Causal Criteria Analysis Methods Manual

A systematic approach to evaluate causality in environmental science

October 2008

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Oct 2008	As per cover	1.0	First revision under eWater 'banner'
Oct 2008	As per cover	1.1	Formatting changes to eWater style
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Legal Information

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CAUSAL CRITERIA ANALYSIS

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1 Introduction

Scientists and managers are commonly faced with a situation where information from various sources provides conflicting results or advice. Therefore, it is important to have a transparent, consistent and logical framework to evaluate evidence and provide confidence in the conclusion drawn from that evidence.

This manual describes how 'causal criteria' (sensu Hill 1965, Susser 1977, Downes et al. 2002) can be used to address questions of causality between environmental stressors, management interventions and ecological outcomes (Norris et al. 2005). More generally, the causal criteria approach is applicable to any scientific literature that aims to demonstrate a relationship between an apparent cause and an apparent effect.

The causal criteria approach was originally developed for studies in epidemiology (medical science), where a lack of experimental data can result in a weak ability to draw inferences about causality (Hill 1965, Susser, 1991). However, a number of pieces of weak evidence may collectively build a sufficiently strong case to infer causality. The causal criteria approach provides a framework whereby the different pieces of evidence can be assimilated. The criteria 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).

Like epidemiology, many ecological, hydrological, or other environmental studies also have limited opportunity for proper replication and randomization of treatments and observations. This weakens our ability to draw strong inferences. Over the last decade there has been a growing interest in applying the principles of causal criteria analysis to ecological questions. The causal criteria approach for ecological applications has been variously referred to as ‘levels of evidence’ (Downes, Barmuta, Fairweather et al., 2002) and ‘multiple lines and levels of evidence’ (Norris et al. 2005). The following causal criteria have largely been adapted from Downes et al. (2002) because of their relevance to ecological investigations (Table 1).

Table 1. Definitions of the Causal Criteria we use in an investigation of causality

Causal Criterion	Description
Plausibility	Is there a plausible mechanism (e.g. biochemical reaction) that could explain the relationship between the causal agent and the potential effect?
Presence of a **Response** (e.g. biological response)	There is evidence of the response in the presence of the causal agent. This criterion includes results from all types experimental designs ranging from 'after impact only' to more complicated studies investigating natural or experimental gradients (see Table 3).
Evidence of a **Dose-Response** relationship with the causal agent	There is evidence of a dose-response relationship between the causal agent and the response, possibly from a study design using a natural or experimental gradient. A "Dose-response" relationship is also a "Response" but this criterion is a more compelling subset of the studies described above for the 'Response' criterion.
Consistency of Association	A consistent spatial and temporal association of causal agent and effect. The expected response occurs in the presence of the causal agent **all** the time or almost all of the time.
Evidence of the causal agent found in biota	Evidence of the causal agent is **found in the organism** of interest, perhaps in the form of a chemical residue.
Agreement across effects	Consistency of evidence across the various effects. This would provide further evidence in favour of a link between a cause and a high level effect (i.e. integrative of several sub-components).

To provide consistency, we define the following terms for use with the causal criteria method.

- A **cause** or **causal agent** is the source of stress (e.g. land clearance) or proximate stressor (e.g. water temperature) that is seen as the cause in the cause-effect relationship
- An **effect** is a system attribute (e.g. increased tadpole abundance, reduction of macroinvertebrate species richness, increased macrophyte biomass, increased occurrence of fish abnormalities, elevated electrical conductivity) that may be affected by the causal agent.
- A **causal criterion** is one of the causal criteria (e.g. consistency of association), which is used to determine the case for inferring that a given agent causes a particular change in the system.
- A **causal criteria analysis** is the use of the framework presented below to investigate the evidence for causality between a putative cause and effect.
- A **study** is an article taken from the scientific literature, or an unpublished study, a number of which are reviewed as part of the causal criteria analysis. Note that a given article may present more than one study.

1.1 The methods manual

In this manual, the Causal Criteria approach is presented as an 8-step framework (Fig. 1), designed to compliment the Causal Criteria Analysis Software (CCAS) tool available through the eWater CRC Toolkit website (www.toolkit.net.au).

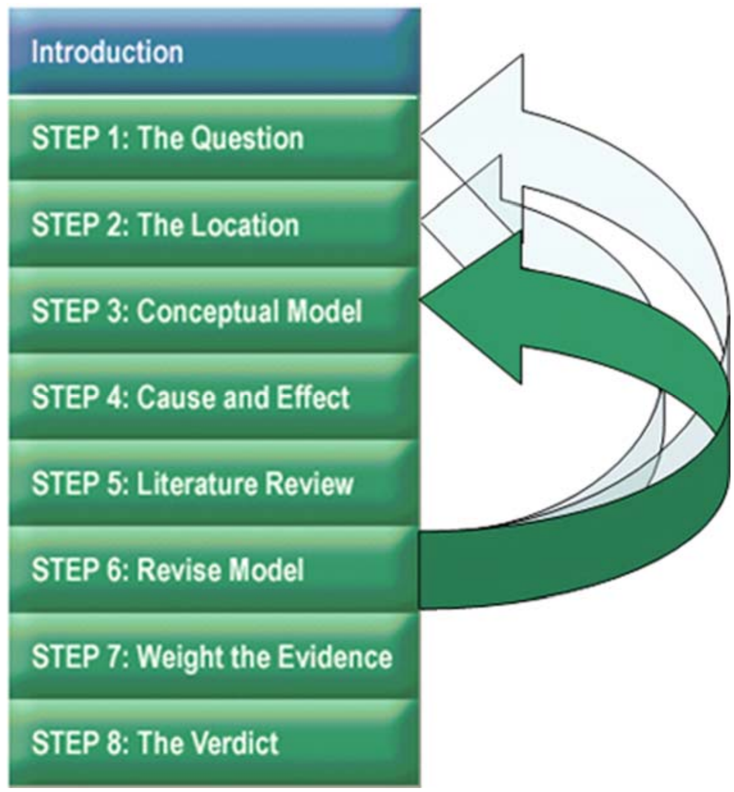

Figure 1. Steps in applying the Causal Criteria framework

The software tool was developed to guide users through the method and assist with the application of the Causal Criteria framework to a research question. The tool evaluates the strength of evidence for a cause-effect relationship for each potential effect using an overt set of rules, and summarizes this evidence in an 'evidence catalogue' according to the Causal Criteria methods presented in this manual.

The 8 steps are an iterative process but they can be roughly divided into three sections as follows.

1.1.1 Problem Formulation

The initial steps of the framework (Steps 1 – 4, 6) are concerned with developing the question that will be assessed by the causal criteria analysis (i.e. does X affect Y?). It is important to pose questions that are sufficiently precise in terms of the potential causes and effects, and the spatial and temporal context. Precise and explicit questions greatly assist the assembly of relevant evidence and the also identification of evidence that is not relevant to the question/s being asked. The initial steps require the user to frame a broad question (Step 1), to place that question in context (Step 2), to develop a conceptual model of potential cause-effect linkages for that question (Step 3), and document the relevant potential causes and effects that will be investigated (Step 4). Following review of the evidence, the user is given a chance to further refine the question/s, or hypothesis, and the conceptual model (Step 6).

