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A framework for guiding the management of urban stream health

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ABSTRACT

Urban stream ecosystems are vulnerable to urbanisation of surrounding land cover and land use. We study 30 sites along two highly urbanised streams in Brisbane, Australia. Fieldwork generated a suite of primary stream health indicators. Geographic information system techniques generated spatially-explicit metrics of land cover and a lumped metric of nearby population that put stress on stream health. Stream health indicators were aggregated into a stream health index, and land-use stress indicators were aggregated into a land-use stress index, using data envelopment analysis (DEA). DEA was then applied to these indices to create an ecological performance index. Dominator analysis generated a set of practical role models for each ecologically underperforming site. A subsequent round of DEA was applied to the stream health index and multiple stress indicators to calculate response elasticities of stream health with respect to specific stress indicators. Empirical findings show widespread deviations beneath best practice, enlightening dominator relationships, and informative variation in response elasticities. Each of these findings can provide guidance to those responsible for allocating scarce resources in an effort to improve the health of Brisbane's urban streams.

1. Introduction

Local catchment groups and governments invest time and money protecting and rehabilitating urban streams, their riparian zones and catchments. It is therefore important from the outset to identify which areas will be most responsive to these efforts so that scarce resources can be allocated for maximum benefit. In this paper we develop an analytical framework that incorporates measures of both urban stream health and land-use stress. The framework begins with fieldwork, continues with geographic information system (GIS) techniques, and concludes with data envelopment analysis (DEA) and dominator analysis. DEA and dominator analysis identify sites most in need of attention and dominating role models for them. DEA also creates endogenous weights for use in constructing health and stress indices and calculating response elasticities of stream health with respect to changes in alternative land-use stress measures. We provide an empirical application to 30 highly urbanised stream sites within the Bulimba Creek and Norman Creek (BCNC) sub-catchments of the Brisbane River, Australia, to illustrate how the framework achieves these objectives. This ecological performance analysis is the first application of DEA to urban stream ecology.

1.1. Addressing Stream Health and Stream Stress Factors

Due to the complex nature of urban stream ecosystem processes, the mechanisms by which land cover and hydrological alteration impact urban stream health have not been directly demonstrated, although correlations have been established. A range of stressors have been shown to influence the health of urban streams, including altered hydrology and channel morphology, habitat fragmentation and loss, high nutrient levels, pollutants, and invasive species of plants and animals, and have been collectively referred to as the "urban stream syndrome" (Meyer et al., 2005; Walsh et al., 2005b). However at different spatial scales and in different locations the relative importance of these urban stream stressors varies. For example, in-stream connectivity was found to be important to fish assemblage, pollution levels and habitat quality in Puerto Rico (Ramírez et al., 2012), hydrological alteration associated with levels of catchment-scale impervious surface was found to be the most important land-cover feature impacting macroinvertebrate and fish community structure in Victoria, Australia (Walsh et al., 2005a) and in Georgia, USA (Roy, 2004), and intact riparian tree cover at the reach scale was found to have a detectable benefit on macroinvertebrate community structure in Victoria (Thompson and Parkinson, 2011).

Failure to apply stream health management intervention at a scale appropriate to capture the driving processes has been blamed for the poor performance of many rehabilitation activities. The most common approach to planning and prioritising stream rehabilitation projects is based on 'available land opportunities', with the result that most stream

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rehabilitation activities are undertaken in headwaters and small tributaries, although the habitat and land-use changes which are most severe are commonly in lowland floodplains and deltas (Bernhardt et al., 2005; Hermoso et al., 2012).

Inspired by the systematic conservation planning used for reserve design (Ardron et al., 2010; Margules and Pressey, 2000), a systematic "efficient planning" approach for river rehabilitation that focuses on ecosystem processes at the whole-catchment scale has been proposed (Hermoso et al., 2012). This approach allows for the efficient selection of areas for rehabilitation based on socio-economic constraints and facilitates decision-making by integrating and prioritising the trade-offs among multiple rehabilitation actions using multiple-objective optimisation (Czyzak and Jaszkiewicz, 1998).

Proponents of systematic planning have not yet articulated a practical framework of how such an approach would be applied to stream rehabilitation. Ideally their framework would allow easier integration and comparison of alternative rehabilitation actions for managers to consider and would address the driving ecosystem processes. The aim of the present study is to further elucidate options for protection and rehabilitation of freshwater urban ecosystems as well as the scale of mitigation efforts that might be required.

1.2. The Southeast Queensland Approach

Healthy Waterways is a not-for-profit, non-government organisation devoted to the protection and improvement of waterways in southeast Queensland (SEQ). It operates an Ecosystem Health Monitoring Program (EHMP) that reveals whether the health of regional waterways is improving or deteriorating. It uses a broad range of biological, physical and chemical indicators of ecosystem health, including fish and invertebrate biodiversity metrics, ecosystem process metrics and water quality metrics.

