Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation

Author

Bunn, SE, Abal, EG, Smith, MJ, Choy, SC, Fellows, CS, Harch, BD, Kennard, MJ, Sheldon, F

Published

2010

Journal Title

Freshwater Biology

DOI

10.1111/j.1365-2427.2009.02375.x

Integration of science and monitoring of river ecosystem health to guide investments in catchment protection and rehabilitation

S.E. BUNN[*], E.G. ABAL[†], M.J. SMITH[§], S.C. CHOY[‡], C.S. FELLOWS[*], B.D. HARCH[¶], M.J. KENNARD[*], F. SHELDON[*]

[*] *Australian Rivers Institute, Griffith University, Nathan, Queensland, Australia, 4111*

[†] *SEQ Healthy Waterways Partnership, Brisbane, Queensland, Australia, 4072*

[§] *Environment Branch, Sunshine Coast Regional Council, Queensland, Australia, 4560*

[‡] *Queensland Department of Environment and Resource Management, Long Pocket Laboratories, Indooroopilly, Queensland, Australia, 4068*

[¶] *CSIRO Mathematical & Information Sciences, Long Pocket Laboratories, Indooroopilly, Queensland, Australia, 4068*

Running Head: Integration of science and monitoring of river health

Keywords: adaptive management, riparian revegetation, river restoration

Correspondence: S.E. Bunn, Australian Rivers Institute, Griffith University, Nathan, Queensland, Australia, 4111. E-mail: *s.bunn@griffith.edu.au*

SUMMARY

1. Stream ecosystem health monitoring and reporting need to be developed in the context of an adaptive process that is clearly linked to identified values and objectives, is informed by rigorous science, guides management actions and is responsive to changing perceptions and values of stakeholders. To be effective, monitoring programs also need to be underpinned by an understanding of the likely causal factors that influence the condition or health of important environmental assets and values. This is often difficult in stream and river ecosystems where multiple stressors, acting at different spatial and temporal scales, interact to affect water quality, biodiversity and ecosystem processes.

2. In this paper, we describe the development of a freshwater monitoring program in South East Queensland, Australia and how this has been used to report on ecosystem health at a regional scale and to guide investments in catchment protection and rehabilitation. We also discuss some of the emerging science needs to identify the appropriate scale and spatial arrangement of rehabilitation to maximise river ecosystem health outcomes and at the same time derive other benefits downstream.

3. An objective process was used to identify potential indicators of stream ecosystem health and then test these across a known catchment land use disturbance gradient. From the 75 indicators initially tested, 22 from five indicator groups (water quality, ecosystem metabolism, nutrient cycling, invertebrates and fish) responded strongly to the disturbance gradient and 16 were subsequently recommended for inclusion in the monitoring program. The freshwater monitoring program was implemented in 2002, funded by local and State government authorities, and currently involves the assessment of over 120 sites, twice per year. This information, together with data from a similar program on the region's estuarine and coastal marine waters, forms the basis of an annual report card that is presented in a public ceremony to local politicians and the broader community.

4. Several key lessons from the SEQ Healthy Waterways Program are likely to be transferable to other regional programs aimed at improving aquatic ecosystem health, including the importance of a shared common vision, the involvement of committed individuals, a cooperative approach, the need for defensible science, and effective communication.

5. *Thematic implications*. This study highlights the use of conceptual models and objective testing of potential indicators against a known disturbance gradient to develop a freshwater ecosystem health monitoring program that can diagnose the likely causes of degradation from multiple stressors and identify the appropriate spatial scale for rehabilitation or protection. This approach can lead to more targeted management investments in catchment protection and rehabilitation, greater public confidence that limited funds are being well spent and better outcomes for stream and river ecosystem health.

Introduction

It can be said that many environmental monitoring programs are simply a useful means of documenting decline (Nichols & Williams, 2006). To be much more than this, monitoring and reporting need to be developed in the context of an adaptive process (*sensu* Walters, 1986), that is clearly linked to identified values and objectives, is informed by new science, guides management actions and is responsive to changing perceptions and values of stakeholders. This approach requires extensive consultation and engagement with interest groups to derive a shared understanding of the range of important environmental assets and values that need to be considered (Meyer 1997; Walters, 1997).

In the case of stream and river ecosystems, these may include essential goods and services such as clean drinking water or fisheries production, conservation and biodiversity values, but also aesthetic and cultural values (Meyer, 1997; Bunn, 2003). The incorporation of a human dimension in which humans value rivers and the goods and services they provide for a range of needs and uses, and where unhealthy rivers satisfy only a subset of these, is critical (Meyer, 1997; Karr, 1999). Although many have argued that an analogy between human health and ecosystem health oversimplifies a complex issue (see Boulton, 1999), incorporating principles of ecological integrity (maintaining ecosystem structure and function) and human values (what society values in the ecosystem) into the definition of river health may provide impetus for advances in aquatic ecology, more effective and sustainable management of aquatic ecosystems, and broader acceptance of management goals and activities by the community (Meyer, 1997; Karr, 1999; Boulton, 1999). In the absence of a statement of agreed objectives, it is difficult to justify public investment in monitoring and even harder to argue for management interventions to protect or restore when issues are identified.

Such an approach also requires an understanding of the likely causal factors that influence the condition or health of important environmental assets and values (e.g. Bailey *et al*., 2007). Without 'diagnostic' capability, monitoring programs cannot be used to guide management intervention with any confidence. This is often difficult in stream and river ecosystems where multiple stressors, acting at different spatial and temporal scales, interact to affect water quality, biodiversity and ecosystem processes (Roth *et al*., 1996; Allan *et al*., 1997; Snyder *et al*., 2003; Townsend *et al*., 2003). The existence of multiple, scale-dependent mechanisms, potentially non-linear responses of biota to disturbance, and the difficulties of separating current from historical effects, can make it difficult to establish relationships between disturbance and ecosystem health indicators or to diagnose the specific sources or mechanisms of human impact (Allan, 2004). However, the development of conceptual models and targeted scientific investigations can inform this process and guide the selection of indicators of ecosystem health (Maddox *et al*., 1999; Thomas *et al*., 2006; Browne *et al*., 2007). Ideally, the indicators chosen should assist in the diagnosis of the likely cause of observed degradation and inform management actions (Dolédec *et al*., 2006; Bailey *et al*., 2007).

Stream and river ecosystem monitoring has traditionally relied on water quality methods and structural measures of the biota, especially fish and invertebrate assemblages though benthic algal communities, protozoa and macrophytes have also been used (e.g., Bunn, 1995; Hill *et al*., 2000; Norris & Hawkins, 2000). Trait based indicators, rather than measures of assemblage composition, have recently been proposed to provide greater diagnostic capability (Dolédec *et al*., 2006; Dolédec & Statzner, 2008). There is also growing recognition of the need to incorporate ecosystem process measures in assessment programs, as many goals of river management relate directly to the maintenance of natural ecological processes (Bunn & Davies, 2000; Gessner & Chauvet, 2002; Bott *et al*., 2006; Von Schiller *et al*., 2008). Such measures are often sensitive to causal factors that are known to affect river health and it is possible to develop simple but powerful predictive models of cause and effect (e.g. Bunn, Davies & Mosisch, 1999; Young *et al*., 2008).

It is clear that some of these indicator groups respond to human disturbances at different spatial and temporal scales to others (Boulton, 1999; Allan, 2004; Buck *et al.*, 2004). Incorporating a range of indicators in monitoring programs can help to identify whether impacts to stream and river ecosystems are the result of local factors (e.g. point source pollution), riparian or reach scale disturbances (e.g. stock access or riparian clearing), the effect of barriers downstream (e.g. Pringle, 1997) or the consequence of broader land use change in the upper catchment. Careful selection of indicators may help to not only diagnose the likely cause of degradation from a range of stressors but also identify the appropriate spatial scale for rehabilitation or protection. This should lead to more targeted management investments, greater public confidence that limited funds are being well spent and better outcomes for stream and river ecosystem health.

This paper describes the development of a freshwater monitoring program in South East Queensland, Australia and how this has been used to report on stream ecosystem health at a regional scale and to guide management responses. It explores some of the emerging science needs, particularly in relation to the effective scale and spatial arrangement of riparian protection and rehabilitation, and highlights the challenge of improving stream ecosystem health while at the same time meeting important environmental objectives downstream. This work also illustrates a need for the development of spatial optimisation tools to allow managers to assess which combination of actions will achieve the maximum environmental benefit(s) for the least cost.