1.1.2 Literature Review

The framework and software tool provide a systematic method for reviewing existing literature or unpublished data (Step 5) to assemble and summarize relevant research on a topic. As part of this process, the evidence contained within each study is explicitly compiled. A systematic procedure is necessary because literature reviews are often affected by elements that introduce subjectivity and bias, such as:

- the thoroughness of the writer's search;
- the quality and reliability of the writer's sources;
- the ability of the writer to relate research studies to one another and to the writer's own purpose; and
- the objectivity of the writer in selecting, interpreting, organizing, and summarizing the research he or she has reviewed.

The approach presented here can reduce some of this bias and subjectivity, leading to a literature review that can help to assess causality.

Any given study may report on more than one effect (e.g. fish abundance, fish taxon richness and a macroinvertebrate index, or salinity values and water flow measurements). For each of these potential effects the evidence within and among different studies can have different reasons for being relevant (or not) to the question/s being asked by the causal criteria analysis. The method requires reviewers to explicitly record the relevance, or lack of relevance, of effects in a given study.

The method’s ease of use will depend on the user’s prior knowledge and expertise within the field of application, a situation not dissimilar to the needs of a traditional literature reviewer. For example, a user wishing to evaluate a causal relationship in the fish biology discipline, and without prior knowledge of study design and fish biology, may find the learning curve steeper than an expert in the field with an intimate knowledge of field study techniques and familiarity with the ‘jargon’ used in the relevant literature.

1.1.3 Weighting evidence and judging causation

The framework presented in this manual also provides procedures for weighting studies (Step 7); and provides guidelines on how to interpret the results. For each study, the quality of the evidence is evaluated in terms of three study quality attributes:

- study design type;
- number of independent sampling units used as control (e.g. reference sites);

- number of (potentially) impacted independent sampling units (e.g. test sites, treatment locations).

Some studies may present multiple effects (i.e. multiple results). The study quality attributes may differ if the effects have been investigated with varying levels of rigor (i.e. different study designs may be applied to various components of a study), thereby affecting the determined ‘quality’ of each piece of evidence.

Once the evidence has been assembled and weighted, an evaluation can be made on whether sufficient evidence, of sufficient quality, has been collected to infer causality (Step 8).

The CCAS program automates the weighting, cataloging and reporting process. We provide recommendations as to the cumulative evidence that might be considered as sufficient to infer causality between the causal agent and potential effect. The weightings used for different types of surveys and experiments, and the thresholds employed to infer causality can be customized by the user to best reflect the nature of the cause-effect question being asked. An example of a Causal Criteria analysis is demonstrated in Section 3.

2 The 8-Step Causal Criteria Framework

This section describes the steps of the Causal Criteria Framework. Each step is explained, and a 'task' is listed which covers what you (the applier of this method) needs to document and/or achieve to complete the step. Examples to aid understanding are given where possible, and a further, worked example appears in Section 3.

2.1 Step 1

> Document the nature of the problem and draft the question under investigation

The first step in the Causal Criteria Framework is to consider and document the nature of the problem under investigation, the potential causes (the human activity, etc.) and the potential effects, including the timing, size and likely magnitudes of any effects. For example:

> The Cotter River has been dammed to create a water supply for Canberra. Water trapped by Bendora Dam is diverted to Canberra for consumption. The flow regime below the Dam has been modified in a number of ways, principally reduction in mean annual flow and reduction in the frequency of small flows. The dam has a multi-level off-take and any downstream releases are generally of a similar temperature to inflow water. However, water quality will sometimes depend on the management of the dam for other problems e.g. release of layers of dirty water.

If more than one cause or effect is under investigation then you will need to either i) have several questions and several assessments (i.e. each combination of cause and effect should be a stand-alone question), or ii) have some defensible scheme for aggregating individual causes into a single cause and/or individual effects into a single effect (e.g. reduction in mean annual flow and reduction in frequency of small flows are parts a larger cause called 'flow regulation').

Thus, the question "Has flow regulation by Bendora Dam altered the downstream aquatic ecosystem?" might be re-posed as a series of questions. For example:

- Has the reduction in mean annual flow reduced fish abundance?
- Has the reduction in frequency of small flows reduced fish abundance?

- Does reduction in the frequency of small flows reduce macroinvertebrate species richness?
- Do dirty-water releases change rates of primary production? Etc.

Alternatively, ask a single question with the individual causes and effects forming components of the conceptual model (see below) and broader question. You may describe 'flow regulation' as the cause but define it more precisely as a number of causes e.g. 'reduction in mean annual flow' and also 'reduction in the frequency of small flows', which you can later combine to answer the broader 'flow regulation' question. Likewise, there are likely to be multiple 'effects' e.g. 'reduced fish abundance', 'reduced macroinvertebrate species richness', 'change rates of primary production', etc. that could later be combined to describe the 'altered downstream aquatic ecosystem'. This issue of 'depth of detail' in describing either cause or effect is important, and is addressed further below.

Task:

- In this step you should document the nature of the problem under investigation; the causes and effects, and draft one or more questions for investigation (note that you may refine this question later).

2.2 Step 2

What type of environment are you investigating?

In what context will the question be asked?

The idea is to set the context and boundaries for the question under investigation.

If you are conducting an experimental investigation, it is necessary to decide whether it is important to restrict the literature review to studies with similar climatic regimes, geomorphology or other environmental features to the location under investigation. Similarly, if your study is a literature review, then you must decide whether the review will be limited to an environment of a particular type, or be more general. In this step you describe the details of the type of location in which you are interested. This description is used later to assist in the identification of the relevant studies to use as evidence. Returning to the example above:

> The Cotter River is an upland river (700-900m) in SE Australia with high aseasonal rainfall (1000mm), and a steep, vegetated catchment. The river has a steep gradient and its substrate is predominantly cobble. It has a constrained channel with much bedrock outcropping. Where the river is impounded the catchment is a national park and has native vegetation. Downstream of the water supply impoundments land-uses are softwood forestry and the catchment

> also has areas of native vegetation. Public access to the water supply catchment area is restricted and so the principal potential impact is river regulation.

Task:

- Describe and document the details of your investigation location or the type of environment relevant to your question.

2.3 Step 3

> Develop a conceptual model and clarify the question
>
> Identify the potential causal relationships. You may also need to refine the question you drafted in Step 1
>
> The operational question/hypothesis should articulate the "quantifiable" cause/s and the "quantifiable" effect/s.

The conceptual model is to be used to address questions of causality, for example:

> Has flow regulation (defined as the reduction in mean annual flow and the reduction in the frequency of small floods of <2 year return:) in the Cotter River downstream of Bendora Dam resulted in the alteration of the aquatic ecosystem?

