Prediction, valuation and ecological effects of future stream water quality based on socio-economic scenarios and climate change predictions for 2050.

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Project "iWaQa":
Integrated management of river water quality within the National Research Program 61 on Sustainable Water Management

Eawag: Swiss Federal Institute of Aquatic Science and Technology
Conceptual framework - project iWaQa
"Integrated management of river water quality"
Decision Analytic Framework

A Define decision context
B Stakeholder analysis
C Formulate and structure objectives
D Create alternatives
E Predict outcomes
F Elicit preferences
G Rank alternatives analyze results
H Discuss results with stakeholders, adaptive management

Aims:
• Learning about management alternatives
• Learning about stakeholder opinions
• Learning about influence of uncertain future
• Identification of potential consensus-solutions
→ separating prediction of outcomes (experts) from evaluation (subjective opinion)

Schuwirth et al. 2012 EJOR: Methodological aspects of multi-criteria decision analysis for policy support: A case study on pharmaceutical removal from hospital wastewater
### Decision Analytic Framework

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2. **B Stakeholder analysis**
3. **C Formulate and structure objectives**
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7. **G Rank alternatives, analyze results**
8. **H Discuss results with stakeholders, adaptive management**

**How to improve river water quality in a catchment of the Swiss Plateau?**
C Objectives River Management

Good river management strategy

Good ecological state of a river network
- Good ecological state of river sections
  - Long connected sections of good state
  - Natural longitudinal connectivity
  - Natural floodplains
  - Complementarity of river sections

Good ecosystems services
- High level of flood protection
- High self-purification capacity
- Good groundwater supply
- High hydropower generation
- High recreational value
- High aesthetic value

Low costs
- Low implementation costs
- Low maintenance costs
- Low loss of agricultural land/workplaces
- Low loss in forestry sector

Conformity with regulation
- Conformity with law

Robust design
- Conformity with orders
- Leave options for modified objectives
- Leave for corrections of failures

Reichert et al. 2011 WEL; Reichert et al. (submitted): The Conceptual Foundation of Environmental Decision Support
C Objectives Water quality management

chemical state

nutrients
- TP
- TP filt.
- PO4
- TN
- NO3
- NO2
- NH4
- TOC
- DOC
- BOD5

pesticides
- Photosynth
- VLCFASI
- AChEI
- AuxinAct
- fish toxic substances
- toxic for invertebrates
- toxic for algae

micropoll continuous

micropollutants

heavy metals
- Zinc
- Copper
- Lead
- Cadmium
- Mercury
- Nickel
- Chromium

costs

good water quality management
D Create alternatives

Sources of impairment

- **agriculture**
  - surface runoff

- **agriculture**
  - tile drainage

- **river water quality**: sources of pollution

- **urban**
  - material protection

- **urban**
  - gardening

- **urban drainage**
  - sewer overflows

- **Waste-water-treatment - plants**
D Create alternatives
Management alternatives to improve water quality

- none: current management practice
- A: combination of all measures
  - fac: banning the use of biocides in facades
  - cso: increase CSO buffer volume
  - pav: decrease area of impermeable pavements
  - inf: increase rain water infiltration from roofs
  - wwt: upgrade WWTP to remove micropoll.
  - bio: change to organic farming
  - nat: change to ext. agriculture - nature park
  - buf: install buffer strips to reduce spray drift

urban material protection
urban drainage sewer overflows
WWTP
agriculture
E Socio-economic scenarios horizon 2050

Boundary conditions that cannot be influenced by WQ management alternatives

<table>
<thead>
<tr>
<th></th>
<th>mean income</th>
<th>population</th>
<th>urban area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status quo</td>
<td>+0.4 %/year</td>
<td>as today</td>
<td>as today</td>
</tr>
<tr>
<td>Boom</td>
<td>+4</td>
<td>+730 %</td>
<td>+300 %</td>
</tr>
<tr>
<td>Doom</td>
<td>-1.5</td>
<td>-20 %</td>
<td>-</td>
</tr>
<tr>
<td>Quality of life</td>
<td>+2</td>
<td>+20 %</td>
<td>+5 %</td>
</tr>
</tbody>
</table>

Developed in a stakeholder workshop, Lienert et al. (submitted)
E Climate change - horizon 2050

- IPCC A1B emission scenario (scenarios hardly differ until 2050)
- 10 ENSEMBLES GCM-RCM model chains, daily data for precipitation & air temperature
- Neyman-Scott Rectangular Pulses (NSRP) model to generate hourly precipitation
- UKCP09 weather generator (which is based on the NSRP model) for daily values of other weather parameters