South East Queensland study region

South East Queensland (SEQ) provides an excellent case study of the challenges for ecologically sustainable management of rivers and coastal ecosystems in the face of global change (Abal, Bunn & Dennison, 2005a; Bunn *et al*., 2007). With 15 major catchments and a combined area of nearly 23,000 km^2, it is the fastest growing region in Australia with a current population of nearly 3 million people. The receiving waters of Moreton Bay and associated estuaries are of high conservation value and support significant fisheries, and are extensively used for recreation and tourism (Abal, Bunn & Dennison, 2005b). The western catchments are the region's primary water supply, largely for urban use but also for agriculture.

Human activity in SEQ since European settlement has left a significant ecological footprint with only about one quarter of the native vegetation in the region remaining intact, and often much less along stream and river corridors in some catchments. The catchment hydrology has been substantially altered, not only from interception by dams and weirs but also because of changes in land-use and vegetation that have resulted in altered run-off responses to rainfall events and 'flashier' stream flows. Nutrients, fine sediments and, to a lesser extent, other toxicants were identified as causes of significant environmental problems (Abal *et al*., 2005b).

SEQ Healthy Waterways Partnership

Although public concern about declining water quality in Moreton Bay and the Brisbane River was noted in the mid-1970s, it was only in the 1990s that a coordinated approach began to address this. A key milestone was the development of the SEQ Regional Water Quality Management Strategy (SEQRWQMS, 2001), which led to the formation of the *Moreton Bay Waterways and Catchments Partnership* in 2002 – now known as the SEQ *Healthy Waterways Partnership* (www.healthywaterways.org). The Strategy was a joint Federal, State and local government initiative and was supported by an independent Scientific Expert Panel, a Technical Advisory Group of State and local government officers, and an Industry and Community Advisory Group of non-government representatives from industry, fishing, conservation, catchment management, Landcare and indigenous groups. Extensive consultation with the wider community was also undertaken.

An important aspect of the Strategy was the early development and agreement by all stakeholders of a single, clear vision for the future health of the region's waterways: "*By 2026, our waterways and catchments will be healthy ecosystems supporting the livelihoods and lifestyles of people in South East Queensland, and will be managed through collaboration between community, government and industry*" (SEQHWP, 2007). In the context of this vision, a broad range of values for the region's waterways was identified through numerous workshops with stakeholders from across the region. Once this agreed set of values was identified, measurable water quality and ecosystem health objectives were then determined to protect these values. Research organisations in the region collaborated to provide the rigorous science underpinnings for the monitoring program (Abal *et al*., 2005a). Finally, management actions were identified to achieve these objectives, working directly with policy makers.

Staged approach to research and monitoring

The SEQ Healthy Waterways Partnership adopted a staged approach in the development of the Strategy and its underpinning research and monitoring program (Abal *et al*., 2006, Bunn *et al*., 2007). The early research focus (1996 to 1998) was on urban areas in the lower catchment and estuarine areas of the Moreton Bay region (Dennison & Abal, 1999). A key finding was the identification of a large plume of organic-rich sediments at the mouth of the Brisbane River and re-suspension from tidal and wave action and increased turbidity is thought to be responsible for declines in seagrass in the western embayments, and associated declines in populations of dugongs, turtles and other biota (Abal *et al*., 2005a).

From 1999 to 2001, the Strategy turned its attention to the freshwater catchment areas and expanded the regional coverage to the north and south of the Brisbane River catchment. A major focus of research, modelling and monitoring during this period was on the catchment sources of sediments in Moreton Bay and estuaries. Initial catchment modelling combined with sediment tracer studies of cores taken from the Bay and its rivers indicated that most of the sediment originated from the south-western catchments (Caitcheon & Howes, 2005). Furthermore, these studies also indicated that channel erosion and not hill-slope erosion dominates throughout much of the region (Caitcheon & Howes, 2005). This result was not surprising given that about 50% of the 48,000 km of streams in South East Queensland have degraded riparian zones. Poor riparian condition is also a major cause of poor water quality and aquatic ecosystem health in streams in the region (Bunn *et al*., 1999; Rutherford *et al*., 2004; Smith, Carruthers & Bunn, 2005).

Commitment to an adaptive management process

Consistent with the philosophy of adaptive management (Walters, 1986; Nichols & Williams, 2006), the Healthy Waterways Partnership is committed to: (i) ongoing knowledge acquisition, (ii) the critical importance of monitoring; (iii) continuous improvement in the identification and implementation of management actions; and (iv) effective communication of knowledge for policy and planning. The approach recognises that management intervention can seldom be postponed until the information required to fully understand the situation is available (Abal *et al*., 2006). It is designed specifically to deal with the uncertainty that characterizes most problems in environmental management and is an iterative process that directly integrates monitoring (Nichols & Williams, 2006).

The Partnership has continued to invest in the refinement and testing of conceptual models (Thomas *et al*., 2006). These visual tools are not only used to improve our scientific understanding and to identify key knowledge gaps but also to communicate important processes to stakeholders. An Environmental Management Support System (EMSS) was developed to explore how point and diffuse source loads of sediment and nutrients influenced ambient water quality, and to assess whether water quality objectives can be met downstream (Vertessy & McAlister, 2005). The output of this catchment modelling tool provides input for a receiving water quality model for the tidal waterways and Moreton Bay. Decision support tools such as these have proven useful not only in evaluating the potential efficacy of various management actions aimed at the improvement of water quality, but also to assist stakeholders in determining sustainable loads and setting resource condition targets for waterways.

Equally important, has been the commitment to monitoring the effectiveness of management interventions. A comprehensive estuarine and marine Ecosystem Health Monitoring Programme (EHMP) was developed in Stage 2 of the Strategy and implemented in 1999 as part of Stage 3 (Smith & Grice, 2005). This program involves routine (monthly) sampling of water quality parameters at over 250 sites across the region. Other measures of ecosystem health (e.g. seagrass mapping, riparian condition) are also undertaken.

Development of the freshwater EHMP

The development of the freshwater EHMP formed a key component of the Partnership's science and monitoring framework in Stage 3 (Abal *et al*., 2005a). The aim was to develop a cost-effective, coordinated ecosystem health monitoring program for freshwaters of the region that could be used to measure and report on current status and future changes in ecological health and, where necessary, guide management actions.

When it comes to assessing the ecological health of freshwaters, there is often considerable debate about the best methods (Wicklum & Davies, 1995) and it is no coincidence that the proponents of various approaches promote their own "pet" indicators (see Bunn, 1995; Boulton, 1999). There is a clear need for an objective and comparative approach to assess the robustness and utility of the many potential indicators that are available. To overcome this, we adopted a similar approach to that previously developed by the Group of Experts on Environmental Pollution (GEEP) to detect anthropogenic impacts in marine systems (Bayne *et al*., 1988; Addison & Clarke, 1990; Stebbing & Dethlefsen, 1992). These studies objectively evaluated a broad range of indicators against a known disturbance gradient to identify those that best responded. The major land uses in South East Queensland are grazing and cropping (Abal *et al*., 2005b), and indicators were evaluated against multiple descriptors of the disturbance gradient within this setting.

The selection of the freshwater indicators was undertaken in two major phases (Fig. 1). Phase 1 was primarily a desk top study incorporating several workshops that identified a suite of potential indicators of ecosystem health, outlined initial monitoring protocols and the development a physical classification of stream types in the study area. This initial Phase concluded with a series of pilot studies for indicators that required additional development before considering further. In Phase 2, a major field trial was undertaken to test the short-listed indicators of ecosystem health across the known disturbance gradient. Results of the major field trial were used to evaluate which indicators were most suitable for inclusion in the EMHP for freshwaters (Fig. 1).

Disturbance gradient descriptors

Disturbance descriptors of the catchment land use gradient were derived from measurements made at the field sites as well as from catchment data layers available in Geographical Information System (GIS) format (Table 1). These descriptors were assigned to one of six broad categories and included: catchment land-use measures obtained using ArcGIS analysis of subcatchment boundaries upstream of field sites and the State Land and Tree Survey data (Queensland Natural Resources and Water; SLATS, 1999); indices of channel condition and erosion sensitivity; an index of barriers to dispersal downstream of sample sites; measures of riparian vegetation conditions; and measures of in-stream habitat (Table 1). In addition, water quality data collected as potential chemical indicators of the land use disturbance gradient were also used as secondary disturbance descriptors for other (biological) indicator groups (Table 1). A principal components analysis of the water chemistry data was undertaken and the four principal components used as disturbance descriptors in some analyses. PC1 accounted for 53% of the variation and was associated with variation in major ion concentrations, PC2 reflected a nutrient gradient (25%), PC3 reflected an alkalinity-pH gradient (7%) and PC4 reflected a turbidity gradient (5%). Further details of the disturbance gradient descriptors can be found in Smith & Storey (2001).