To quantify our effect, 'alteration of the aquatic ecosystem', we break it down into its quantifiable component effects. Such effects might include:

- Change in fish abundance;
- Change in algal biomass;
- Change in riparian condition;
- Change in macrophyte richness;
- Change in macroinvertebrate richness;
- Change in macroinvertebrate abundance;
- Change in the predicted macroinvertebrate community composition.

Likewise, the causal agent 'flow regulation' is composed of different quantifiable sub-causes e.g. the reduction in mean annual flow and the reduction in the frequency of small floods of <2 year return.

The need for a conceptual model is paramount, thus further suggestions are provided in Appendix A, which provide some guidance on how to develop an appropriate conceptual model for the Causal Criteria application. An example of a conceptual diagram is shown below (Fig. 2). This shows multiple potential effects that may occur because of 'flow regulation' as defined above.

In assessing causality, we have adopted the convention that if there are multiple possible causal pathways linking cause to effect, then strong evidence for *one or more* of these pathways is sufficient to infer strong evidence for cause and effect overall. Thus, if we are assessing whether reduction in flow (cause) has led to alteration of the aquatic ecosystem (effect), and we find strong evidence that flow reduction leads to armouring of the bed substrate, and independently find that armouring is associated with reduced macroinvertebrate richness, then our convention implies that we have identified strong evidence for a causal link between reduced flows and alteration of the aquatic ecosystem.

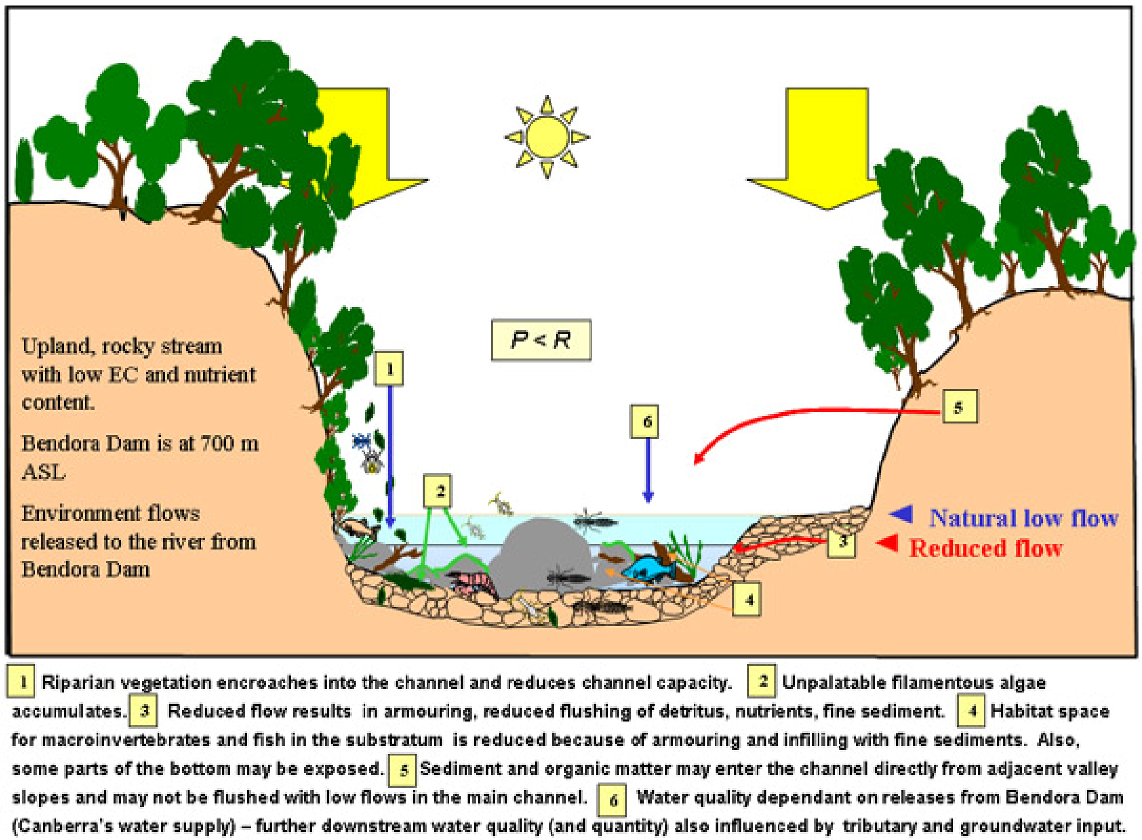

Figure 2. An example of a conceptual diagram for the 'alteration of the aquatic ecosystem' below Bendora dam.

Task:

- Develop a conceptual model of the relationships in question, making sure that the potential causes and effects are identified.
- Refine the he operational question if needed to include the "quantifiable" causes and the "quantifiable" effects.

2.4 Step 4

Decide on the relevant causes and effects and list them

How will an effect be determined?

The previous step should have provided a very specific question for your investigation and you should be able to articulate the "quantifiable" causal agents and the "quantifiable" effects.

Based upon the conceptual model, refine the preliminary list of potential causes and effects. The conceptual model developed in Step 3 identifies those cause-effect relationships that are likely to be important and those that are unlikely to be important. For transparency you need to now list the causes and effects you will be investigating in each application of the causal criteria analysis.

The level of resolution of an effect will be implicit in your operational question for that effect. For example, is the effect a community-level change for fish (e.g. species richness), or is it change to the population size for one particular species?

At first, it may help to divide effects into major categories e.g. fish, algae, macrophytes, macroinvertebrates, etc. Below this level the definition of the effects would be guided by your conceptual model for the hypothesis being investigated. Using the conceptual model as a guide, it may be more appropriate to fit effects into broad lines of evidence, e.g. a change to the macroinvertebrate community. In other cases it would be best to use more specific effects as they would be described in the source literature or study under evaluation; e.g. an increase in or a decrease in macroinvertebrate biomass relative to 'normal'. Repeat this process for the cause, if it can be broken down into sub-components.

Note: Step 4 is an iterative step. Following the literature search the conceptual model and causes and effects should be reviewed.

Task:

- Document the relevant causes and effects for your current investigation.

2.5 Step 5

Conduct the literature search and review
Review the literature to locate the studies judged to be relevant to the investigation

2.5.1 Record your search strategy

The transparency and repeatability of the Causal Criteria approach requires the literature reviewer to document the method used to search the literature. For example, when searching on-line publication databases, what key words or phrases did you use to search, how were they combined (which Boolean operators), and which databases did you search? For example:

Databases searched:	Web of Science Current contents CSS
Search terms used:	Reduced flow Flow + macroinvertebrates low flow effects

Include justification for the inclusion (or exclusion) of all studies initially delivered from the search. Exclusion prior to review is usually a function of the search terms returning inappropriate studies. For example; 'environmental flows' will return studies concerning the movement of goods and monies around economies, as well as studies about rivers. Other reasons for excluding studies prior to detailed review may be more subtle. These must be documented.