Pollutant transport management

- Retention of runoff
- Improving permeability

Urban runoff

- Combined sewer
- Parasitic water

CSO
- Increasing CSO buffer capacity
- Overflow

WWTP
- Treated effluent
- Improving removal efficiency

Rainwater sewer

- Solute transport
- Changing landuse
- Restoring riparian buffer zones

Intensive agriculture

Sewage

- Separated sewer

Honti et al. (in prep.)
Multi-attribute value theory

1. value functions for lowest level sub objectives

2. hierarchical aggregation: trade-offs between objectives

Schuwirth et al. 2012 EJOR: Methodological aspects of multi-criteria decision analysis for policy support: A case study on pharmaceutical removal from hospital wastewater
F Elicitation of Preferences

- Higher levels: societal values elicited from stakeholders case specific

- Lower levels of some branches: require expert knowledge should be generic translation of existing assessment methods, e.g. www.modulstufenkonzept.ch, LAWA, ...

Reichert, Schuwirth, Langhans (2013): Constructing, evaluating and visualizing value and utility functions for decision support, *Environmental Modelling & Software* 46, 283-291. [see also R-package “utility”.]
Reichert, Schuwirth, Langhans (2013): Constructing, evaluating and visualizing value and utility functions for decision support, *Environmental Modelling & Software* 46, 283-291. [see also R-package “utility”.]
Reichert, Schuwirth, Langhans (2013): Constructing, evaluating and visualizing value and utility functions for decision support, *Environmental Modelling & Software* 46, 283-291. [see also R-package “utility”.]
Prediction of ecological effects: Streambugs

Motivation - predicting the community composition of macroinvertebrates in (wadeable) streams to:

• test understanding of ecosystem functioning
• test hypotheses on food-web stability
• identify influential sources of human disturbance
• predict consequences of management options (river restoration, upgrade of waste water treatment plants)
• assess impact of future development (climate change, land use)
Prediction of ecological effects: Streambugs

Ecological traits from databases

- feeding types
- body mass $M$
- energy content
- habitat tolerances (current, temperature, substrate, pH, salinity)
- sensitivity towards pollutants (pesticides, saprobic conditions)
- mobility, emergence, ....

E.g. www.freshwaterecology.info
SPEAR ("Species at risk", Liess et al 2008)
Tachet (Tachet et al. 2000)
Site specific model input

1. environmental conditions
   • Temperature (mean water temperature, summer maximum)
   • Flow conditions (no-slow-medium-high current class)
   • Microhabitat/substrate
   • Light conditions (shading, light intensity at the river bed)
   • Input of organic material (leaf litter input, suspended OM)
   • Water quality (nutrients, organic matter, organic contaminants)

2. regional taxa pool (to exclude dispersal limitation)

Model output

• observation probability for each taxon at each site from equilibrium biomass density at constant environmental conditions
Model output - Food webs

taxa with p(obs)>0.5  taxa with p(obs) < 0.5
### Results with prior parameter distribution (without calibration)

<table>
<thead>
<tr>
<th>sub-catchments</th>
<th>no of presence/absence records*</th>
<th>max no. of results in agreement with observations</th>
<th>sum of taxa modelled correctly</th>
<th>% correct</th>
<th>c/b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pfäffikersee</td>
<td>1155</td>
<td>957</td>
<td>731</td>
<td>0.76</td>
<td>1.15</td>
</tr>
<tr>
<td>Mönchalt. Aa</td>
<td>1600</td>
<td>1296</td>
<td>966</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Glatt 1</td>
<td>2275</td>
<td>1839</td>
<td>1325</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Glatt 2</td>
<td>2030</td>
<td>1689</td>
<td>1253</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>total</td>
<td>7060</td>
<td>5781</td>
<td>4275</td>
<td>0.74</td>
<td>0.74</td>
</tr>
</tbody>
</table>

*6-11 sites per subcatchment, 4-9 observations per site, ca. 32 taxa

Model calibration with Bayesian inference at each sub-catchment increases compliance with data (to about 90%)
Importance of environmental influence factors - traits

% correct results with mean prior parameter values

<table>
<thead>
<tr>
<th>sub-catchments</th>
<th>incl. all</th>
<th>excl. T-pref.</th>
<th>excl. sapro.</th>
<th>excl. current</th>
<th>excl. pest.</th>
<th>excl. feedt.</th>
<th>excl. TSCP</th>
<th>excl. TSCPf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pfäffikersee</td>
<td>0.76</td>
<td>0.77</td>
<td>0.74</td>
<td>0.71</td>
<td>0.63</td>
<td>0.73</td>
<td>0.54</td>
<td>0.44</td>
</tr>
<tr>
<td>Mönchalt. Aa</td>
<td>0.74</td>
<td>0.74</td>
<td>0.72</td>
<td>0.69</td>
<td>0.60</td>
<td>0.73</td>
<td>0.50</td>
<td>0.48</td>
</tr>
<tr>
<td>Glatt 1</td>
<td>0.71</td>
<td>0.70</td>
<td>0.71</td>
<td>0.64</td>
<td>0.63</td>
<td>0.61</td>
<td>0.53</td>
<td>0.40</td>
</tr>
<tr>
<td>Glatt 2</td>
<td>0.72</td>
<td>0.71</td>
<td>0.71</td>
<td>0.63</td>
<td>0.66</td>
<td>0.60</td>
<td>0.55</td>
<td>0.39</td>
</tr>
<tr>
<td>total</td>
<td>0.73</td>
<td>0.73</td>
<td>0.72</td>
<td><strong>0.66</strong></td>
<td><strong>0.63</strong></td>
<td><strong>0.65</strong></td>
<td>0.53</td>
<td>0.42</td>
</tr>
</tbody>
</table>