Selection of potential indicators

There is growing agreement that measures of ecosystem health should include aspects of organization (e.g. biodiversity, species composition, food web structure), vigour (e.g. rates of production, nutrient cycling) and resilience (e.g. ability to recover from disturbance) (Rapport, Costanza & McMichael, 1998; Bunn & Davies, 2000, Von Schiller *et al*., 2008). In an initial workshop of government agency and university scientists, potential indicators of ecosystem health were identified. A preliminary list of over 50 approaches was developed, some with multiple indicators, based on the experience and expertise of the team and drawing on the scientific literature. This included indicators of ecological processes and patterns, as well as a suite of physical and chemical indicators. Some of these were commonly used water quality and biotic parameters while others had never previously been used in routine stream or river health assessment.

A recognised strength of the science and monitoring undertaken by the Healthy Waterways Partnership has been the use of conceptual models to illustrate the effects of human disturbances on coastal waterways (Thomas *et al*., 2006). These models are simple diagrams that: (i) show how healthy aquatic ecosystems function, (ii) show how they are likely to respond to disturbance, (iii) indicate critical biotic components/processes in the system to target for monitoring, and (iv) highlight possible management actions for protection or rehabilitation. Conceptual models were developed for each of the proposed freshwater indicator groups to illustrate how they would respond to the land use disturbance gradient (e.g. through loss of riparian vegetation, increased turbidity, or nutrient enrichment) (Smith & Storey, 2001). Development of these conceptual models allowed us to explore how well we understood the likely direct and indirect response of indicators to the disturbance gradient. These were presented and discussed at a second scientific workshop of the project team. For many of the proposed indicator groups, identification of cause and effect proved difficult and this conceptual analysis was used to cull the initial list to a more manageable number (Table 2).

Clustering of stream types

Hierarchical cluster analysis was undertaken to divide the study area into a stream type classification. This was to ensure that comparisons between streams in different catchments or in different settings within a single catchment were valid (i.e. to compare 'apples with apples'). It was also important to assess whether some indicators were more effective in different stream types, to assist in setting regional water quality and ecosystem health guidelines, and to assist in stratifying our field sites across all major stream types.

Attributes used in the cluster analysis had to be independent of the proposed land use gradient and readily available for the study region. GIS was used to divide each of the six major catchments within the study area into a series of small subcatchments, each with a unique identifying number. In turn, each of these subcatchments was divided into a series of over 1600 numbered polygons containing a short segment of stream and its surrounding catchment. Each stream segment was assigned a value for stream order, rainfall, altitude and slope assigned to each. The data were then clustered using an unweighted paired grouped mean arithmetic average technique based on the Gower association measure (Belbin, 1993). From this, three broad stream types were ultimately identified: (i) Upland – small, steep streams in high rainfall areas at high altitudes; (ii) Lowland – larger streams with lower gradients and less rainfall at low altitudes; (iii) Coastal – small to moderate sized coastal streams at low altitude and with relatively high rainfall. The coastal streams were subsequently divided into two subgroups because the northern coastal area (north of the Caboolture River) is dominated by acidic, tannin-stained "Wallum" streams which are chemically and ecologically distinct from those to the south (Coaldrake, 1961; Smith *et al.*, 2005).

Pilot studies

Potential indicators identified at the conclusion of our initial scientific workshops were sorted into two categories: those that were well established or proven in the literature (e.g. some water chemistry measures), and those that were less proven as monitoring tools (e.g. benthic metabolism). The latter were subjected to statistically valid pilot studies (small field or laboratory experiments or analysis of existing data sets) to determine if they were suitable for inclusion in the major field trial. The reasons for pilot studies varied depending on the indicator. For example, concerns were raised about small scale spatial and temporal variability in measures of benthic metabolism. Statistical analysis of the data from field trials (using analysis of variance methodology) indicated that this was small in comparison to likely differences between sites (Fellows *et al*., 2006). Measures of nutrient flux (N and P) from stream sediments were proposed using Perspex benthic domes. Statistical analysis of these field trial data showed considerable variation over small spatial scales that could not be easily explained by local factors and these indicators were not considered further. Small ceramic tiles were trialled to obtain measures of algal biomass accrual but were prone to vandalism and sedimentation. Statistical analysis of a large regional reference site data set on stream fish communities was undertaken to evaluate predictive models based on native species richness and assemblage composition (Kennard *et al*., 2006a; b) and these were considered sufficiently robust enough to trial against the disturbance gradient. Indicators based on the distribution, abundance and biomass of alien fish species were also evaluated against the disturbance gradient (Kennard *et al*., 2005). Two other indicators showed promise in early trials. A laboratory assay was undertaken to look at the composition of amino acids in aquatic plants exposed to varying combinations of ambient nutrients (Schmitt, 2005). A field trial to assess microbial communities was undertaken using standardized 96-well microtitre plates (ECOplates™) that provide a variety of carbon substrates for bacteria (Choi & Dobbs, 1999;

de Lipthay *et al*., 2004). Initial results for both of these indicators were promising but additional research was thought to be necessary before they could be fully developed as a field method.

Phase 2: Major field trial

In spring (September) 2000, 53 sites were selected across the study region stratified according to the four stream types given by the cluster analysis. These sites represented a complete gradient of disturbance from minimally disturbed 'reference' sites (chosen to establish ecosystem health guidelines), through moderately disturbed to heavily disturbed 'test' sites. This ecocentric approach to the definition of reference condition (Fairweather, 1999; Bailey *et al*., 2007) was consistent with the Strategy's vision of "healthy waterways". Four teams of field researchers were deployed to collect samples. All indicators were measured at exactly the same sites within a four week period, and as such, any differences observed were likely to be due to technique rather than spatial and/or temporal variability in weather conditions as there were no large rainfall events during this time.

Detailed methods for the indicators of benthic metabolism and nutrient processes can be found in Fellows *et al.* (2006) and Udy *et al*. (2006), respectively. Similarly, methods for the collection of data for fish indicators can be found in (Kennard *et al*., 2006c). Electrical conductivity, spot temperature and DO, and pH were measured in situ using hand held meters. Water samples were collected in polyethylene bottles to determine total ionic composition (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}), hardness, turbidity, alkalinity, TDS, total N and P. An additional sample was filtered (0.45 μm) in the field and frozen prior to analysis of dissolved inorganic nutrient species (NH_3, NO_x and FRP). Diel measurements of water temperature and dissolved oxygen were taken every 10 minutes using a DO and temperature sensor attached to a data logger and deployed for 24 hrs (see Fellows *et al*., 2006). Aquatic macroinvertebrates were sampled using a 250 μm pond net from both edge and pool habitats, then live picked and identified in accordance with standard AusRivAS (Australian River Assessment System) protocols (Davies, 1994; 2000). Additional details of the methods can be found in Smith & Storey (2001) or in the more recent EHMP technical reports (EHMP, 2008a; www.ehmp.org).

Protocol for data analysis

In keeping with the GEEP-style approach (Bayne *et al*., 1988), a protocol for data analysis was devised to enable a consistent and direct comparison of each indicator. Initially, distributional properties of the data were checked to identify outliers and any required transformations for subsequent statistical analyses. Preliminary investigation of relationships between disturbance gradients and indices were explored using scatter plots and Spearman rank correlation coefficients to ascertain whether any simple bivariate relationships existed.

A Generalised Linear Modelling (GLM) framework was used to determine whether particular indices could be used to detect the underlying disturbance gradient(s). While a number of multivariate approaches could have been taken, stepwise regression modelling (simultaneously searching both forwards and backwards) was employed because it accommodates for the different distributional forms of the indices (e.g. normal, Poisson, binomial). Furthermore, the approach quantifies the proportion of variation accounted for by each disturbance measure, and additionally quantifies the proportion of variation accounted for by each disturbance measure. The Akaike Information Criterion (AIC) was used for variable selection within the regression modelling procedure. Indicators were assessed in terms of the approximate amount of variation explained (approximate R^2 value) by the model and the proportion of this variation explained by individual descriptors of the disturbance gradient. Data were analysed using the S-PLUS 2000 - Professional Release 3 (MathSoft Inc.) statistical software.

A subset of the disturbance gradient descriptors was chosen for the analysis of each group of indicators, drawing on the initial conceptual models of likely causal factors, to avoid over-parameterization of the regression models (Table 1). This included a range of descriptors from five of the disturbance categories for the different physical and chemistry indicators; 13 descriptors from four disturbance categories for the benthic metabolism indicators (see Fellows *et al.*, 2006); 15 descriptors from five disturbance categories for the nutrient indicators (see Udy *et al*., 2006); 25 descriptors from six disturbance categories for the macroinvertebrate indicators; and 28 descriptors from six disturbance categories for the fish indicators (Kennard *et al.*, 2005; 2006b) (Table 1).