The EHMP was fully implemented in 2002/03. 135 freshwater stream sites, rural and urban, in SEQ are sampled biannually (spring and autumn), their health indicators are measured, and report cards are made public in annual reports. The overall health of a site is measured relative to an agreed reference condition (Bunn et al., 2010). Many local councils use the results of the EHMP as a guide to how well they are protecting their streams.

The general poor health of urban streams in the Lower Brisbane Catchment is well documented. In the 2013 EHMP report, the Lower Brisbane Catchment, which includes the BCNC sub-catchments, received a grade of D-, down from a grade of D+ in 2012 but up from a grade of F in the previous six years (www.healthywaterways.org). Grades are based exclusively on stream health indicators, and although EHMP health indicators help identify the most likely stressors, and EHMP acknowledges "significant signs of stress," particularly at urban sites, EHMP does not consider stressors in the calculation of report card grades.

Effective management of urban stream health requires an understanding of the interrelationships among health indicators, among stressors, and between the two. Achieving such an understanding requires an analytical framework that incorporates both health and stress indicators. We introduce such a framework below.

1.3. Evaluating the Relative Performance of Stream Sites

We use fieldwork to generate stream health indicators, and GIS techniques to generate stress indicators, at stream sites. We apply DEA to the two sets of indicators to generate a health index and a stress index. A best-practice ecological performance frontier created from these indices is used to benchmark the performance of each site against best practice. We augment DEA with dominator analysis to identify for each site a set of role model sites that exhibit superior ecological performance. Dominators are not necessarily ecologically efficient, but they are healthier than dominated sites that have equal or less stress. An investigation of dominators can lead to the discovery of important factors not included in the DEA models.[1]

DEA is particularly useful when comparing like with like, and sites in the BCNC sub-catchments have relatively homogeneous environmental features (climate, topography, soils, geology and natural vegetation), and being contained in the Lower Brisbane Catchment, they can all be classed as degraded.

As a performance evaluation tool DEA has four noteworthy virtues: (1) it accounts for *both* stream health *and* stress factors when evaluating sites; (2) it combines *multiple* health indicators and *multiple* stress indicators that are measured in their own units; (3) its evaluation of each site is *relative* to the performance of all other sites in the sample, rather than to an agreed reference condition used by EHMP; and (4) being a linear programme, DEA has both primal and dual formulations, and the dual formulation creates endogenous weights for index construction and for the calculation of elasticities of stream health with respect to specific stress indicators at each site. Thus, while BCNC may well be in generally poor health, a DEA can distinguish degrees of poor health at the sampled sites, and it can relate degrees of poor health to specific stress indicators at sampled sites.[2] The endogenously determined weight profile of a site reveals its relative ecological strengths and weaknesses, and provides clues to the underlying processes.

DEA and dominator analysis can complement systematic planning by assisting in both adaptive management of rehabilitation projects already implemented (Wenger et al., 2009), and proactive management to identify which catchments and sites are priorities for future rehabilitation (Hermoso et al., 2012).

The paper unfolds as follows. In Sections 2 and 3 we explain how we have created our data set. In Section 4 we contrast index construction using exogenous and endogenous weights. In Section 5 we present DEA and dominator analyses, which construct health, stress and performance indices, calculate response elasticities, and identify role models for each site. Section 6 contains our empirical findings and discussion, and Section 7 concludes.

2. Data Collection

Data used in this study were generated by fieldwork and GIS techniques.

2.1. Fieldwork

Brisbane, the state capital located on the Lower Brisbane River, is the major population centre in SEQ, with approximately 2 million people in the greater Brisbane area and 3 million in the region. Population growth continues to be one of the key threats to the sustainability of stream health in SEQ.

Stream health data (macroinvertebrate and water quality) were collected for 30 sites in the BCNC sub-catchments of the Lower Brisbane River, during the post-wet season in April 2010. Sites were selected to include a range of levels of total sub-catchment impervious land cover and associated stormwater drains and piping, as well as a range of tree, grass and impervious riparian land cover at the reach and catchment scales. Another objective of site selection was to include nested sites and longitudinally connected sites that covered an extensive

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[1] Cooper et al. (2000) provide a comprehensive survey of DEA and its uses, and Tulkens (2006) does the same for dominator analysis.

[2] A reviewer notes that much stream condition-stressor analysis is based on residuals generated by multiple regression analysis, and asks how different this is from distances from a DEA best practice frontier. The motivations are similar, but DEA offers three advantages: (a) its *best-practice* standard is more appealing than an *average-practice* standard; (b) it requires no pre-specified functional form, and so allows the data to determine the standard, whereas a regression-based standard is conditional on the functional form of the regression equation; and (c) it accommodates multiple outputs and multiple inputs naturally, and so is not constrained to specify a single dependent variable, as regression analysis is. The latter two advantages also apply to stochastic frontier regression analysis.