- excl. **temperature** preference and **saprobic** valence has minor influence
- **current** preference, sensitivity to **pesticides** and feedingtypes are important factors to predict community composition of macroinvertebrates
Conclusions

• mechanistic models are valuable tools to integrate and communicate knowledge about cause-effect relationships and to test hypotheses

• most critical aspect is treating uncertainty in an adequate way

• multi-criteria decision support provides a framework to combine objective scientific predictions about future development and consequences of management alternatives with subjective valuation of stakeholders

• facilitates synthesis of large interdisciplinary projects
Thanks for your attention!

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Rosi Siber, Nico Ghielmetti, Jörg Rieckerman, Mark Gessner

All people who gave access to databases and measured data!
References MCDA in environmental management


Reichert, Schuwirth, Langhans (2013): Constructing, evaluating and visualizing value and utility functions for decision support, *Environmental Modelling & Software* 46, 283-291. [see also R-package “utility”].


Conceptual framework - project iWaQa
"Integrated management of river water quality"
F Value functions based on assessment programs

Translated from Modul-Stufen-Konzept
www.modulstufenkonzept.ch
Langhans und Reichert 2011 WEL
Langhans et al. 2013 Ecological Indicators

AWEL method based on Chèvre et al. 2006
Junghans et al. 2013,
based on Götz et al. 2010

AWEL method based on LAWA criteria

LAWA: Übersicht über Qualitätsanforderungen der EG, der internationalen Flussgebietsgemeinschaften und der LAWA;
www.umweltbundesamt.de/wasser/themen/ow_s2_2.htm
F Value function for lowest level sub-objectives
Translation of existing assessment procedure into measurable value functions

www.modulstufenkonzept.ch

<table>
<thead>
<tr>
<th>Quality class</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>very good</td>
<td>C &lt; $\frac{1}{2} Z$</td>
</tr>
<tr>
<td>good</td>
<td>$\frac{1}{2} Z \leq C &lt; Z$</td>
</tr>
<tr>
<td>moderate</td>
<td>$Z \leq C &lt; 1.5 Z$</td>
</tr>
<tr>
<td>poor</td>
<td>$1.5 Z \leq C &lt; 2 Z$</td>
</tr>
<tr>
<td>bad</td>
<td>$C \geq 2 Z$</td>
</tr>
</tbody>
</table>

Z: legal quality standard, C: concentration

**advantage:** improvement within a class is visible, avoids rounding error

**assumptions:** all class transitions are equally valuable, piece-wise linear interpolation

Langhans et al. 2013 *Ecological Indicators*, Langhans & Reichert 2011 *Wasser Energie Luft*
Visualizing results

Propagating uncertainty to overall value

- 90% uncertainty interval
- Status quo
- Alternative 1
- Alternative 2
- Alternative 3
- Alternative 4

Compare alternatives, stakeholders, scenarios - identification of potential consensus solutions
ERIMO: Ecological River Model based on functional groups

Schuwirth, Kühni, Schweizer, Uehlinger, Reichert 2008 Freshwater Biology
Schuwirth, Acuña, Reichert, 2011 Ecological Modelling
ERIMO: Ecological River Model based on functional groups

• good representation of functional aspects
• short term dynamics: seasonal effects, disturbance, ecosystem resilience
• functional groups not (that) sensitive to water quality
• omnivory can not be implemented
• structural aspects hidden
  → taxonomic resolution needed
Differential equations for the biomasses of all taxa and of organic matter per river length $B = (B_1, \ldots, B_n) \, [\text{gDM/m}]$

stoichiometric coefficients $v = \{v_{ij}\}$

process rates $r = (r_1, \ldots, r_m) \, [\text{gDM/m}^2/\text{a}], \text{which depend on parameters } \theta$

$$\frac{dB}{dt} = v \ r \left( \frac{B}{w}, \theta \right) \ w$$

R-package "stoichcalc"
Reichert & Schuwirth 2010, Environmental Modelling and Software
Fig. 2. Mass dependence (mass measured in grams) of temperature-corrected maximal rates of whole-organism biomass production ($P_{EKT}$, measured in grams per individual per year) for a wide variety of organisms, from unicellular eukaryotes to plants and mammals (from Ernest et al. 2003). Data, which span >20 orders of magnitude in body size, have been temperature corrected using Eq. 6. The allometric exponent, indicated by the slope, is close to the predicted value of ¾ (95% CI, 0.75–0.76).