Indicator response to the disturbance gradient

General Linear Modelling showed that 22 indicators responded significantly to the disturbance gradient ($p<0.05$; Table 3) and these were further considered for inclusion in the EHMP. Of the 31 physical and chemical indicators trialled (including the 4 PCA axes) (Smith & Storey, 2001), only five showed a strong response to the disturbance gradient (>50% variance explained) and most of these responded to descriptors of land-use, channel condition and riparian condition (Table 3). Measures of conductivity and diel DO and water temperature were the most responsive physical and chemical indicators. Measures of ambient nutrient concentrations did not show a significant response to the disturbance gradient ($p>0.05$).

Of the eight indices of stream ecosystem metabolism assessed (Fellows *et al*., 2006), measures of benthic metabolism (GPP and R_{24}) both responded strongly to the disturbance gradient though P:R did not (Table 3). GPP was influenced primarily by water chemistry and riparian condition, while R_{24} responded to factors relating to the water and sediment chemistry. $\delta^{13}C$ signatures of aquatic plants showed a very strong response to the disturbance gradient, especially to water chemistry and riparian condition. Neither algal biomass (Chl *a*) nor $\delta^{13}C$ were found to be good surrogates of GPP (Fellows *et al*., 2006). Of the seven indices assessed for nutrients (Udy *et al.,* 2006), the algal bioassay responded well to the disturbance gradient, indicating that benthic algae in SEQ streams were limited by nitrogen (Table 3, see also Mosisch, Bunn & Davies, 2001). The $\delta^{15}N$ signature of aquatic plants also responded strongly to the disturbance gradient (see also Udy & Bunn, 2001). While measures of denitrification responded reasonably well to the disturbance gradient they were not recommended for inclusion in the ambient EHMP because they were considered to be too technically difficult and labour intensive (Udy *et al.*, 2006).

Eighteen macroinvertebrate indices were calculated from the same data set and the GLMs showed that many of these responded in similar ways (Smith & Storey, 2001). Macroinvertebrates responded to land use and water chemistry aspects of the disturbance gradient, with samples from edge and pool habitats showing similar patterns (Table 3). Three indices responded best to the disturbance gradient in both habitats: (i) Total richness – the number of macroinvertebrate families identified in each sample; (ii) PET family richness – Plecoptera, Ephemeroptera and Trichoptera considered most sensitive to water quality; and (iii) SIGNAL Index – (Stream Invertebrate Grade Number Average Level; Chessman, 1995; 2003), where pollution tolerant taxa are assigned a score of 1 and sensitive taxa a score of 10. The SIGNAL index was calculated by averaging scores for all families at a site.

Fourteen indices for fish communities were considered but the three that were most strongly associated with the disturbance gradient were: (i) Percentage of Native Species Expected (PONSE) – the proportion of native species observed divided by the number of native species predicted from a referential model based on relationships between environmental conditions and fish assemblages from minimally disturbed reference sites (Kennard *et al*., 2006a). (ii) Percentage alien individuals (% alien) – the proportion of individuals in the sample that were alien (i.e. introduced) species (Kennard *et al*., 2005); and

(iii) Fish assemblage O/E_{50} – the comparison of the species composition of the community observed against that predicted by a referential (AusRivAS-style) model (Kennard *et al*., 2006b). All three fish indices responded to a range of catchment and reach scale descriptors of the disturbance gradient but in particular to descriptors of in-stream habitat (Table 3).

Identifying 'redundancy' within and between indicator groups

It was clear that some of the indicators tested in the field trial responded in similar ways to the disturbance gradient because of causal relationships, and that inclusion of more than one of these would need to be strongly justified if the program was to be cost-effective. Bivariate scatter plots and correlation analysis were used to look for redundancy among indicators within the same group. Most showed no relationship between indicators, however, several highlighted two indicators responding in a similar manner to the disturbance gradient. In some instances, this was justification for dropping an indicator; however, in other instances both were retained because the additional information could be obtained at no additional cost.

Four of the five proposed physical and chemical indicators were retained for the EHMP (Table 4). Alkalinity was dropped after finding it showed a strong curvilinear relationship with pH ($p<0.05$). The latter was retained in preference to alkalinity because it was seen as a more appropriate indicator given regional issues with naturally low pH streams and acid sulphate soils and because many community groups have the capacity to directly measure pH but would have to pay for laboratory analysis of alkalinity. Conductivity, pH, diel temperature change and DO change were all been retained for the EHMP because they appear to respond well to the catchment-scale, land use disturbance gradient. Each describes a different water quality attribute and all four are likely to have a direct influence on aquatic biodiversity and ecosystem processes. Furthermore, accurate measurement of these parameters requires little technical training and many catchment groups already have the necessary instruments to measure these parameters.

All four indicators of ecosystem processes were recommended for inclusion in the EHMP (Table 4; Fellows *et al.*, 2006). Although GPP and R_{24} were clearly correlated ($p<0.001$), they responded to different attributes of the disturbance gradient (Table 3). The $\delta^{13}C$ signature of aquatic plants was also included as a potential integrative surrogate of GPP and data could be obtained at no additional cost when samples were analysed for $\delta^{15}N$ (see below). Aquatic plants may become carbon limited at high GPP and low stream flows and lead to relative ^{13}C-enrichment (see Finlay, 2001). The algal bioassay indicators were also recommended for inclusion in the EHMP because they responded to water/sediment chemistry and riparian condition and, in association with nutrient amendment treatments, provide useful information on stream nutrient limitation (Table 3). This information is particularly important given none of the nutrient concentration indicators responded to the disturbance gradient. Furthermore, it is not nutrient concentrations *per se* but their effect on algal growth that is an important consideration for stream ecosystem health. The stable nitrogen isotope signature of aquatic plants was also recommended because it responded well to a suite of disturbance gradient categories, particularly water and sediment chemistry (Udy & Bunn, 2001; Udy *et al*., 2006).

Macroinvertebrates (three indicators sampled from both pool and edge habitats) were the only biological measures assessed in the field trial that appeared to respond to catchment-scale land use aspects of the disturbance gradient (Table 3). Both habitats are generally sampled in the National River Health Program protocol (Davies, 2000), however, indicators from edge and pool habitats responded in a similar fashion and inclusion of data from both was not justified. Edge habitat data were preferred over the pool habitat because the former is easier to sample and more frequently encountered in local streams in South East Queensland. Bivariate plots of Richness, PET and SIGNAL showed there was no significant correlation between any of these indicators and as such all three were retained for the EHMP (Table 4).

The three proposed fish indices appeared to be sensitive to the disturbance gradient (high approximate R^2 values) and were unique in that they responded to all disturbance gradient categories, though in particular, the in-stream habitat category (Table 3). Bivariate plots and correlation analysis showed there was a strong correlation between Fish assemblage O/E_{50} and PONSE (r = 0.86), however, both indicators were retained for the EHMP because they provide different information about fish communities (Table 4). The Fish assemblage O/E_{50} indicator takes into account which of the predicted assemblage of species occurs and is based on AusRivAS modelling, whereas PONSE does not take into account which species are expected at a site (Kennard *et al*., 2006a; b). The % Alien indicator was also recommended because it was strongly related to indicators of disturbance intensity describing local in-stream habitat and riparian degradation, water quality and surrounding land use, particularly the amount of urban development in the catchment. This indicator was also considered to have potentially broad appeal because of its practicality (i.e. relative ease of sampling, identification and analysis) and conceptual simplicity (it is easy to communicate results to managers and the wider community) (Kennard *et al.*, 2005). It is worth noting that all three indices are derived from the same sample at no additional field cost (Kennard *et al.*, 2005; 2006a; b).

Reporting on Ecosystem Health

The Freshwater EHMP was fully implemented in 2002/03, funded largely by local and State government, and currently involves the measurement of 16 indicators from the five indicator groups above, at over 120 stream sites across the region, twice per year. Technical data for all indicators are collected for each site and summarised by catchment in a series of annual reports that are publicly available (e.g. EHMP, 2008a; www.ehmp.org). Each of the indicators is first standardised (0-1), where reference condition = 1 (for a particular stream type) and values $\geq$ the 90%tile recorded or the theoretical minimum (e.g. 0 for invertebrate richness) = 0 (i.e. 'worst case'). Indicators within each of the five indicator groups are then averaged to produce a single value for each type, and presented as a pentagon (Eco-H plot; see EHMP, 2008a). These summary plots provide a snapshot assessment of the overall health of the site relative to an agreed reference condition. Assessment of the relative performance of the various indicators groups can be used to interpret likely causal processes, knowing that some indicators respond more closely to riparian disturbances (e.g. GPP) while others appear to respond to land use activities at the broader catchment scale (e.g. macroinvertebrates).

