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Evidence-based model structure: The role of causal analysis in hydro-ecological modelling

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Abstract: Understanding the mechanisms by which human interventions affect environmental values is fundamental to sound environmental decision-making and the development of environmental response models used in decision making. The structure of an environmental response model, either conceptual or mathematical, should be based on pathways of causation linking input variables to model outputs and predictions. In ecological systems, these causal pathways are often not well-established, resulting in model structures that are based largely on expert opinion. The published literature can provide considerable qualitative and quantitative evidence to support the development of more rigorously-based model structures. However, collating that literature in a rigorous, repeatable and easily collated manner is difficult.

Through the use of tools developed by the eWater CRC, we believe modellers can begin to better test their model structures and demonstrate that their conceptual representation of ecological systems is well supported. The tools allow for the testing of causality using evidence available in the literature. Available causal evidence from the literature is collated in a searchable on-line database. This evidence can then be evaluated in a transparent and repeatable way using analysis software to assess the level of support for causality. The database and software use a set of 'Causal Criteria' adapted from epidemiology in assessing the available evidence.

This approach encourages the use of existing knowledge in a well-documented, transparent, repeatable and quantitative manner – something that is done poorly in most branches of science. The tools make the existing knowledge and evaluation methods accessible to a broad range of users. This paper gives a detailed explanation of the suggested methodology for using causal criteria for model development. The causal criteria methodology and tools are explained via a case study about modelling ecological response to flow modification (e.g. an environmental flow).

Keywords: *Causal criteria, tools, levels of evidence, conceptual models, model structure*

1 INTRODUCTION

1.1 Overview

Understanding the mechanisms by which human interventions affect environmental values is fundamental to environmental decision-making. This understanding also feeds into the development of response models, which are used in decision making and the production of quantitative predictions. The scientific rigour of these models is often the focus of arguments for and against various environmental management decisions, so the models must be defensible. We believe that transparency in the decision making process is essential and this work focuses on addressing this in the early stages of model development.

A common, high profile and often controversial situation in Australia involves modelling and decision making for environmental flow allocation. Managers and scientists are asked to make decisions about how much water is needed and where/when it should be released. These decisions are then made in light of the predicted impacts, with a major focus on maximum positive impact on ecological response (which is quantified in various ways). The cost of providing environmental water is substantial, with billions of dollars currently being invested in water recovery (efficiency measures, licence buybacks, etc.) for the Murray-Darling Basin alone. There are also major impacts on the amount of water held in storages and subsequently on the other users of the resource. Environmental water managers need models that can provide transparent and defensible trade-off decisions, or these allocations of environmental water are likely to be challenged in the courts.

1.2 Modelling ecological response to flow modification

Throughout this paper, we will use the scenario of modelling ecological response to flow modification (e.g. an environmental flow) as our primary case study. When modelling ecological responses to flow alteration, the most commonly used approach is the Physical Habitat Simulation Model (PHABSIM), or some derivation thereof. Despite criticisms, this approach has been used (in various forms) for many years and in many areas around the world (Jowett 1989; Gore et al. 1991; Gippel and Stewardson 1995).

These various implementations of PHABSIM all focus predominantly on the effects of flow alteration on physical habitat conditions, with the consequential changes in biota (i.e. the actual ecological response) being assumed (Palmer et al. 1997). However, while the physical modelling required to predict habitat response is well-understood and provides precise predictions, the predictions of biotic response are generally not supported by strong scientific evidence. The high costs of releasing environmental water make it difficult to undertake rigorous experiments to quantify these impacts, although efforts are underway to remedy this (e.g. Cottingham et al. 2005). Considering that most environmental flow methods require some form of quantitative response model (Arthington et al. 2006), it is clear that this application area needs to make use of all available evidence to strengthen model linkages.