It takes time to properly assess the causal evidence in studies, so you should try to avoid having too many 'irrelevant' papers. If too many papers are returned to be evaluated, try restricting the search to relevant attributes that relate to your question. For example, is geographic location important; given your question, can studies conducted on sand-bed streams be compared to those on gravel-bed rivers; do you have a valid reason to eliminate studies before a specific publication date, etc.

From experience, the number of studies to be reviewed in a causal assessment will vary from one question to another but generally a short literature review requires about 15 - 20 primary research articles. We provide this information as a general guide to indicate that you should expect to review at least this number of studies. However, you should by no means limit yourself to this number.

Note that an unpublished study (generally evidence from a case study or study you have not yet published) and the literature evidence are both evaluated the same way in the causal criteria analysis.

2.5.2 Determining Relevance

It is important that you justify and document how the study reported in the literature is relevant to your investigation, and why non-relevant studies were deemed as such.

The conceptual model will be relied upon heavily to guide the choice of 'relevant' studies. For example, justification may include:

- A combination of geographical proximity, altitude, similarities in ecosystem processes and similar cause and/or effect to those you are investigating.
- Similar/applicable temporal and spatial scales.
- Consideration of biogeography, ecology, etc.

If you are attempting to extrapolate across species (or other groups of effects), then the reasons for doing so must be made clear. For example, if the question relates specifically to reproduction success of Murray Cod, is it appropriate to use supporting evidence from a study on Golden Perch, considering the different types of eggs?

The information required to **establish relevance** of the literature can generally be found in the abstract, results and methods sections of the papers, meaning that the entire paper may not need to be read.

Tasks:

- Search for relevant literature and record your search strategy
- Record details of the literature reviewed (e.g. author, publication date, title, etc.). It is also important to retain a record of those studies deemed to be not relevant.
- For each study reviewed, document the justification for including (or excluding) the study in your investigation i.e. document how the study is comparable or relevant to the investigation?

When using the Causal Criteria Analysis Software tool, all the above information can be easily entered directly into the program or alternatively, can first be recorded in a spreadsheet.

2.5.3 Extracting evidence

Once a study has been designated as relevant to the Causal Criteria analysis being done, its evidence must be collected. The CCAS software provides a standard user interface for collecting this information as part of the review process.

Study type, control and impact locations

The study design type, and number of independent sampling units (both controls and impact locations) will contribute to the strength of evidence from any particular study. The study design components of space and time are defined in a number of different ways in the literature. It is important to have consistent definitions when using these concepts to weight studies in Causal Criteria analyses. Accordingly, we have adopted the definitions below (Table 2), mostly according to Downes et al. (2002).

Table 2. Definition of some study-design terms used in the Causal Criteria framework

Term	Definition
Periods	Time is viewed as two major sampling periods, Before and After an impact. Within these periods are time intervals, which can be of different temporal scales, e.g. monthly or yearly sampling.
Locations or independent sampling units	Locations are spatial units that may be in areas in which the same kind of human activity occurs (i.e. true replicates of the impact), or independent areas that serve as comparisons to impacted areas (i.e. replicates of un-impacted areas). Locations are presumed to be spatially distinct to the extent that conditions at one location are independent of conditions at another location.
Replicate	A replicate is the same treatment in a different location. We consider replication at the location level. For instance, replicate locations can be in different rivers or catchments. There can also be replication in time if the sampling time intervals (see period above) are large enough. Samples through time from one location may be replicates (rather than sub-samples) because the large intervals mean that the samples will tend to represent independent and random observations. Part of the formal analysis in such cases may include preliminary tests for temporal autocorrelation.
Sub-samples	Sub-samples are observations within a location or within a single time interval. The first level of sub-samples is sites within the impact location. There can be further sub-samples within the sites depending on the study. Sub-samples can also be observations from the same location on multiple occasions with small sampling time intervals (i.e. can be assumed or shown to be non-independent).
Sites	Sites are the first level of sub-samples from a (control/reference or impact) location.
Reference location	Reference locations are areas that are as close as possible to the state of the environment undisturbed by human activity. Reference locations are not chosen with a particular impact in mind but to represent what other locations could be like in the absence of human disturbance.
Control location	Control locations are areas that are as similar as possible in all respects to the impact location, except for the presence of the agent or stressor. The intention is to use the control locations to isolate the effect of the particular human activity from a range of other processes. Under some circumstances, when a human activity occurs in an otherwise undisturbed area, control and reference locations may have the same attributes. However, when a new activity is contemplated for an area that has already been highly modified, the controls should be locations that are themselves modified in similar ways.

Counting independent sampling units

When counting independent sampling units (i.e. impact locations and control locations), we do not count sub-samples because they do not increase inferential power in the way that replicate locations do.

For example, in the illustration below, there are two sites on the main stem of a river below the dam and three sub-samples at one of the sites. These sub-samples represent a single independent sampling unit or impact location because the three sub-samples are not independent. Similarly, there are only two control locations even though two sites were sampled on one of the tributary streams.

In addition, it is important to consider the number of controls or impact locations actually used in the analysis of each effect because in some cases not all of the control locations reported in a paper are used for the analysis of every effect reported. If possible, check the degrees of freedom for statistical analyses of each result you are accepting as a relevant effect.

