ASSESSING THE EFFECTS OF RAPID FLOW CHANGES ON A MACROZOOBENTHOS COMMUNITY IN THE ALPINE RHINE USING CASIMIR-GIS

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Abstract

The recent efforts of European governments aimed at the reduction of CO_2 emissions are causing a marked increase in the contributions of wind and solar to the electricity market. It is expected that the larger proportion of volatile renewable energy produced by wind and photovoltaic installations will result in a commensurate increase in the demand of peak hydropower energy for grid stabilization and network balancing. This energy production results in a rapidly changing flow regime, or hydropeaking downstream of storage hydropower plant outlets without lower storage reservoirs.

Major impacts of hydropeaking on macrozoobenthos manifest themselves in a general reduction of regions offering suitable habitat conditions. Wetted areas may have acceptable conditions during periods of base flow, but the extreme velocities which occur during hydropeaking can quickly render them inhabitable.

The recently developed CASiMiR-GIS is a rule-based ecohydraulic approach incorporating a unsteady flow analysis suitable for macrozoobenthos habitat modeling. Operating within the ESRI ArcGIS environment, the model allows the user to apply the native CASiMiR fuzzy-logic engine for any combination of parameters relevant to the determination of habitat suitability.

The model has been developed and tested in three morphologically diverse stretches of the Alpine Rhine upstream of Lake Constance. Simulations were performed for a variety of hydrological regimes and provide quantitative information on both habitat quality and availability under hydropeaking operations of different intensity. Special attention is given to colmation effects and their influence on macrozoobenthos habitat quality. Results of the benthos habitat simulations and findings related to future research needs are presented.

Introduction

In its current state, the Alpine Rhine is both hydrologically and morphologically highly modified along large portions of its length. Anthropogenic changes to the river in the form of diversion and regulatory structures have to a large extent deprived it of its structural diversity, largely resulting in a monotone channel. The river is also subject to a highly variable flow regime due to the production of peak energy producing hydropower plants. In total, there are some 40 weir structures and power plants located within the river catchment area.

In order to determine suitable remediation strategies considering the river's current state, the International Government Commission of Alpine Rhine (IRKA) is undertaking the project "Quantitiative Analyis of Hydropeaking Hydrographs using Modeling". The project's goal is to create sustainable strategies for the optimization of hydropeaking hydrographs on the Alpine Rhine considering the interplay of ecological and economic interests in the region.

The project includes the modeling of the status quo as well as the investigation of four worse-case (winter minimum flow) hydrographs with varying levels of ramping mitigation (minor to complete). Three investigation reaches (figure (1)) with contrasting morphologies have been chosen for study using hydraulic and habitat models: the reach at *Mastrils* has close to natural conditions, *Buchs* has alternating gravel banks, and the *International* reach has a typical channelized cross section.

Data from field investigations and a 2D hydraulic model are combined into a fuzzy-logic based biotic modeling framework in order to determine the habitat requirements and response to hydropeaking for the brown and lake trout, as well as for the macrozoobenthos community. The result is a GIS-based habitat modeling framework which can be applied to estimate the ecological impacts of hydropeaking as well as provide quantitative analysis of proposed remediation measures before they are constructed. The impact of different morphological characteristics in the Alpine Rhine can also be investigated in order to improve recommended structural changes in reaches chosen for remediation.

Study Area

Due to the current state of the Alpine Rhine, the possibility of establishing a reference reach in an area having a natural flow regime simply does not exist. After Poff et al. (1997), the flow rate and its temporal variability count as one of the most important factors driving the development of both the biotic and abiotic processes in fluvial ecosystems. Thus the ecological quality and functioning of a river are highly influenced and to a large part determined by its flow regime. The physical processes affected by chronic hydropeaking flow regimes as well as their ecological impacts are well established.

As seen in figure (1), the Alpine Rhine consists of a reach some 93 km in length, beginning at the confluence of the Anterior and Posterior Rhine in Reichenau, and ending at Lake Constance.

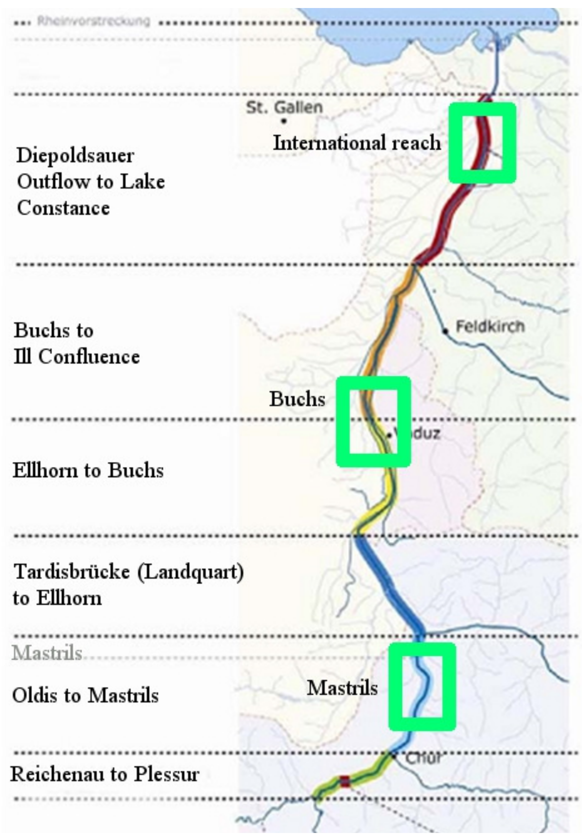

Figure 1: Overview of the Alpine Rhine. (after Eberstaller et al. 2007).