1.3 The model development process

The structure of any environmental response model, either conceptual or mathematical, should be based on pathways of causation linking input variables to model outputs and predictions. The first stage of development should involve testing the postulated causal mechanisms of ecological response (i.e. model linkages) against all available evidence. These tests can guide the choices made regarding which processes will (and which will not) be represented in the model.

In ecological systems, these causal pathways are not well-established, resulting in model design that is based largely on expert opinion rather than strict process understanding. This stage of model development is often given a fairly cursory treatment and where there is extensive, unchecked reliance on expert opinion, many of the choices become subject to bias and overconfidence (Morgan et al. 1990). The published literature can provide considerable qualitative and quantitative evidence to support (and occasionally refute) expert opinion, but interpreting it in a consistent and rigorous manner can be difficult. It is also difficult to combine the findings from a broad literature review into concise and useful summaries. Throughout this paper, we encourage users to complete a systematic review of the existing literature to reduce bias when identifying the causal mechanisms that underpin a model.

When conceptual models are to be used to make predictions or test hypotheses, it is necessary to further develop them into numerical models. The choices about numerical model must be guided by our conceptual model and understanding. For example, if our conceptual model contains no causal linkage between a particular environmental variable and the modelling endpoint, then there is no need to consider this variable within any set of potential mathematical models. This can help maintain a better theoretical justification for the numerical models we choose. If we lose this linkage to the conceptual model, then the choice of numerical model is nothing more than a question of model fit to the data (Chatfield 1995), which may result in a model that considers spurious relationships.

1.4 Decision making in epidemiology using causal criteria

The field of epidemiology (i.e. the study of disease as it occurs in populations, rather than in individuals) provides us with an approach to evaluate the strength of hypothesised causal linkages. Epidemiology relies heavily on evidence-based assessment of such linkages, as it is a field in which rigorous experimental design is impossible to implement for ethical (i.e. cannot test impact of a disease on people randomly) and practical (i.e. populations may involve tens of thousands of people) reasons. This restriction has led to development of Causal Criteria, which represent a broad range of logical devices to test hypotheses against experimental evidence.

The causal criteria had their beginning in the mid 19^{th} century through landmark investigations, such as that into the causes of London's cholera epidemics by Dr John Snow. However, they were assembled in their modern form in a landmark 1964 report prepared by an advisory committee to the US Surgeon General on the health effects of smoking (USDHEW 1964). In that report, the committee recognised that:

> *"Statistical methods alone cannot establish the proof of a causal relationship in an association. The causal significance of an association is a matter of judgment which goes beyond any statement of probability. To judge or evaluate the causal significance of the association between cigarette smoking and lung cancer a number of criteria must be utilized, no one of which by itself is pathognomonic or a sine qua non for judgement. These criteria include:*
>
> *(a) The consistency of the association*
> *(b) The strength of the association*
> *(c) The specificity of the association*
> *(d) The temporal relationship of the association*
> *(e) The coherence of the association"* (USDHEW 1964, p.182).

They identified five criteria to be considered when evaluating the significance of a cause/effect linkage and went on to provide greater clarification about why these criteria were important (and what aspect of the linkage they help to reinforce).

Since this landmark report, there have been minor refinements to the causal criteria suggested for use in epidemiology (Hill 1965; Susser 1991) and numerous comments on the suitability of their application (e.g. Phillips and Goodman 2006). It is generally accepted that these criteria provide valuable considerations for assessing a cause/effect relationship. Later in this paper we will explain the set of operational causal criteria that we consider of most relevance for modelling cause-effect relations in ecology.

2 CONCEPTUAL MODEL DEVELOPMENT

A conceptual model is essentially a tool for documenting and communicating an individual or collective understanding of hypothesised causal pathways in the system under investigation. These causal pathways are often shown as linkages/arrows in an influence diagram, but they can also be expressed purely as text or using a variety of tabular and graphical forms. Figure 1 shows an example of a conceptual model influence diagram for fish response to flow alteration. If we were developing a quantitative model from this diagram, we would seek to represent each of these causal pathways in mathematical form. As such, conceptualising these pathways and ensuring that they are valid is an important initial step in model development and one that can ensure further model development efforts are well directed.