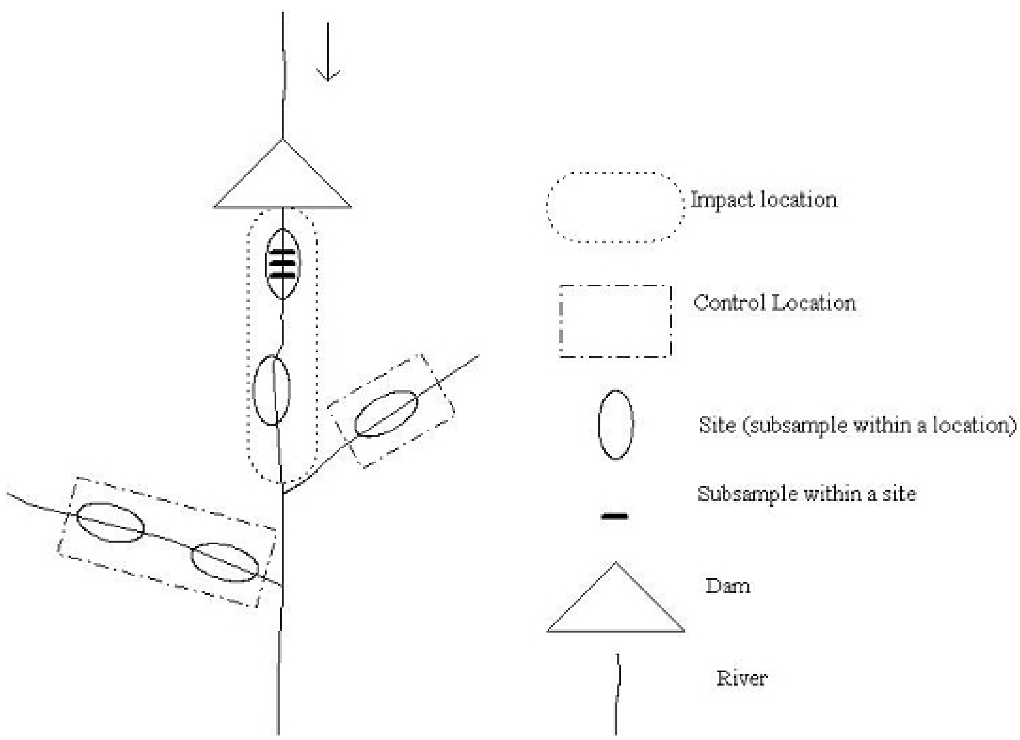

Figure 3. Some study design components of space (locations, sites and subsamples) in a scenario where the independent sampling unit is a location below a dam (the one impact location has two sites and subsamples within the sites) is being compared to two similar independent sampling units unaffected by a dam (i.e. 2 control locations).

Study design types

Some study types are more susceptible to confounding effects than others, which weakens the argument for causality. Thus, different study design types contribute more or less to the overall assessment of causality for a given analysis. It is important to capture the study design for use when weighting evidence (Step 7). Different study types are outlined below (Table 3).

Table 3. Definitions for the study types used in the Causal Criteria framework.

Study design type	Description
After impact only	A comparison of variable(s) from impact locations with a standard of some kind but not with control/reference location/s, and with no data before the impact compared (e.g. DO measured at impact location and compared to a standard).
Control/Reference vs. Impact - no before	Any case where reference/control locations are being compared to impact locations without before-impact data for the impact locations. This may include cases where locations are compared to output from models based on reference/control locations (e.g. RIVPACS or AUSRIVAS). In such a case the number of impact locations will be the number of impact locations sampled and compared to the model whereas the number of control locations will be set to any value that will give maximum weight for the number of controls study quality attribute. The numbers of control locations are counted in this way to acknowledge the enhanced inferential power from the number of reference/control locations in the predictive model. The reviewer needs to check or assume that the predictive model is robust and has been cross-validated.
Before vs. After - no reference/control	Sampled Before and After the onset of a causal agent with no reference/control.
Gradient Response Models	An investigation of an association between the causal agent and response along a gradient of the agent (e.g. using correlation or regressions). The data may include pristine locations through to highly disturbed locations or may have no pristine locations but have locations disturbed to different degrees. The number of control locations and the number of impact locations are set to a value that will give maximum weight to the control and impact study quality attributes to take into account the greater inferential power from a dose response gradient. Gradients may also occur through time, with sequential sampling of location/s providing the 'dose-response' relationship.
BACI/BARI	Before After Control Impact or Before After Reference Impact. 1 control/reference location, 1 impact location sampled once (may include sub-sampling within a location). Compares changes at two locations, i.e. Control/Reference and Impact locations, Before and After the impact.
BACIP	1 control location, 1 impact location sampled through time at the same times, i.e. paired measurements from control and impact locations. Sampling through time with large intervals during both the Before and After periods is used to estimate the temporal variation in the differences between control and impact locations. The temporal variation is used to assess the average difference Before and After the activity commences. The time intervals are large enough to prevent autocorrelation in these differences, and are viewed as a random sample of possible values in each time period.
MBACI/MBARI	Either Multiple Control/Reference locations and 1 or many Impact locations. Either multiple impact locations and 1 or many control/reference locations. Also includes replication in time.

Task

Document the study details (e.g. study type, number of impact and control independent sampling units or locations – see definitions above) that are used to weight the evidence and to determine the quality of the evidence documented in the literature or local data.

- Specify the study type. The different study types are assigned different weights. A study may include evidence for many effects, some may be relevant to your question and others not, this situation may require a closer look at the study design. A study type should be assigned to each cause and effect identified from a single study if not all of the evidence is relevant.

- Specify the number of independent sampling units (i.e. reference or control locations). Having a control brings an improvement in inferential power (Downes et al. 2002).

- Specify the number of independent sampling units for impacts or impact locations. A larger number of impact locations leads to a better estimate of the range of dynamics that might be experienced by the impact locations and the control conditions with which they are being compared.

During this step, the Causal Criteria Analysis Software also requires the input of other details of the evidence from the study. This includes:

- Descriptions of the cause and effect in greater detail than those broad categories recorded at Step 4. For example, 'flow reduction' might be manifested in a paper as 'reduction in baseflow discharge between the months of October and April'. You will be required to 'map' these detailed cause and effects to those broader categories made in Step 4. Using our previous example, the 'reduction in baseflow discharge between the months of October and April' could (with justification) be mapped to 'reduction in mean annual flow'.

- An assessment of whether a response was found consistent with the cause-effect hypothesis, and if so whether that response could also be described as a dose-response (see below for more information on this).

- Whether there was evidence of the causal agent in the organism of interest. This question will not be applicable sometimes, but will be very applicable to studies of toxic effects in ecosystems.

- An assessment of whether the study is relevant or not, and why

- Whether statistical analyses were performed.

2.6 Step 6

Refine conceptual model

During the literature review, you may discover new causes and effects relevant to the question you are asking. Alternatively, you may decide that some previously listed causes and effects are not relevant. These should be recorded.

Task:

- Review your conceptual model and revise as necessary in light of changes to the causes and effects suggested by the literature review.
- Re-visit Step 4 to make any necessary changes to the lists of causes and effects.
- Document these changes.

2.7 Step 7

Catalogue and weight evidence
Evaluate the literature and the local data

2.7.1 Cataloguing and weighting process - overview

In the cataloguing process, the amount and strength of evidence is recorded alongside the different causal criteria for each cause-effect linkage in the conceptual model. The first step in this process is to weight the evidence.

Process for weighting evidence

Overall study weight

Studies are weighted on three characteristics to provide an overall study weight:

1. type of study design;
2. number of independent sampling units used as controls; and
3. number of independent sampling units used to investigate impacts.

For each piece of cause and effect evidence identified from a study, the weighting value for each of the above three categories are summed to give an overall study weight. If you are using the CCA Software, the program will do the summing and categorizing for you. The study-weight scores can also be converted to quality categories. The advantage of using study quality categories is that it more immediately relays the importance of the study than a numerical value. For example, the default values for overall study weight are 5-10 = **High quality** and 1-4 = **Low quality** study (however it is the numerical study weights that are combined in the CCAS program to provide the end result).

People may wish to set their own weights, and the software package allows for this. However, we have provided our justification for the default values below, and if users wish to change them, they also need to provide justification.

Type of study design

Justification of the weighting: Studies in which error terms are well controlled (e.g. BACI designs) should exert greater influence than less rigorously controlled designs (e.g. only impact locations sampled). Therefore, studies with rigorously controlled designs have more weight than studies for which we lack information, such as after impact only (Table 4).

