A qualitative cross-impact balance analysis of the hydrological impacts of land use change on channel morphology and the provision of stream channel services

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Abstract
The need to attain or preserve good ecological status under the WFD increases the planning importance of the hydrogeomorphologic effects of land use change, which will be exacerbated by expanding populations, population redistribution, and climate change. Land use planners do not always take into account the long-term impacts of land cover and associated hydrology changes on the loss of or need for stream channel services. Current land use development is often opportunistic and may start with expensive and time consuming land acquisition, engineering design, permitting application, financial, and legal efforts. Stream restoration projects are often designed and implemented on relatively short reaches, usually in the context of current land use hydrology. Future changes in land use and the associated hydrology may reset stream channel geomorphologic evolution with unintended consequences on already existing restoration projects or may result in the need for future restoration. For REFORM, IRSTEA has developed a Cross-Impact Balance (CIB) analysis hypermatrix, in ScenarioWizard 4.11, for land use planners and stream restoration stakeholders to use as a tool to anticipate the potential impacts of drainage area hydrology changes on stream channel morphology, ecological function, and services provision.

Introduction
For REFORM, IRSTEA has developed a Cross-Impact Balance (CIB) analysis hypermatrix, in ScenarioWizard 4.11 (Weimer-Jehle, 2013), for land use planners and stream restoration stakeholders to use as a tool to anticipate the potential impacts of drainage area hydrology changes on stream channel morphology, ecological function, and services provision. This tool is designed for use by non-scientist planners to better understand the impacts of changed hydrology on stream channel services in headwater catchments. It may also be used by scientists and engineers as a tool to guide discussion with non-scientist planners.

The long-term impacts of land use change and the need for new or the potential loss of stream channel services are not always part of the initial analysis of a land use change proposal. Once significant time and money have been spent, it is often difficult for planners and enforcement agents to stop or reverse the course of land use change. The results may be costly to the taxpayer and the environment in the short and long-term.

Headwater stream restoration projects are often designed and implemented on relatively short reaches, usually in the context of current land use hydrology. Future changes in land use and the associated hydrology may reset stream channel geomorphologic evolution with unintended consequences on already existing restoration projects or may result in the need for future restoration.

An initial, qualitative impact analysis may be useful to municipal planners, regulatory agencies, investors, restoration designers, and other watershed stakeholders to get a more global view of the short and long-term impacts and the potential benefits and/or costs of land use change on stream channel services and restoration.

Hydrogeomorphology is a complex subject and may intimidate elected officials, citizen planners, and watershed stakeholders. There are many variables to consider, quantitative and qualitative. We have developed the CIB analysis hypermatrix to make initial analysis relatively accessible without the need for engineers or scientists. However, the use of the matrix and its future development would certainly be improved by additional expert judgment.

Context

Science and expert judgment

The CIB analysis hypermatrix involves calculated values, but may often include expert judgments as well. Ideally, the hypermatrix is populated during a process interaction between all stakeholders and scientific and professional experts. In the case of our CIB hypermatrix, the equations and some of the expert judgment come from the scientific literature, while the calculations and additional expert judgment are provided by the author.

General principles of hydrology, soil science, traditional and stormwater runoff best management practices (BMPs), hydraulics, sediment transport, and stream ecology were used as the basis for all decisions. The general context is confined to a temperate climate, moderate topography (not mountainous or tidal), mixed geology (no extensive karst features or active tectonics), and North American or European cultural norms. Use of this hypermatrix for a particular site may require that the underlying decisions made in its creation be reviewed by experts for applicability to all contextual aspects.

Stream channel services provision

Stream channel services are affected by the relationships between 1. land use, land management, and land cover; 2. runoff and sediment regimes to the channel; 3. changes in channel morphology; and 4. provision of stream channel services. The services may be divided into three distinct groups.

- Process regulation services: flood control, stormwater conveyance
- Use services: energy, navigation, water supply
- Ecosystem services: habitat and biological diversity, autopurification, temperature control

Methods

The CIB Analysis Tool

To get an initial idea of the interactions consequent to a proposed change in land use, an impact analysis tool for municipal planners, regulatory agencies, investors, and other watershed stakeholders to determine the effects of land use change on hydrology, channel morphology, and stream services would be very useful. Such a tool must have several important characteristics, including,

- Be understandable and useable by and transparent to both policy makers and technical experts
- Incorporate scientific principles and expert social, legal, and scientific judgment

- Accept both quantitative and qualitative data
- Include spatial information
- Not require temporal information
- Be able to handle multiple descriptors with conflicting possible states
- Enable the selection of different scenarios
- Indicate consistencies and inconsistencies of scenarios

Cross-impact balance analysis, using ScenarioWizard 4.11: Constructing Consistent Scenarios Using Cross-Impact Balance (CIB) Analysis (Weimer-Jehle, 2013), is such a tool. For analytical tasks that do not permit the exclusive use of computational models due to their disciplinary complexity and the inclusion of qualitative knowledge, but that are too complex for an argumentative systems analysis, cross-impact analyses may be useful. (Weimer-Jehle, 2013) CIB analysis is used to explore the interdependence of multidisciplinary network elements and to develop network behavior scenarios by determining the conditional probability of event pairs.