The conceptual model should be made explicit during the model development process. From our collective experience, it is not uncommon for model developers to simply propose a model in mathematical form without first documenting the causal mechanisms they believe are (and are not!) fundamental to the responses they are modelling. However, this approach lacks the openness required for constructive scientific review and makes efforts to improve upon a model difficult.

The discipline of explicitly articulating a conceptual model forces the modeller and/or other stakeholders to express their beliefs concerning causal mechanisms and also facilitates the process of model revision during development (Burgman 2005). Failure to document and justify the conceptual model increases the likelihood of expert bias remaining undetected and considerable modelling effort might be wasted in attempting to

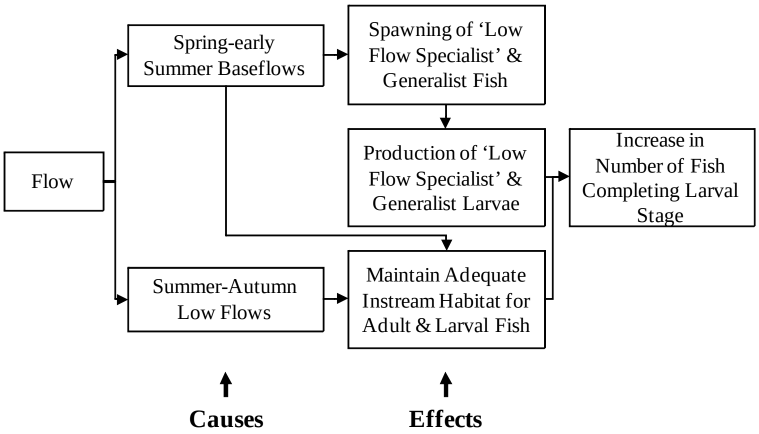

Figure 1: A conceptual model of fish response to flow alteration (adapted from Stewardson and Webb submitted). The linkages shown express the conceptual knowledge that summer and autumn low flows create slow water habitat for larval and juvenile fish, allowing spawning and production, which in turn results in increased numbers of recruits and greater abundance.

model processes that have little influence on the ecological responses of interest. These factors point to a need for a methodology within which the evidence collected during model development can be collated.

Consider that in hydro-ecological modelling, evidence regarding the key mechanisms by which flow alteration affects river ecosystems is usually incomplete and fragmented. This lack of evidence means that experts are frequently asked to make judgements of the key effects of flow alteration, driven by a need to plan environmental flows. Experts generally use sophisticated conceptual models in their reasoning about how a river responds to flow alteration and these models are important to document. These expert judgements can lead to proposals for reallocating water resources from human to environmental use and they are often questioned and challenged by those adversely affected (Marohasy 2003). Accordingly, the expert-based approach to developing environmental flow recommendations is vulnerable to political and legal challenges, particularly where there is no basis for resolving differences in opposing expert views (Norris et al. 2005).

Robust testing of conceptual models against the available scientific literature should help to reduce differences of scientific opinion and improve the credibility of knowledge used in planning environmental flows. There is a substantial and rapidly growing body of scientific knowledge that might be used for such tests in hydro-ecological modelling. An analysis of the literature – based on keyword searches in ISI Web of Science and a subsequent review of abstracts – shows that scientific papers providing evidence of the environmental effects of flow alteration has grown from a total of 17 in all years prior to 1990, to 190 in 2005 with a total of 1491 papers published prior to mid-2006 when our survey was conducted (Stewardson and Webb submitted).

While it previously might have been argued that expert opinion was the only way to produce conceptual models of ecological response to flow alteration, this vast expansion in the literature available tells us this is no longer the case. It is the responsibility of scientists to make better use of this literature than has been the case in the past. Causal criteria analysis provides a promising approach to achieving this.