A key element of the monitoring program is the development and public presentation of annual 'Report Cards' on the health of waterways in the region. These are presented to politicians and senior policy makers each year in a public (televised) ceremony (EHMP, 2008b; www.ehmp.org). Data for each site within a catchment for both seasons are averaged across all indicator groups to produce a single score for each reporting region. These are converted to Report Card 'scores', where 'A' reflects a catchment in near reference condition and 'F' is where the condition fails to meet the ecosystem health objectives that underpin agreed values for the regions streams and rivers (EHMP, 2008b). The annual release of an independent Report Card undoubtedly causes some apprehension in government circles; however, there is broad acceptance of the need for open and transparent reporting to address public concerns about the health of regional waterways. The aim is not to embarrass or shame governments into action, and briefings with senior officials prior to the report card launch provide an opportunity to prepare their response to the findings. Although a simple communication tool, there is confidence that each Report Card is underpinned by a robust dataset (e.g. EHMP, 2008a).

Links to policy

An important contributing factor to the success of the Healthy Waterways Partnership has been the strong link between science and decision makers. The Partnership model has facilitated an open and frank dialogue between the Scientific Expert Panel, comprised of respected scientists selected on the basis of their expertise, and key local and State government policy makers and managers. This has included regular presentations of scientific findings to senior technical and policy staff and briefings to mayors and State government ministers, especially before the release of the annual report card. Maintaining the independence of the Scientific Expert Panel from government has also been a key factor. Development of this relationship of mutual trust and respect between the Scientific Expert Panel and decision-makers has helped to achieve targeted management actions, including waste water treatment plant upgrades and riparian restoration (SEQRWMS, 2001; SEQHWP, 2007).

Implementation of the Healthy Waterways Strategy

Since 2001, the Partnership has placed considerable emphasis on the science and monitoring required to underpin the implementation of the Healthy Waterways Strategy. Many of the management actions agreed to in the 2001-2006 Strategy (SEQRWMS, 2001) have been completed or are well underway, including multi-million dollar upgrades to wastewater treatment plants. This has led to a 40% reduction in nitrogen loads to Moreton Bay and other estuaries, despite a considerable increase in population at the same time. In addition, governments have invested in stormwater quality improvement and waterway management and restoration projects (Abal *et al*., 2006; Bunn *et al*., 2007).

However, despite these investments, it is clear that a “business as usual” approach will not be sufficient to maintain and improve the health of the region’s waterways, especially in the face of a changing climate and rapidly increasing urban population. While there has been considerable success in addressing point source pollution (Costanzo *et al*., 2005; EHMP, 2008a), there is an urgent need to tackle diffuse source loads of pollutants (especially sediment) entering waterways from non-urban and developing urban areas. The recently released 2007-2012 SEQ Healthy Waterways Strategy (SEQHWP, 2007) involves 50 stakeholder groups and lists over 500 actions, including the use of water sensitive urban design (WSUD) in 'green-field' urban areas, the progressive retrofit of WSUD in existing urban areas and a significant investment in riparian restoration, channel stabilisation and best-practice land management in rural areas. The latter is estimated to require an investment in riparian 'infrastructure' in the order of $350-500 m over the next decade.

Science challenges

A major challenge for water resource practitioners is to understand the aggregative effects of human activities within a catchment (Allan, 2004; Bernhardt *et al*., 2006). We need to identify the optimal spatial configuration of development, protection and restoration that will minimize impact on water resources and maintain essential ecosystem services and products. Previous research undertaken by the Partnership has clearly identified the priority regions contributing to diffuse source loads and the major causal processes that are responsible (Abal *et al*., 2005a; see also additional reports on www.healthywaterways.org). The freshwater ecosystem health monitoring program continues to highlight which catchment streams are in poor condition (EHMP, 2008b). We are confident we have the techniques and tools to rehabilitate riparian zones, stabilise eroding gullies and stream banks (e.g. Price & Lovett, 1999; Rutherford *et al*., 2004; Lovett & Price, 2007). However, additional research and modelling is required to provide advice on the optimum size and spatial arrangement of restoration to achieve the greatest range of benefits for the least cost. This would attempt to optimise restoration to achieve an overall 50% reduction in diffuse sediment loads entering the receiving waters from catchment sources and improve stream ecosystem health. A 50% reduction in diffuse non-urban loads and an 80% reduction in urban loads are the targets agreed to in the 2007-2012 Health Waterways Strategy (SEQHWP, 2007).

A large multi-million dollar ‘proof of concept’ study, the “Healthy Country Program” has been initiated, which involves the selection of several ‘no regrets’ trial areas to showcase a range of restoration activities, including riparian fencing and replanting, and gully stabilisation (http://www.healthywaterways.org/healthy-country.html). The program will be underpinned by the development of a spatial optimisation framework, additional catchment process studies and a targeted monitoring program. The aim is to provide natural resource managers with a spatially explicit framework to consider the full range of management interventions, from ‘do nothing’, to fencing, revegetation and/or stream stabilisation works. For each of these options, there will be a predicted contribution to the reduction of diffuse load downstream and improvement to stream ecosystem health (as measured by EHMP). There will also be a life time cost function and a measure of the likely ‘willingness’ of landowners to undertake the restoration (e.g. Hajkowicz *et al*., 2005). In addition to the modelling challenge, this work will require a better understanding of the spatial scale of land use influences on stream ecosystem health. We are currently analysing the past six years of EHMP data to look more closely at land use influences at nested spatial scales (e.g. riparian, non-spatial lumped land use, catchment pattern metrics and inverse distance weighted measures). We also need to determine whether there are minimum spatial thresholds (of width/length) of riparian/stream rehabilitation to be effective (e.g. Rutherford *et al*., 2004) and whether there are aggregative effects (i.e. several rehabilitated stream sections positioned together give a greater benefit than would be predicted by the some of the parts).

Conclusions

There are several key lessons from the SEQ Healthy Waterways Program that are likely to be transferable to other regional catchment management programs aimed at improving water quality and aquatic ecosystem health. These include the importance of getting early agreement on a shared vision of the desired state of local waterways into the future and adopting a cooperative and inclusive approach. There is no doubt that success also depends on the involvement of committed individuals, including scientists, politicians, managers and community members, and we have been very fortunate to have had some outstanding champions in South East Queensland. There is an obvious need for defensible science and a commitment to a robust monitoring program and transparent reporting. Although we do not advocate that all of the ecosystem health indicators developed in this study will be widely applicable in stream health assessments, we do believe that the approach taken to identify appropriate indicators is robust and defensible. Finally, we cannot overemphasise the importance of effective communication (see www.healthwaterways.org). These factors underpin the success of the Healthy Waterways Partnership and have been important in generating a growing awareness in the region of the important connections between healthy waterways and their catchments.

Acknowledgements

We thank the other members of the DIBM3 team for their contribution to this project: Angela Arthington, Jo Clapcott, Steve Mackay, Nick Marsh, Andrea Schmitt and James Udy (Griffith University); Peter Davies and Andrew Storey (University of Western Australia); Bill Venables (CSIRO); Christina Dwyer, Chris Marshall and Peter Negus (Queensland Department of Natural Resources and Water); Andrew Moss and Fiona Redfern (Queensland Environmental Protection Authority); and Richard Norris (University of Canberra). We thank the partners of the SEQ Healthy Waterways Partnership for their financial support and guidance. This paper is dedicated to our friend and colleague, Dr Christy Fellows, who tragically passed away in December 2008.

References

Abal E.G., Bunn S.E. & Dennison W.C. (Eds) (2005a) *Healthy Waterways, Healthy Catchments: Making the connection in south east Queensland*, Moreton Bay and Catchments Partnership, Brisbane Queensland, 222pp.

Abal E.G., Dennison W.C. & Bunn S.E. (2005b) Setting. In: *Healthy Waterways, Healthy Catchments: Making the connection in south east Queensland* (Eds E.G. Abal, S.E. Bunn & W.C. Dennison), pp. 13–34. Moreton Bay and Catchments Partnership, Brisbane Queensland.

Abal E.G., Greenfield P.F., Bunn S.E. & Tarte D.M. (2006) Healthy Waterways: Healthy Catchments – An Integrated Research/Management Program to Understand and Reduce Impacts of Sediments and Nutrients on Waterways in Queensland, Australia. pp. 1126–1135. Frontiers of WWW Research and Development – APWeb 2006: Proceedings 8th Asia-Pacific Web Conference, Harbin, China, January 16–18, 2006.

Addison R.F. & Clarke K.R. (1990) The IOC/GEEP Bermuda workshop. *Journal of Experimental Marine Biology and Ecology*, **138**, 1–8.

Allan J.D. (2004) Landscape and riverscapes: The influence of land use on river ecosystems. *Annual Reviews of Ecology, Evolution and Systematics*, **35**, 257–284.

Allan J.D., Erikson D.L & Fay J. (1997) The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biology*, **37**, 149–161.