Table 4. Study design types and default weight values (see Table 3 for study design definitions).

Study design type	Weight
After impact only	1
Reference/Control vs. impact (no before)	2
Before vs. after (no reference/control)	2
Gradient response model	3
BACI or BARI MBACI or Beyond MBACI	4

Number of control independent sampling units

Justification of the weighting: Having a control brings an improvement in inferential power (Downes et al., 2002). There is some increase in inferential power derived from having more than one control. A larger number of control locations or sampling units is important because it better estimates the envelope of 'normal' behavior (Downes et al., 2002) so that departure from 'normal' can be detected with more confidence. Therefore, studies with 2 or more controls have more weight than studies with no controls (Table 5).

Table 5. Number of control locations & proposed weights

Number of controls / reference locations	Weight
0	0
1	2
>2	3

Number of independent sampling units for impacts

Justification of the weighting: A larger number of impact locations leads to a better estimate of the range of dynamics that might be experienced by the impact locations and the control conditions with which they are being compared. Therefore, studies with more than 2 impact locations have more weight than studies with only 1 impact location (Table 6).

Table 6. Number of impact locations & proposed weights

Number of impact locations	Weight
1	0
2	2
>2	3

Overall study weight - calculated from the above 3 tables

The weight values for the above three categories for each study are summed to give an overall study weight. We considered that at this point it was useful to convert these scores to quality categories.

A study that meets the minimum criteria for a satisfactory study would at least have an 'after-only' study type, no control locations and 1 after impact location, resulting in a minimum study weight of 1 (i.e. 1 + 0 + 0).

A much better study would have a reference versus impact study type, 1 control location and 1 impact location. The weight for that study would be 4 (i.e. 2 + 2 + 0). That study would still be considered a low quality study because it has no replication.

A study weight above 4 would mean that the study at least has a reference versus impact study type and at least control location replication or impact location replication. Such studies would have a maximum weight of 10 and have been classed as high quality studies because their inferential power is greatly increased by the presence of replication (Table 7).

Table 7. Scheme for categorizing the importance of each study

Overall study weight	Study importance category
5-10	High quality
1-4	Low quality

Catalogue the evidence

Evidence collected in Step 5 and weighted in Step 7 can now be assembled into an evidence catalogue. Develop the catalogue listing the evidence against the Causal Criteria, which can then used to accept or reject your hypothesis (or determine that you have insufficient evidence to make this decision).

2.8 Step 8

What is the verdict?

Assess your evidence against the Causal Criteria

Accept or reject your hypothesis

2.8.1 Combining studies and causal criteria

In numerically weighting the evidence for assessing causality, we do not employ all of the causal criteria listed in the introduction (Table 1). Rather, we use three of the causal criteria to organize and weight the evidence (in terms of the number of High and Low quality studies) for the association between a given potential cause and effect. The three criteria used are:

- Response (presence of a response)
- Dose Response (a dose relationship between cause and effect, given that there is a response)
- Consistency of Association among studies

High levels of evidence for one of the 'Response' and the 'Dose response' causal criteria demonstrate an association between a cause and effect (see definitions in Table 1). The association develops into a strong causal link, and thus provides support, if the expected response (e.g. a biological effect) is always observed, or observed most of the time under our weighting process, when the particular causal agent of interest occurs (i.e. the 'Consistency of Association' criterion).

The argument for causal inference can also be supported by the use of other causal criteria to further strengthen confidence in your conclusion (Table 1), but these other criteria are not used to quantify cause-effect evidence in our framework. The table below re-iterates the causal criteria (defined in Table 1), and details the role of each one in our application of the Causal Criteria framework (Table 8).

Table 8. Causal Criteria used in an investigation of causality and the way that they are employed in our framework.

Causal criterion	Comments
Plausibility	This component has been absorbed into our conceptual model rather than kept as a separate criterion, and is not used in the weighting process.
Presence of a Response (e.g. biological response)	This is a recasting of the Downes et al. (2002) "experimental evidence" criterion, but includes evidence from all types of studies
Evidence of a Dose-Response relationship	As described by Downes et al. (2002) The relationship between the amount of exposure (dose) to some causal agent and the resulting response (effect). A dose-response effect means that as the dose increases, so does the magnitude of the effect.
Consistency of Association	As described by Downes et al. (2002). If the response or dose-response under investigation is not detected in a relevant study then the weight of that study will count against the 'consistency of association' criterion (i.e. it will contribute toward a lack of consistency). Thus, if a particular study is deemed relevant to the question under investigation (which implies that the causal agent is present) but no response was detected, then the association lacks consistency.
Evidence of the causal agent found in biota	Currently, this evidence should be reported but is not used in the weighting process. This evidence would provide support and strengthen confidence in your conclusion.
Agreement across effects	An output table should be constructed to catalogue the evidence, showing the number of cause/effect associations in favour of the hypothesis, compared to total number of effects identified. This evidence should be reported but currently not used in the weighting process.

For the 'Response' and 'Dose response' causal criteria, **combinations** of studies with a summed quantitative study weight of **20 or more** are deemed to have a **HIGH level of support**. A cause and effect with a summed quantitative study weight of **less than 20** has a **LOW level of support** for the 'Response' and 'Dose response' causal criteria. Hypothetical examples of this process are detailed below showing the different levels of support provided by various combinations of high and low quality studies (Table 9). Note that as few as 3 high quality studies may provide enough evidence for support, whereas, 7 low quality studies may not (Table 9).

Table 9. Examples of the application of the decision rules for **Response** and **Dose response** causal criteria. **Note:** The values representing the number of low and high quality studies were selected at random and are used as **examples only**. **20 or more** = a **HIGH level of support** and a weight of **less than 20** = **LOW level of support.**

Number of low quality studies showing support	and	Number of high quality studies showing support	Sum of the quantitative study weights	Level of support for 'Response' and 'Dose response' causal criterion
0	and	3	(0 x 2.5^) + (3 x 7.5^) = 22.5	High
2	and	2	(2 x 2.5^) + (2 x 7.5^) = 20	High
1	and	2	(1 x 2.5^) + (2 x 7.5^) = 17.5	Low
7	and	0	(7 x 2.5^) + (0 x 7.5^) = 17.5	Low

^ Median study weights are used here for the purpose of the examples (2.5 for low quality studies and 7.5 for high quality studies – from Table 7), however, the actual overall study weights (based on study design, control and impact locations) for each of the studies would be used in a real situation.

To assess 'Consistency of Association', we sum the study weights from those comparable studies that do not show support for the hypothesis under consideration. A summed weight of High and Low quality studies equaling **20 or more** indicates a **LACK of consistency** for the cause and effect relationship, and argues against causality, whereas a summed study weight of **less than 20** indicates **HIGH Consistency of Association** for the cause and effect relationship (High level of support) (Table 10).