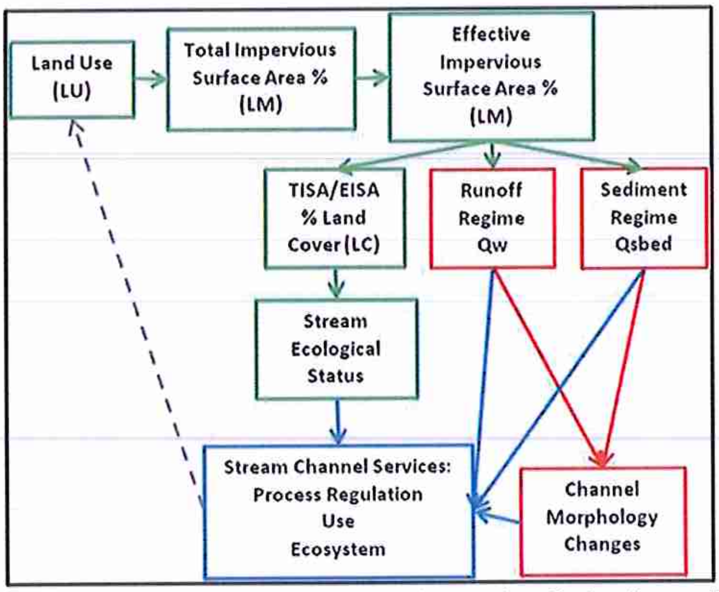

Figure 1. Map of CIB analysis descriptor interactions. The dashed grey line is not part of the CIB analysis, but rather indicates the possibility of resetting the scenario to achieve different results.

A CIB Analysis Application

A hypermatrix was created with 14 descriptors, 9 of which are primary descriptors (Figure 1) and 5 are intermediate linking descriptors, each having between 4 and 9 possible states. The descriptors and their states were chosen to

1. link land use through land management to land cover;
2. link the impacts of land cover changes on stream ecological quality;
3. link land cover changes to changes in flow and sediment regimes and resulting changes in channel morphology; and
4. link the changes in stream ecological quality, regime changes, and channel morphology to the provision of stream channel services.

Hypothetical Land Use Change Example

An example land use change proposal for a 15 ha plot presents a change of use from perennial agriculture using good soil conservation practices to a high density residential land use. Two alternative land management approaches are considered, the traditional, complete storm sewer system approach and the maximum detention and stormwater infiltration approach.

1. Initial land use scenario: perennial agricultural
   Total imperviοous surface area (ISA): 0.75 ha (5%)
   Choose agricultural practice: soil conservation agricultural practices
   Calculate effective ISA: 0.006 ha
   Calculate percent of parcel effective ISA: 0.04%
2. Planned land use Scenario A: traditional high density residential
   Total ISA area: 11.5 ha (77%)
   Choose effective ISA equation: totally connected EIA = ISA (Sutherland, 2000)
   Calculate effective ISA: 11.5 ha
   Calculate percent of parcel effective ISA: 77%
3. Planned land use Scenario B: high density residential with maximum detention and stormwater infiltration
   Total ISA area: 11.5 ha (77%)
   Choose effective ISA eq.: somewhat connected EISA = 0.04 ISA^1.7 (Sutherland, 2000)
   Calculate effective ISA: 2.54 ha
   Calculate percent of parcel effective ISA: 17%

Results of the CIB Matrix Analysis

In Table 1, the direction and degree of regime and channel morphology changes are given for each variation with the likely change in stream channel service provision and a score.

Conclusion

The utility of the hypermatrix lies in the relative simplicity of the links between descriptors, the incorporation of scientific expert judgment, and the accessibility of the ScenarioWizard 4.11 platform. Using this hypermatrix may encourage land use planners and stream restoration project decision-makers to consider the long-term impacts of land use change on hydrogeomorphology, the provision of stream channel services, and the resulting, potential costs and/or benefits.

Table 1. CIB analysis impact scores for two, proposed, high density residential land uses with different land management approaches on a parcel with an initial use of perennial agriculture using soil conservation practices. Where: Qw = water discharge, Qsbed = bedload, w = channel width, d = channel depth, w/d = width to depth ratio, su = sinuosity, and S = slope. (Schumm, 1969).

CIB analysis impact scores by Stream Channel Service for 3 Land Use Change Scenarios			
Stream Channel Services	Initial Impact Score: Perennial Agriculture with Equilibrium Channel (Qw0,Qsbed0)	Proposed Scenario A Impact Score: High Density Residential Traditional (Qw++,Qsbed--, d+, w/d-, S-)	Proposed Scenario B Impact Score: High Density Residential Stormwater BMPs (Qw+, Qsbed+ , w+, w/d+, su-)
Flood control	0 Not needed.	-1 Flood control is now needed due to increased flow.	0 May not be needed. Runoff retained in upper watershed.
Storm sewer connectivity	0 Not needed.	-1 Stream channels will now act as stormwater conveyances. Channel incision will reduce floodplain connectivity.	0 May not be needed. No direct storm sewer outfalls.
Water quality	0 Good. No excess sediment.	-2 Degradation due to increased runoff pollutant concentrations.	-1 Some degradation due to increased runoff pollutants and sediment (turbidity).
Biology	0 Sensitive. Good water quality.	-4 Urban drainage. No biosystem due to poor water quality and increased flow energy. Base flow probably reduced.	-1 Impacted. Some loss of biodiversity due to decrease in WQ (increased temperature) and to loss of bed habitat diversity with increase in w/d.
Ecological status	0 Sensitive species supported.	-4 Urban drainage. Poor.	-1 Impacted. Possible status degradation.
Reservoir capacity	0 If use present, no change.	-1 If use present, decrease in WQ. Elevation control infrastructure possibly at risk.	-1 If use present, decrease in WQ and possible sedimentation.
Navigability	0 If use present, no change.	2 If use is not present, it may become possible with increase in flow and decrease in sediment.	-1 If use present, decrease in flow depth.
Hydro-energy capacity	0 If use present, no change.	2 If use is not present, it may become possible with increase in flow and decrease in sediment.	1 If use is not present, it may become possible with increase in flow.

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