Bailey R.C., Reynoldson T.B., Yates A.G., Bailey J. & Linke, S. (2007) Integrating stream bioassessment and landscape ecology as a tool for land use planning. *Freshwater Biology*, **52**, 908–17.

Bayne B.L., Addison R.F., Capuzzo J.M., Clarke K.R., Gray J.S., Moore M.N. & Warwick R.M. (1988) An overview of the GEEP workshop. *Marine Ecology Progress Series*, **46**, 235–243.

Belbin L. (1993) *PATN, pattern analysis package.* Division of Wildlife and Ecology, CSIRO, Canberra, Australia.

Bernhardt E., Bunn S.E., Hart D.D., Malmqvist B., Muotka T., Naiman R.J., Pringle C., Reuss M., & van Wilgen B. (2006) Perspective. The challenge of ecologically sustainable water management. *Water Policy*, **8**, 475–479.

Bott T.L., Montgomery D.S., Newbold J.D., Arscott D.B., Dow C.L., Aufdenkampe A.K., Jackson J.K. & Kaplan L.A. (2006) Ecosystem metabolism in streams of the Catskill Mountains (Delaware and Hudson River watersheds) and Lower Hudson Valley. *Journal of the North American Benthological Society*, **25**, 1018–1044.

Boulton A.J. (1999) An overview of river health assessment: philosophies, practice, problems and prognosis. *Freshwater Biology*, **41**, 469–479.

Browne M., Kuhnert P., Peterson E., Bartley R., Steven A. & Harch B. (2007) Review of existing approaches used to develop integrated report card frameworks (IRCF) and their relevance to catchments draining to the Great Barrier Reef. Australian Government Department of the Environment and Water Resources. 62pp.

Buck O., Dev K. Niyogi D.K. & Townsend C.R. (2004) Scale-dependence of land use effects on water quality of streams in agricultural catchments. *Environmental Pollution*, **130**, 287–299.

Bunn S.E. (1995) Biological monitoring of water quality in Australia: workshop summary and future directions. *Australian Journal of Ecology*, **20**, 220–227.

Bunn S.E. (2003) Healthy River Ecosystems: vision or reality? *Water*, **30**, 7–11.

Bunn S.E., Abal E.G., Greenfield P.F. & Tarte D.M. (2007) Making the connection between healthy waterways and healthy catchments: South East Queensland, Australia. *Water Science and Technology*: *Water Supply*, **7**, 93–100.

Bunn S.E. & Davies P.M. (2000) Biological processes in running waters and their implications for the assessment of ecological integrity. *Hydrobiologia*, **422/423**, 61–70.

Bunn S.E., Davies P.M. & Mosisch T.D. (1999) Ecosystem measures of river health and their response to riparian and catchment degradation. *Freshwater Biology*, **41**, 333–345.

Caitcheon G. & Howes T. (2005) Sediments. In: *Healthy Waterways, Healthy Catchments: Making the connection in south east Queensland* (Eds E.G. Abal, S.E. Bunn & W.C. Dennison), pp. 69–92. Moreton Bay and Catchments Partnership, Brisbane Queensland.

Chessman B.C. (1995) Rapid assessment of rivers using macroinvertebrates: a procedure based on habitat-specific sampling, family level identification and a biotic index. *Australian Journal of Ecology*, **20**, 122–129.

Chessman B.C. (2003) New sensitivity grades for Australian river macroinvertebrates. *Marine and Freshwater Research*, **54**, 95–103.

Choi K.-H. & Dobbs F.C. (1999) Comparison of two kinds of Biolog microplates (GN and ECO) in their ability to distinguish among aquatic microbial communities. *Journal of Microbiological Methods*, **36**, 203–213.

Coaldrake J.E. (1961) The ecosystem of the coastal lowlands ("wallum") of southern Queensland. *CSIRO Bulletin No. 283* (Commonwealth Scientific and Industrial Research Organisation: Melbourne, Australia.)

Costanzo S.D., Udy J., Longstaff B. & Jones A. (2005) Using nitrogen stable isotope ratios ($\delta^{15}N$) of macroalgae to determine the effectiveness of sewage upgrades: changes in the extent of sewage plumes over four years in Moreton Bay, Australia. *Marine Pollution Bulletin*, **51**, 212–217.

Davies P.E. (1994) *Monitoring River Health Initiative: River Bioassessment Manual.* Land and Water Resources Research and Development Corporation, Canberra.

Davies P.E. (2000) Development of a national river bioassessment system (AUSRIVAS) in Australia. In: *Assessing the Biological Quality of Fresh Waters: RIVPACS and Other Techniques* (Eds J.F. Wright, D.W. Sutcliffe & M.T. Furse), pp. 113–124. Freshwater Biological Association, Ambleside.

De Lipthay J.R., Johnsen K., Albrechtsen H.J., Rosenberg P. & Aamand J. (2004) Bacterial diversity and community structure of a sub-surface aquifer exposed to realistic low herbicide concentrations. *Microbiology Ecology,* **49**, 59–69.

Dennison W.C. & Abal E.G. (1999) *Moreton Bay Study: a scientific basis for the healthy waterways campaign.* South East Queensland Regional Water Quality Management Strategy. 245pp.

Dolédec S. & Statzner B. (2008) Invertebrate traits for the biomonitoring of large European rivers: an assessment of specific types of human impact. *Freshwater Biology*, **53**, 617–634

Dolédec S., Phillips N., Scarsbrook M., Riley R.H. & Townsend C.R. (2006) Comparison of structural and functional approaches to determining landuse effects on grassland stream invertebrate communities. *Journal of the Nth American Benthological Society*, **25**, 44–60.

EHMP (2008a) *Ecosystem Health Monitoring Program 2006–07 Annual Technical Report.* South East Queensland Healthy Waterways Partnership, Brisbane (www.ehmp.org).

EHMP (2008b) *Report Card 2008 for the waterways and catchments of South East Queensland.* Ecosystem Health Monitoring Program, South East Queensland Healthy Waterways Partnership (www.ehmp.org).

Fairweather P.G. (1999) State of environment indicators of 'river health'; exploring the metaphor. *Freshwater Biology*, **41**, 211–220.

Fellows C.S., Clapcott J.E., Udy J.W., Bunn S.E., Harch B.D. & Davies P.M. (2006) Benthic metabolism as an indicator of stream ecosystem health. *Hydrobiologia*, **572**, 71–87.

Finlay J.C. (2001) Stable-carbon-isotope ratios of river biota: implications for energy flow in lotic food webs. *Ecology*, **82**, 1052–1064.

Gessner M.O. & Chauvet E. (2002) A case for using litter breakdown to assess functional stream integrity. *Ecological Applications*, **12**, 498–510.

Hajkowicz S., Perraud J.M., Dawes W. & DeRose R. (2005) The strategic landscape investment model: a tool for mapping optimal environmental expenditure. *Environmental Modelling and Software*, **20**, 1251–1262.

Hill B.H., Herlihy A.T., Kaufmann P.R., Stevenson R.J., McCormick F.H. & Johnson C.B. (2000) Use of periphyton assemblage data as an index of biotic integrity. *Journal of the North American Benthological Society*, **19**, 50–67.

Karr, J.R. (1999). Defining and measuring river health. *Freshwater Biology*, **41**, 221–234.

Kennard M.J., Arthington A.H., Pusey B.J. & Harch B.D. (2005). Are alien fish a reliable indicator of river health? *Freshwater Biology*, **50**, 174–193.

Kennard M.J., Harch B.D., Pusey B.J. & Arthington A.H. (2006a). Accurately defining the reference condition for summary biotic metrics: a comparison of four approaches. *Hydrobiologia*, **572**, 151–170.

Kennard M.J., Pusey B.J., Arthington A.H., Harch B.D. & Mackay S.J. (2006b) Development and application of a predictive model of freshwater fish assemblage composition to evaluate river health in eastern Australia. *Hydrobiologia*, **572**, 33–57.

Kennard M.J., Pusey B.J., Harch B.H., Dore E. & Arthington A.H. (2006c) Estimating local stream fish assemblage attributes: sampling effort and efficiency at two spatial scales. *Marine and Freshwater Research*, **57**, 635–653.

Lovett, S. & Price, P. (Eds) (2007) *Principles for riparian lands management.* Land and Water Australia, Canberra.

Maddox D., Poiani K. & Unnasch R. (1999) Evaluating management success: Using ecological models to ask the right monitoring questions. In: (Eds W.T. Sexton, A.J. Malk, R.C. Szaro & N.C. Johnson), *Ecological Stewardship: A Common Reference for Ecosystem Management. Volume III*, pp. 563–584. Elsevier Science Ltd, USA.

Meyer J.L. (1997) Stream Health: Incorporating the human dimension to advance stream ecology. *Journal of the North American Benthological Society*, **16**, 439–447.