Growth, respiration and death rates

\[ r_{\text{gro on } j} = f_{\text{gro}} \cdot f_{\text{gro } i} \cdot f_{\text{lim food}} \cdot f_{\text{pref } j} \cdot f_{\text{self inh}} \cdot f_{\text{basal } i} \cdot r_{\text{basal metab}} \]

\[ r_{\text{resp } i} = f_{\text{resp}} \cdot f_{\text{basal } i} \cdot r_{\text{basal metab}} \]

\[ r_{\text{mort } i} = f_{\text{mort}} \cdot f_{\text{basal } i} \cdot r_{\text{basal metab}} \cdot f_{\text{org contam}} \cdot f_{\text{saproby}} \]

\[ f_{\text{org contam}} \] factor dependent on pesticide pollution and sensitivity of the taxon

\[ f_{\text{saproby}} \] factor dependent on organic matter pollution and classification of the taxon in the saprobi system

\[ f_{\text{self inh}} \] factor depending on temperature regime, current regime, substrate
Growth rate of consumers

\[ r_{\text{gro on } j}^{\text{cons}} = f_{\text{gro}} \cdot f_{\text{gro } i} \cdot f_{\text{lim food}} \cdot f_{\text{pref } j} \cdot f_{\text{self inh}} \cdot f_{\text{basal } i} \cdot r_{\text{basal metab}} \]

fit from large datasets

basal metabolic rate
Growth rate of consumers

\[ r_{\text{cons}}^{\text{gro} \text{ on } j} = f_{\text{gro}} f_{\text{gro } i} f_{\text{lim food}} f_{\text{pref } j} f_{\text{self inh}} f_{\text{basal } i} r_{\text{basal metab}} \]

taxon specific parameters, prior mean = 1

account for variation of individual taxa around MTE predictions
Growth rate of consumers

\[ r_{\text{cons}}^{\text{gro on } j} = f_{\text{gro}} f_{\text{gro } i} f_{\text{lim food}} f_{\text{pref } j} f_{\text{self inh}} f_{\text{basal } i} r_{\text{basal metab}} \]

\[ f_{\text{lim food}} = \frac{D_{\text{food}}^q}{K_{\text{food}}^q + D_{\text{food}}^q} \]

One process for each food source \( j \)

\( D_{\text{food}} \) biomass density of the sum of all food sources

\( K_{\text{food}} \) halfsaturation density, at which growth rate is reduced to 50% of the max
Growth rate of consumers

\[ r_{\text{cons}}^{\text{gro on}} = f_{\text{gro}} \cdot f_{\text{gro i}} \cdot f_{\text{lim food}} \cdot f_{\text{pref } j} \cdot f_{\text{self inh}} \cdot f_{\text{basal } i} \cdot r_{\text{basal metab}} \]

food preference factor

\[ f_{\text{pref } j} = \frac{D_j \cdot p_j}{\sum_{f} D_f \cdot p_f} \]

One process for each food source \( j \)
\( D_j \) biomass density of food source \( j \)
\( p_j \) preference factor for food source \( j \)
Growth rate of consumers

\[ r_{\text{cons}}^{\text{gro on } j} = f_{\text{gro}} \cdot f_{\text{gro } i} \cdot f_{\text{lim food}} \cdot f_{\text{pref } j} \cdot f_{\text{self inh}} \cdot f_{\text{basal } i} \cdot r_{\text{basal metab}} \]

self inhibition

Two alternative formulations (Monod and Blackman)

\[ f_{\text{self inh Monod}} = \frac{K_{\text{dens}}}{K_{\text{dens}} + D} \]

\[ f_{\text{self inh Blackman}} = \begin{cases} 1 - \frac{D}{2K_{\text{dens}}} & \text{for } D < 2K_{\text{dens}} \\ 0 & \text{for } D \geq 2K_{\text{dens}} \end{cases} \]

\( D \) biomass density of the taxon
\( K_{\text{dens}} \) half-inhibition density where growth rate is reduced to 50% of the max

\[ K_{\text{dens}} = h_{\text{dens}} \cdot f_{\text{current}} \cdot f_{\text{temp}} \cdot f_{\text{substrate}} \]

depends on habitat conditions and specific preferences of the taxon
Catchment Glatt - Greifensee, Canton Zurich