Table 10. Examples of the application of the decision rules for the 'Consistency of Association' causal criterion. Note that a comparable study with the relevant causal agent present but a response not consistent with your hypothesis will contribute to a lack of consistency. Study weight of 20 or more = Low level of support, whereas a weight of less than 20 = HIGH level of support.

Number of low quality studies that do not support the relationship	and	Number of high quality studies that do not support the relationship	Sum of the quantitative study weights	Level of support for the 'Consistency of Association' causal criterion
0	and	3	(0 x 2.5^) + (3 x 7.5^) = 22.5	Low (Lack of consistency)
2	and	2	(2 x 2.5^) + (2 x 7.5^) = 20	Low
1	and	2	(1 x 2.5^) + (2 x 7.5^) = 17.5	High (High consistency)
7	and	0	(7 x 2.5^) + (0 x 7.5^) = 17.5	High

^ Median study weights are used here for the purpose of the examples (2.5 for low quality studies and 7.5 for high quality studies – from Table 7), however, the actual overall study weights (based on study design, control and impact locations) for each of the studies would be used in a real situation..

2.8.2 The Evidence Catalogue

The evidence catalogue should document the summed quantitative study weightings supporting the three main causal criteria ('Response', 'Dose Response' and 'Consistency of Association') as described in 2.8.1. The number of High quality and Low quality studies for each of the causal criteria can be listed to examine the break-up of study quality.

These quantitative study weightings can then be converted to quality categories using the default decision rules for assigning High and Low level of support (detailed in Tables 9 and 10 and summarized in Table 11) for the three causal criteria (or let the software program do this for you).

Table 11. Decision rules for assigning High and Low level of support for the three causal criteria.

'Dose' and 'Response' causal criteria		
Summed qualitative study weighting	Result category	Result category acronym
<20	Low level of support	L
>= 20	High level of support	H
'Consistency of Association' causal criteria		
Summed qualitative study weighting	Result category	Result category acronym
<20	High consistency	H
>= 20	Lack of consistency	L

The evidence for the causal relationships under investigation, provided by the three main causal criteria (Response, Dose Response, Consistency), should then be aggregated to arrive at a conclusion about the total level of support for your hypothesis. The possible outcomes for a given causal criteria assessment are show below (Table 12). The conclusions show whether the evidence supports a causal relationship between a given cause and effect, or whether there is no support, insufficient evidence or inconsistent evidence.

Table 12. Possible outcomes depending on the strength of evidence for the causal criteria of a given cause and effect relationship. H = High; L = Low. Note that where no evidence is supplied it should also be noted in the table.

Outcomes	Response	Dose Response	Consistency of Association	Conclusion
Outcome 1	H	H	H	Support for hypothesis
Outcome 2	H	L	H	Support for hypothesis
Outcome 3	L	L	H	Insufficient evidence
Outcome 4	H	H	L	Inconsistent evidence
Outcome 5	H	L	L	Inconsistent evidence
Outcome 6	L	L	L	Support for alternative hypothesis
Outcome 7	No evidence supplied	No evidence supplied	No evidence supplied	No evidence supplied

2.8.3 Interpreting the outcome

There are four different outcomes that can be arrived at using the Causal Criteria framework:

1. Support for hypothesis;
2. Insufficient evidence;
3. Inconsistent evidence; or
4. Support for alternative hypothesis.

1. Support for hypothesis

A conclusion of 'support for the hypothesis' provides a strong scientific basis for making management decisions. Based on the Causal Criteria assessment, managers can conclude with a degree of confidence that the given human activity or natural event in question will have a particular effect.

2. Insufficient evidence

A conclusion of 'insufficient evidence' may indicate a knowledge gap with respect to the potential causal relationship in question.

The next step would be to conduct a more extensive literature search, in an attempt to find more articles that address the question being asked. If further information is not available even after an extensive literature search then the knowledge gap could be addressed by research designed to gain a better understanding of the problem in question. Such studies would provide valuable information for the future environmental management. If you are managing in the presence of knowledge gaps an adaptive management approach is recommended.

3. Inconsistent evidence

A conclusion of 'inconsistent evidence' means that although there are studies that show a response to the causal agent that is consistent with your hypothesis, there are also studies that do not show the expected response even though the potential casual agent was present.

Our experience has suggested that such an outcome is often due to inconsistent treatment of evidence in different studies (i.e. user error). Although all Causal Criteria Assessments should be reviewed for accurate and consistent recording and interpretation of evidence, a finding of 'Inconsistent evidence' might warrant extra vigilance in this regard.

4. Support for alternative hypothesis

A conclusion of 'support for alternative hypothesis' means the supporting evidence for the causal relationship is low; and a sufficient number of studies show a lack of support for 'consistency of the association'. To arrive that this conclusion, a number of studies showed that the response or dose-response under investigation was not detected in the relevant studies (even though the causal agent was present), so the weight of those studies contributes toward a score for lack of 'consistency of association'. The combination of LOW scores for all three of the major causal criteria used to weight the evidence (response, dose-response and consistency of association) indicates support for an alternative hypothesis or the hypothesis of 'no effect', analogous to the null hypothesis in standard statistical tests.

No evidence supplied

The words 'no evidence supplied' should be reported when no evidence is provided for a hypothesized cause-effect linkage for any of the causal criteria.

2.8.4 Arriving at a conclusion

The minimum requirement for demonstration of a causal relationship is "Response" and "Consistency" to be HIGH for at least one of the causal relationships.

The argument supporting the hypothesis can also include evidence from the other causal criteria that are not used in the weighting process (Tables 1 and 8) and could strengthen confidence in the verdict. Agreement across the different effects may provide further support your conclusion. If using the software, the program can construct a table similar to Table 12 for each effect.

At this stage, a 'magic formula' has not been created to mechanically proceed from Table 12 to a conclusion about your hypothesis. The questions to be addressed are too variable to permit this level of automation.

Documenting the evidence catalogue, and any other evidence you use will provide transparency to show the logic and evidence used to reach your verdict.

Some questions may require evidence across many causal relationships in order to infer causality.

In a Causal Criteria assessment, the final conclusion is always a matter of judgment by the user. The Causal Criteria Analysis method and software program are designed to facilitate this judgment, but cannot be the sole arbiter. This systematic framework for assembling evidence and reporting the findings provides a transparent basis upon which to make this judgment, and provide a mechanism for scrutiny by others of your argument.

Task:

- Assemble the catalog of evidence (note, the Causal Criteria software program can output the various tables of evidence).
- Report on each Step of the framework (the software can also provide this report).
- Record the verdict. Accept or reject the hypothesis based on the evidence you have collected.

3 Causal Criteria Analysis - An EXAMPLE

In this fictitious example:

> A river manager needs to determine whether reducing the mean annual flow downstream of a dam will have adverse ecological impacts.