Mosisch T.D., Bunn S.E. & Davies P.M. (2001) The relative importance of riparian shading and nutrients on algal production in subtropical streams. *Freshwater Biology*, **46**, 1269–1278.

Nichols J.D. & Williams B.K. (2006) Monitoring for conservation. *Trends in Ecology & Evolution*, **21**, 668–673.

Norris R.H. & Hawkins C.P. (2000) Monitoring river health. *Hydrobiologia*, **435**, 5–17.

Price, P. & Lovett, S. (Eds) (1999) *Riparian Land Management Technical Guidelines. Volume Two: On-ground Management Tools and Techniques*. Land and Water Resources R&D Corporation, Canberra.

Pringle C.M. (1997) Exploring how disturbance is transmitted upstream: going against the flow. *Journal of the North American Benthological Society*, **16**, 425–438.

Rapport D.J., Costanza R. & McMichael A.J. (1998) Assessing ecosystem health. *Trends in Ecology and Evolution*, **13**, 397–402.

Rosgen, D.L. (1994) A classification of natural rivers. *Catena*, **22**, 169–199.

Roth N.E., Allan J.D. & Erikson D.E. (1996) Landscape influences on stream biotic integrity assessed at multiple spatial scales. *Landscape Ecology*, **11**, 141–156.

Rutherford J.C., Marsh N.A., Davies P.M. & Bunn S.E. (2004) Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? *Marine and Freshwater Research*, **55**, 737–748.

Schmitt A. (2005) *The influence of nutrients on aquatic primary production and food webs in subtropical streams of south east Queensland, Australia.* PhD Thesis, Faculty of Environmental Sciences, Griffith University.

SEQHWP (2007) *South East Queensland Healthy Waterways Strategy. 2007–2012.* SEQ Healthy Waterways Partnership.

SEQRWMS (2001) *South East Queensland Regional Water Quality Management Strategy. 2001–2006.* Moreton Bay Waterways and Catchments Partnership.

SLATS (1999) Land Cover Change in South-East Queensland, 1988–1997. Queensland Department of Natural Resources, Indooroopilly.

Smith M., Carruthers T. & Bunn S.E. (2005) Aquatic Habitats. In: *Healthy Waterways, Healthy Catchments: Making the connection in south east Queensland* (Eds E.G. Abal, S.E. Bunn & W.C. Dennison), pp. 35–68. Moreton Bay and Catchments Partnership, Brisbane Queensland.

Smith M. & Grice A. (2005) Ecosystem Health Monitoring Program. In: *Healthy Waterways, Healthy Catchments: Making the connection in south east Queensland* (Eds E.G. Abal, S.E. Bunn & W.C. Dennison), pp. 149–182. Moreton Bay and Catchments Partnership, Brisbane Queensland.

Smith M.J. & Storey A.W. (Eds) (2001) *Design and Implementation of Baseline Monitoring (DIBM3): Developing an Ecosystem Health Monitoring Program for Rivers and Streams in Southeast Queensland.* Unpublished report to the South-East Queensland Regional Water Quality Management Strategy, Brisbane, 416 pp. (www.ehmp.org).

Snyder C.D., Young J.A., Villella R. & Lemarié D.P. (2003) Influences of upland and riparian land use patterns on stream biotic integrity. *Landscape Ecology*, **18**, 647–664.

Stebbing A.R.D. & Dethlefsen V. (1992) Introduction to the Bremerhaven workshop on biological effects of contaminants. *Marine Ecology Progress Series*, **91**, 1–8.

Thomas J.E., Saxby T.A., Jones A.B., Carruthers T.J.B., Abal E.G. & Dennison W.C. (2006) *Communicating Science Effectively: A Practical Handbook for Integrating Visual Elements*. IWA Publishing, London, 136 pp.

Townsend C.R., Dolédec S., Norris R., Peacock K. & Arbuckle C. (2003) The influence of scale and geography on relationships between stream community composition and landscape variables: description and prediction. *Freshwater Biology*, **48**, 768–785.

Udy J.W. & Bunn, S.E. (2001) Elevated δ^{15}N values of aquatic plants in cleared catchments: why? *Marine and Freshwater Research*, **52**, 347–351.

Udy J.W., Fellows C.S., Bartkow M., Bunn S.E., Clapcott J.E. & Harch B.D. (2006) Measures of nutrient processes as indicators of stream ecosystem health. *Hydrobiologia*, **572**, 89–102.

Vertessy R. & McAlister T. (2005) Integration. In: *Healthy Waterways, Healthy Catchments: Making the connection in south east Queensland* (Eds E.G. Abal, S.E. Bunn & W.C. Dennison), pp. 184–208. Moreton Bay and Catchments Partnership, Brisbane Queensland.

Von Schiller D., Martí E., Riera J.L., Ribot M., Marks J.C. & Sabater F. (2008) Influence of land use on stream ecosystem function in a Mediterranean catchment. *Freshwater Biology*, **53**, 2600–2612.

Walters C.J. (1986) *Adaptive Management of Renewable Resources* (McGraw-Hill, New York).

Walters C. (1997) Challenges in adaptive management of riparian and coastal ecosystems. *Conservation Ecology* **1**, 1. URL: http://www.consecol.org/vol1/iss2/art1.

Wicklum D. & Davies R.W. (1995) Ecosystem health and integrity. *Canadian Journal of Botany*, **73**, 997–1000.

Young R.G., Matthaei C.D. & Townsend C.R. (2008) Organic matter breakdown and ecosystem metabolism: functional indicators for assessing river ecosystem health. *Journal of the North American Benthological Society*, **27**, 605–625.

Table 1. Six categories of descriptors used to characterise the land use disturbance gradient for the freshwater EHMP field trial. Measures indicated by asterisk were used in the development of Generalised Linear Models for each of the indicator groups.

	Indicator Group	**Water quality**		**Metabolism**	**Nutrient flux**	**Macro-invertebrates**	**Fish**
Disturbance descriptors		**Chem.**	**Phys.**				
Land use							
% Cleared	Percentage catchment upstream cleared	*	*	*	*	*	*
% Cropped	Percentage catchment upstream cropped	*	*	*		*	*
% Grazed	Percentage catchment upstream grazed	*	*			*	*
% Urban	Percentage catchment upstream urbanised	*	*			*	*
Catchment index	Categorical variable (0-4), where 1 = urban, 4 = undisturbed	*			*		
Adjacent land use	Categorical variable (0-4), where 1 = urban, 4 = undisturbed					*	
Water quality							
PCA1	Ions gradient – PCA axis 1 water chemistry data		*	*	*	*	*
PCA2	Nutrient gradient – PCA axis 2 water chemistry data		*			*	*
PCA3	Alkalinity gradient - PCA axis 3 water chemistry data		*			*	*
PCA4	Turbidity gradient - PCA axis 4 water chemistry data		*			*	*
NO_x	Dissolved nitrite and nitrate (mg l^{-1})			*	*		
NH_4	Dissolved ammonium (mg l^{-1})			*	*		
TN	Total nitrogen (mg l^{-1})			*	*		*
PO_4	Filterable reactive phosphate (mg l^{-1})			*	*		
TP	Total phosphate (mg l^{-1})			*	*		*
Max temp	Temperature recorded by data logger over 24 hrs (°C)			*	*		
Diel temp range	Temperature recorded by data logger over 24 hrs (°C)	*	*			*	*
DO minimum	DO recorded by data logger over 24 hrs				*		
Diel DO	DO recorded by data logger over 24 hrs	*	*			*	*
Turbidity	Spot measurement, hand held meter (NTU)			*			*
pH	Spot measurement, hand held meter						*
Conductivity	Spot measurement, hand held meter (μSm^{-1})	*					*