3 CAUSAL CRITERIA ANALYSIS

Causal criteria have been proposed for use in identifying human impacts on the environment (USEPA 2000; Downes et al. 2002; Norris et al. 2005). Unlike epidemiological studies, hydro-ecological studies have some scope to undertake experiments and can often implement pre-impact monitoring (e.g. such as when a major impact has been proposed). This ability can provide experimental rigour to the examination of cause/effect and makes the assessment of causal criteria quite different to what is possible in epidemiology. For example, hydro-ecological studies can actually have before/after control/impact (BACI) sampling designs, which provide substantial evidence of cause/effect that cannot exist in epidemiology. However, many of the other weaknesses of epidemiological studies remain inherent in hydro-ecological investigations. These include the fact that experimental treatments are never randomly allocated, and very often that treatments and/or controls are not replicated.

Using causal criteria is recommended to ensure scientists and decision makers make full use of the evidence provided in the broader literature. This should be done both as a complement to rigorous experimental design, and also as key evidence where experimentation is not possible or inference is otherwise weak.

As yet, there have been few case study applications that apply causal criteria in environmental applications (Fabricus and De'ath 2004; Adams 2005; Norris et al. 2005). We consider that this may be due to the absence of a defined framework in which to collate the evidence and then analyse it in a repeatable way. To address this, the eWater CRC are currently developing software products to facilitate the use of causal criteria for testing causality in environmental studies.

These products focus on three causal criteria that are emerging as the most useful for testing causality in environmental systems:

- Strength of association;
- Consistency of association; and
- Coherence of association.

These three criteria describe the characteristics of a cause-effect linkage, with the details about each criteria (e.g. the number of positive associations found within a review of the literature) being used to evaluate and quantify the linkage. Phillips and Goodman (2006) point out that in epidemiology, the causal criteria are defined in such a broad manner that they should be treated more as causal 'considerations' rather than criteria. However, for the purposes of application in hydro-ecological studies, we attempt to concisely define each criterion, as well as providing suggested quantitative thresholds for when it has been 'met' (analogous to 'significant' probability values).

The following sections describe the criteria and provide details of the information that is extracted from the literature as evidence. This information would be evaluated against defined thresholds (which can vary with the application) in the subsequent causal criteria analysis. We have given an example of evidence extracted from the environmental flow literature for each criterion to help illustrate.

3.1 Strength of association

The strength of association is the apparent size of the effect associated with the cause. This could be measured by the differences in the effect between samples with and without the cause. A strong association (i.e. a large effect size) provides evidence of a causal relationship. However, weak associations do not necessarily mean that there is no causal link.

The strength of association may be quantified by recording information such as the type of response observed (e.g. binary or continuous), the effect size and how much background variability would be expected.

For example, Sabaton et al. (2008) found an average 167 ± 10 % increase (geometric mean ± standard deviation) in the numbers of larval fish in the bypass channels of hydroelectric plants following an increase in minimum flow rate through these channels. This would qualify as a large effect size.

3.2 Consistency of association

If an association between the effects and hypothesised cause has been observed in a variety of situations using a variety of techniques, then it is more likely there is a cause and effect relationship. Hill (1965) places more weight on similar results reached in quite different ways compared to repeated results using the same methods or populations. As with strength of association, the lack of consistent associations does not necessarily mean that there is no cause-effect relationship.

Consistency is difficult to quantify, but with a large body of literature it is possible to look at trends amongst the evidence. For example, if we determine for each piece of literature whether the association between cause/effect is either (a) statistical or subjective and (b) positive or inverse then we can assign a consistency value to the cause/effect linkage.

For example, in an analysis of the effects of flow regulation on stream channel width (Stewardson, unpublished data), a consistent effect of narrowing with regulation was observed by 4 studies across 9 different rivers and with a variety of experimental designs (spatial comparisons, analysis of temporal trends, Before-After Control-Impact designs).