For this example:

- The literature review identified five papers (note that you would generally review more than 5), which have the same cause and, which were undertaken in close geographical proximity to the dam in question. The 'effect' in each of the studies involved macroinvertebrates as the biological indicators of ecological health.
- Details of the study design, number of control sites and number of impact sites in each of the five papers are provided below (Table 13). The overall study weight (Table 14) has been calculated using the method described in Section 2.7.1 under 'Process for Weighting Evidence'.
- The cause is a reduction in mean annual flow.
- The effect under consideration for this example (although there may be more) is a decrease in macroinvertebrate taxonomic richness.

The hypothesis is that a reduction in mean annual flow downstream of dams will result in reduced macroinvertebrate taxa richness.

In this example, we assume that all of the studies are relevant to the investigation because they have the same causal agent and they are in close geographical proximity to the study site. The first four papers found support for the response criterion, i.e. provided support for the hypothesis (Table 15). However, paper 5 did not find the expected response in the macroinvertebrate assemblages to reduction in mean annual flow and thus contributed to a lack of consistency for the hypothesis (Table 16). None of the papers looked at dose-response relationships.

The study weights for each of the papers that shows a response consistent with the hypothesis are summed (i.e. Papers 1 – 4). This value is greater than 20, thus the 'Response' criteria provides a high level of support from the literature (Table 15).

The sum of the study weights for relevant studies NOT showing a response (i.e. paper 5) is calculated for the 'consistency of association' criterion (Table 16). However, the value was not greater than 20 and thus was not sufficient evidence to show a LACK of consistency or argue against causality for the cause and effect relationship under investigation.

Overall, there was **support** for the hypothesis that reduction in mean annual flow causes a decrease in macroinvertebrate taxonomic richness (Table 17).

Table 13. Example - details of the study design, number of control sites and number of impact sites for five fictitious papers.

Literature	Study design	Number of control Locations or independent sampling units	Number of impact Locations or independent sampling units
Paper 1	BACI	3	3
Paper 2	Reference/Control vs. impact (no before)	2	4
Paper 3	After impact only	0	2
Paper 4	Reference/Control vs. impact (no before)	1	6
Paper 5	After impact only	0	5

Table 14. Example - the overall study weights for five fictitious papers

Literature	Study design weight	Control locations weight	Impact locations weight	Overall study weight	Study quality category 1 - 4 = Low quality; 5 - 10 = High quality
Paper 1	4	3	3	4 + 3 + 3 = 10	High
Paper 2	2	3	3	2 + 3 + 3 = 8	High
Paper 3	1	0	2	1 + 0 + 2 = 3	Low
Paper 4	2	2	3	2 + 2 + 3 = 7	High
Paper 5	1	0	3	1 + 0 + 3 = 4	Low

Table 15. Example - '**Response**' weighting for the five fictitious papers.

Number of low quality studies showing support		Number of high quality studies showing support	Sum of the quantitative study weights(Study weights of 20 or more are deemed to have a HIGH level of support from the literature)	Conclusion – evidence for causal criterion
1	AND	3	(1 x 3) + (1 x 10) + (1 x 8) + (1 x 7) = 28	High

Table 16. Example - decision rule for the '**Consistency of Association**' causal criteria

Number of low quality studies showing lack of consistency		Number of high quality studies showing lack of consistency	Sum of the quantitative study weights (less than 20 shows HIGH consistency of association in the line of evidence)	Conclusion – evidence for causal criterion
1	AND	0	(1 x 4) + 0 = 4	High

Table 17. Example - Causal Criteria Analysis outcome for the example causal relationship

Biological response	Dose response	Consistency	Conclusion
High	No evidence supplied	High	Support for hypothesis

Note that for simplicity this example has used evidence for only one effect (reduced macroinvertebrate taxa richness). If more were to be used you would report each one as in Table 17 and assess for 'agreement across different effects', which may further strengthen the causal assessment.

Note also that while Tables 15 and 16 show the breakdown of high and low quality studies, it is only the numeric study weighting that is used in further calculations.

4 References

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Appendix A - Develop a conceptual model

Further information for developing a conceptual model for Causal Criteria Analysis

Using the information compiled in Steps 1 and 2,

1. Describe and define clearly the area of interest, and define the cause and/or effect of interest. Remember what prompted the investigation. Common reasons are the need to establish the cause for a biological effect (e.g. fish kill), or to identify the biological effects of a particular cause (e.g. change in flow).

List important system descriptors. For example upland river (700-900m) with many tributaries; high aseasonal rainfall (1000mm); substrate is predominantly cobble; the impounded part of the catchment is a national park and has native vegetation.

List and describe the important components in the ecosystem. For example:

- Important geomorphologic components
- Major biological components
- Major processes operating and the relative importance of different pathways

2. Identify the causes or effects of interest in this schema and identify their relationship to each other and to other components / processes in the conceptual model. If possible, develop the model in consultation with others (such as other stakeholders or experts) to help ensure that all the relevant components of the system are identified. Care must be taken to ensure that the model captures only the most important relationships within the system, and does not become burdened by consideration of the minor relationships. An initial conceptual model may need to be pruned back to make it more parsimonious.

If the reason for the investigation is a cause (e.g. change in flow), this will have top down consequences. For the example, the conceptual model should include the necessary flow components with putative causal links to potential effects.

If the reason for the investigation is an effect (e.g. fish kill), this could be the result of a range of yet to be identified causes. The conceptual model should be 'locally realistic', including all potential human and natural influences so that the most likely ones can be identified in the conceptual model in order to clearly frame the question that the Causal Criteria will be used to address. Where multiple causal agents are potentially contributing to an effect, the aim is to identify the dominant causal agents (i.e. those that make the largest contribution).

3. You are now ready to articulate an operational question/s.

- What are the "quantifiable" causal agents?
- What are the "quantifiable" effects?

Appendix B - Glossary

Term	Definition
Adaptive management	Evaluating the performance of new management approaches and changing practices over time as experience is gained.
Bioassessment	Evaluation of the condition of an ecosystem that uses biological surveys and other direct measurements of the resident biota.
Cause	A substance or activity that exerts some force or effect.
Conceptual model	A depiction or representation of the most current understanding of the major ecosystem features and processes (including biological, physical, chemical and geomorphic components) of a particular environment.
Consistency of association	Consistent spatial and temporal association of causal agent (cause) and response (effect). The expected response usually occurs in the presence of the causal agent.
Dose-response relationship	The relationship between the amount of exposure (dose) to some causal agent and the resulting response. A dose-response effect implies a monotonic relationship between cause and effect.
Effect	An change in a system attribute that is investigated in relation to a causal agent (e.g. decreased tadpole abundance)
Hypothesis	A theory or assumption that can be tested by further investigation.
Impact location	A site potentially impacted by a given causal agent, but in unknown condition prior to the investigation (also known as test site).
Response	There is evidence of an effect in the presence of the cause.
Stressor	Any physical, chemical or biological entity that can induce an adverse response.
Study design	The layout of locations, replicates and treatments of an experiment or survey (also referred to as research or experimental design). There are several types of study designs, each with different levels of ability to infer cause-effect relationships.
Treatment	Controlled technique or action applied in a specified process or experiment.