Channel Condition							
Bank erosion	Categorical variable (1-4) where 1 = extensive erosion, 4 = none	*	*			*	*
Channel Condition	Categorical variable (1-4), where 1 = extensive aggradation or degradation, 4 = none	*	*	*	*	*	*
Geomorphic Sensitivity	Sensitivity scour scale (1-6); where 1 = low, 6 = high (based on Rosgen, 1994).	*	*			*	*
Riparian Condition							
Reach cover	Reach scale visual estimate of riparian cover (%)	*	*				*
Reach cover (2)	Reach estimate (3 measures) using densiometer (%)		*			*	
Hemiphot Cover	Site scale measurement using camera and fish-eye lens (%)			*	*		
Vegetation Width	Reach scale measurement of riparian width (m)					*	
Riparian category	Categorical variable (0-4), where 0 = no vegetation and 4 = excellent vegetation		*	*	*	*	*
Flow alteration							
Barriers downstream	Categorical variable (1-3), where 1 = barrier > 5 m; 2 = barrier 1-5 m; 3 = no barrier						*
Seasonal flow regime	Categorical variable; 0 = unaltered, 1 = altered					*	
In-stream habitat							
Flow max	Maximum velocity within habitat (m s^{-1})					*	
% C in sediment	Percent organic carbon in sediments (measured by IRMS)				*		
% Detritus	% organic detritus in stream bed sediments					*	
% Sand	% sand in stream bed sediments					*	
% Silt/Clay	% silt/clay fraction in bed sediments				*	*	
% Mud	Mean % stream bed covered by mud						*
Substrate diversity	H diversity of substrate classes (cobbles, gravel etc)					*	*
Habitat cover diversity	H diversity of organic matter covering stream bed (leaf litter, LWD etc)	*					*
% Filamentous algae	% cover of filamentous algae					*	*
% Macrophytes	% cover of aquatic macrophytes					*	*
% invasive weeds	% cover of invasive terrestrial/riparian weeds						*
Habitat condition	Categorical variable (0-3), where 0 = poor, 1 =moderate, 3 = good)						*

Table 2. List of potential ecosystem health indicator groups identified in workshops and subsequently tested in the major field trial

Ecosystem processes	**Water chemistry**
Benthic metabolism (including GPP, R_{24})	Nutrient concentrations (water & sediment)
Catchment disturbance of the nitrogen cycle (using $\delta^{15}N$)	Salinity/conductivity/ionic composition
Use of $\delta^{13}C$ as a potential surrogate of GPP	Alkalinity/pH
Nitrogen cycling – denitrification	Dissolved oxygen – snapshot & diel
Chlorophyll a – as surrogate of GPP	Water temperature – snapshot & diel
Algal bioassays	Turbidity
Biological patterns	**Direct measures of stream disturbance**
Structure and function of fish communities	Measure of riparian canopy cover
Structure and function of invertebrate communities	Assessments of channel integrity
Structure of microbial community-ECOplates™	

Table 3: The 22 indicators of stream ecosystem health that responded to the disturbance gradient, including the total amount of variability explained (approximate R^2) in the Generalised Linear Models (GLM) and the % contribution of each of the associated disturbance gradient categories (*disturbance gradient variables from this category were not included in the GLM).

Indicator type	Proposed Indicators	Disturbance gradient category						
		Approximate R^2 %	Land use %	Channel condition %	Riparian condition %	Water quality %	In-stream habitat %	Flow alteration %
Water quality	Conductivity	60	46	6	8	*	0	*
	pH	46	33	4	1	*	8	*
	Alkalinity	52	36	6	10	*	0	*
	Diel Temperature	60	23	3	23	*	*	11
	Diel DO	82	29	26	17	*	*	10
Ecosystem metabolism	GPP (Cobble sites)	89	0	0	13	76	*	*
	R_{24} (Cobble sites)	91	0	0	0	91	*	*
	$\delta^{13}C$ (aquatic plants)	92	3	9	48	32	*	*
	Algal bio-assay - Control	72	0	0	19	53	0	*
Nutrient processes	$\delta^{15}N$ (aquatic plants)	79	9	12	7	42	9	*
	Algal bio-assay - (+N)	80	0	0	27	26	27	*
	Algal bio-assay - (+P)	37	0	0	15	22	0	*
	Algal bio-assay - (+NP)	68	0	0	33	2	33	*
Invertebrates	PET richness (Edge)	67	32	4	12	12	0	7

	SIGNAL score (Edge)	61	34	0	15	8	4	0
	Family richness (Edge)	55	40	0	3	3	0	9
	PET richness (Pool)	74	34	10	8	13	9	0
	SIGNAL score (Pool)	72	35	26	7	4	0	0
	Family richness (Pool)	64	11	26	5	0	22	0
Fish	% Native species richness expected	73	11	13	17	13	17	2
	% alien individuals	87	12	0	14	14	35	12
	Fish assemblage O/E_{50}	65	11	12	0	11	31	0

Table 4: List of indicators recommended for the ambient ecosystem health monitoring program of rivers and streams in South East Queensland.

Indicator type	Recommended indices
Water quality	Conductivity
	pH
	Diel change in Temp (includes max & min)
	Diel change in DO (includes max & min)
Ecosystem processes	GPP
	R_{24}
	$\delta^{13}C$ (aquatic plants)
	Algal bioassay (Controls)
Nutrient processes	$\delta^{15}N$ (aquatic plants)
	Algal bio-assay (N+P/Control)
Macroinvertebrates	PET richness (Edge habitats)
	SIGNAL score (Edge habitats)
	Family richness (Edge habitats)
Fish	Percentage Of Native Species Expected (PONSE)
	% alien individuals
	Fish assemblage O/E_{50}

Figure caption:

Fig. 1. Flow chart illustrating the process undertaken to develop the freshwater EHMP for South East Queensland.

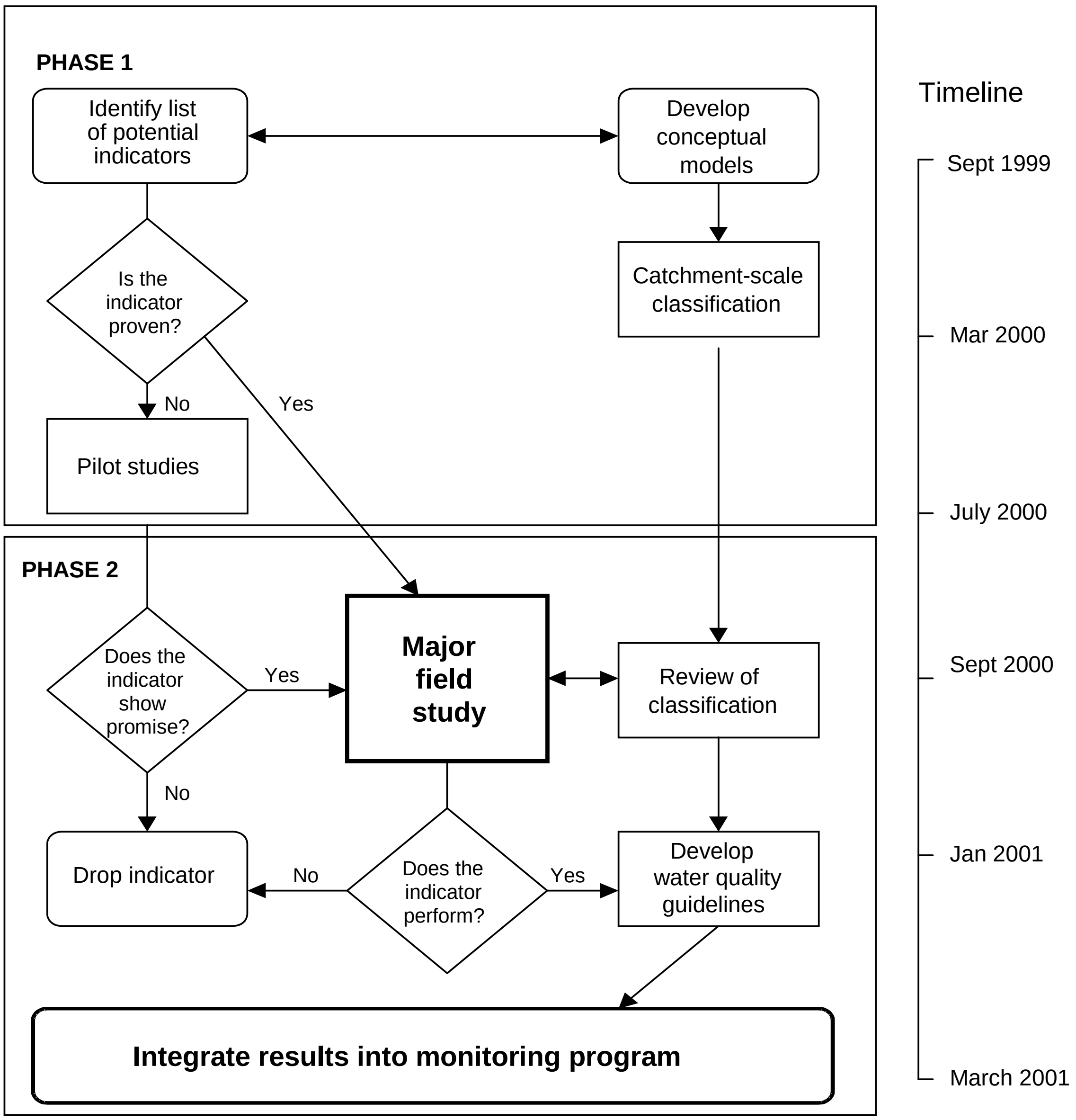

Fig. 1 – Bunn *et al.* (FWB-S-Mar-09-0140)