3.3 Coherence of association

Coherence of association refers to the observation of patterns in the association which are consistent with current theory and knowledge about the (possible) causal linkage. This can also be thought of a factual coherence, in that many pieces of literature support the same concepts/facts. The most obvious example is the existence of a coherent dose-response relation, where increasing size of effect is associated with a more severe application of the cause.

By recording the coherence with known facts as some form of classification (e.g. strong/weak), as well as any information about dose-response relationships that exist, it becomes possible to determine a value for coherence.

For example, Humphries et al. (2006) used small-scale flow manipulations to demonstrate an inverse relationship between flow velocity and abundance of fish larvae. This result was consistent with a long-standing hypothesis that slow-flow areas provide an energetic refuge for poor-swimming fish larvae. However, they also found no effect of flow manipulation on the standing crop of prey species, refuting another equally long-standing hypothesis that slow-flow areas have greater food supplies for larval fish.

4 CAUSAL CRITERIA TOOLS

The eWater CRC is developing tools to collate evidence from the literature and catalogue this evidence against the causal criteria, so as to build a case for causality. The Causal Criteria tools consist of:

- CCED - The causal criteria evidence database: an on-line searchable database containing attributes and results of individual studies that deal with cause and effect in environmental systems; and
- CCAS – The causal criteria assessment software: a software package that uses data from CCED and other sources to test for causality using the criteria above, culminating in a summary report.

Through the use of these tools, we believe modellers can begin to better test their model structure and demonstrate that their conceptual understanding is well supported. The tools are all provided through the eWater CRC Toolkit website (http://www.toolkit.net.au).

4.1 Causal criteria evidence database (CCED)

The evidence database is focused on providing a tool that allows evidence from the literature to be collected (or banked) in a way that captures the key information needed for assessment against the causal criteria. It provides a mechanism to catalogue and share evidence that is contained in many different studies. Some of the key features of CCED are:

- A capability to search for evidence on particular causal links, including filtering of the returned evidence based on particular spatial and temporal domains;
- Users can record key values from the literature that capture the evidence in a repeatable and standardised manner;
- Provides a central database of causal evidence that encourages and facilitates rigour in the development of conceptual models of hydro-ecological impacts; and
- Gives access to evidence extracted from the literature by experts, and provides an on-line community of users contributing to a shared knowledge base, reducing the amount of effort involved in any single causal criteria assessment.

4.2 Causal criteria analysis software (CCAS)

Causal evidence can be difficult to evaluate in a transparent and repeatable way. The analysis software is designed to assess the level of support for causality by using an 8-step process. The process gives users a framework in which they can clearly define their conceptual model, draw together information from the literature (via CCED), substantiate the causal linkages, weight them appropriately and then summarise the overall strength of support for the model in question. It must be noted that this is an interactive process, **not** just a 'black-box' type process that takes extracted evidence and returns a value of 'causal linkage strength'.

4.3 Integration and usage

The evidence database and analysis software have been designed to work together. They use common terminology and treat evidence from the literature in a consistent manner. While the tools can be used individually, it is expected that the evidence database would be used in the initial stages of model development for collating and storing evidence from the broader literature. Once the literature review is complete, the analysis software can then be used to synthesise the evidence for each conceptual model linkage and evaluate the strength of that link before moving onto further model development.

5 CONCLUSIONS

The approach presented here for conceptualising and documenting the early stages of model development encourages users to harness existing knowledge and consider the meaning of all linkages in their model of choice. As Phillips and Goodman (2006) note, causal criteria (or considerations) have immense value in encouraging all users to apply scientific common sense in model development.

By providing some tools for working with causal criteria in a repeatable manner, we believe that improvements to model development and subsequent decision making can be made. This paper has provided some guidance along that path and the adoption of these tools over time will reveal how well this fits within the workings of the broader hydro-ecological community.

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