stakeholders. Then they can check the influence of objective priorities (e.g. giving more importance to sediment reduction than to nutrient reduction) on rehabilitation priorities (actions and their spatial allocation). Note that in this systematic approach actions have been integrated into solutions in the optimization method, so every solution contains an optimized combination of rehabilitation actions. In this way the identification of particular actions to be implemented is facilitated to stakeholders.

Figure 3. Optimal allocation of rehabilitation actions throughout a catchment for different rehabilitation priorities. In an ideal scenario, with enough money, the whole catchment could be rehabilitated. However, the budget available constrains the implementation of rehabilitation actions. Optimizing the spatial allocation of actions throughout the catchment (planning scale) helps to find efficient ways of achieving the rehabilitation goals. Actions are implemented at the local scale but the plan is developed at the whole catchment scale. The identity and spatial allocation of rehabilitation actions (rehabilitation priorities) will depend on the relative weight that stakeholders give to each objective. Each dot in the Pareto front represents a particular combination of rehabilitation actions that maximizes the gain in one of the objectives while minimizing the loss in the others. For example, when a high importance is given to one of the objectives (solutions close to axes), most of the budget will be spent on remediating that particular objective (e.g., eradication of invasive species or remediation of bank erosion, D and F respectively). Intermediate solutions can also be found showing better compromise in the trade-offs between different objectives (E).