Today there are few remnants of the river's extensive braided morphology, where the modern landscape is now dominated by an extensive network of flood control structures. The vast majority of the Alpine Rhine has been straightened, channelized, and its banks modified with revetment. However, notable exceptions do exist at the river fork at Oldis and the near-natural conditions still existing in the lowlands at Mastrils.

Key morphological features

The primordial Alpine river landscape contains a spectrum of morphological features which can be further classified according to their specific river bed structures:

Main arm: hydraulically active region of the Rhine which contains the majority of the river's flow.

Side arm: smaller secondary flow regions consisting of gravel terraces which remain submerged during low and mean flow conditions.

Side arms, not permanently submerged: flow regions which become hydraulically active only during periods of mean or flood flows. These regions are elevated above bed forms which remain inundated during low flows. Shallow channels or furrows form a chain of small pools along the varial zone after hydropeaking, and may lead to fish stranding.

Tributary transitions: found in the areas between the main river and its floodplains, elongated smaller reaches (many of which are several hundred meters in length) which run parallel to, and effectively connect the Rhine and its tributaries. These regions are mostly hydraulically active during mean flow periods.

Oxbow lakes: Channel systems in the floodplains existing due to channel forming extreme flow events or are the remnants of an old channel. Oxbow lakes are only partially connected to the Rhine, where their frequency is predominantly determined by their height and distance to the main channel.

Figure 2: Braided section of the Posterior Rhine in the Rhaezuenser Lowlands during minimum flow. Here the main river channel as well its side arms are clearly visible.

Each one of these river bed structures provides a unique spectrum of ecological conditions. Together they form an interconnected mosaic along the river, offering a wide range of habitats and furnishing the basis for an especially species-rich community, as seen in figure (2). Bifurcations connecting the side arms and tributary regions are found almost along the entirety of the few remaining unregulated portions of the Alpine Rhine. In spite of the high flow velocities commonly found in the main channel during hydropeaking events, local low flow regions can be found in scour holes, small bays, and along heterogeneous, structure rich banks. In these regions, the adults of most fish species are the most commonly found, where juveniles prefer to reside in the side arms and tributaries where the hydraulic and predatory stresses are typically lower.

Macrozoobenthos

The community of organisms forming the macrozoobenthos includes all visually identifiable invertebrates (size >1 mm), which reside on and in the river bed. The organisms themselves are referred to as macroinvertebrates.

The macroinvertebrates consist primarily of two types; those which are functionally immobile, or sessile, and those which are conditionally mobile, possessing a small radius of action. As a result of their limited mobility and small size, it is difficult for most macrozoobenthos to react during hydropeaking events, whereas strong changes in behavior can be observed by both juvenile and adult fish. Instead, the only option (outside of drift) is for the benthic organism to recede into the upper layer of bed sediment (interstitial) when the local flow velocity increases to a point where the mechanical stability of the organism at the sediment surface is no longer practicable. In cases where the interstitial is filled with fine sediment (inner colmation), a retreat into the pore spaces is no longer possible. Currently, the degree to which an organism can retreat during the upramping portion of the hydrograph is under debate (Imbert, 1996; Wood et al., 2010).

Due to their habitat needs and limited reaction potential to hydropeaking flow regimes, the habitat requirements of macroinvertebrates can be seen as most closely related to the requirements of trout eggs and larvae.

To be able to estimate the impact of hydropeaking activity in the Alpine Rhine on the macrozoobenthos community, it is necessary to evaluate the habitat suitability within individual model elements. The dependence of the habitat suitability on selected environmental variables is determined and described in terms of preference functions, and is then incorporated mathematically into a fuzzy-logic, rule-based system. In order to create the necessary rules, three methodologies were adopted:

1) The evaluation of existing, quantitative benthos data from previous works on the Alpine Rhine. Based on the data collected, it can be determined which water depths and velocities correspond to sum parameters for macrozoobenthos (e.g. frequency, species diversity). From this it is then possible to generate preference curves for the environmental parameters of interest.

2) Selected samples of aquatic plants (phytobenthos) and visual inspections of easily recognizable colonies of current-loving (rheophilen) larvae and black flies (Simuliidae) at a wide variety of locations in both the Buchs and Mastrils investigation reaches. The close relationship between the abundance and population density for macrozoobenthos is readily known (Moog & Janecek, 1991) and has been already established in the Alpine Rhine (ARGE Limnologie, 2001). The phytobenthos, especially the growth of filamentous macroalgae which are easily observable with the naked eye, serve as indicators for regions which may be suitable for macrozoobenthos.

3) Field samples of macrozoobenthos in specific habitat regions. These samples do not provide a representative picture of the benthic population in general, but do serve to provide insight for especially striking habitats. Such locations exhibit increased biomass and/or species diversity as well as above average stocks of particularly sensitive macrozoobenthos species, and were often capable of surviving through the critical winter periods. In these ‘hot spots’ it may also be feasible that additionally important natural processes impacting the well-being of the river’s ecological community, such as fish reproduction are able to take place. Examples from the Alpine Rhine and similar rivers are riffles and side channels along gravel banks which are hydraulically connected to the river throughout the year.

Along with the benthos sampling, the abiotic parameters of water depth, current velocity, substrate and outer colmation were recorded, whereas the data taken from external sources commonly only included the water depth and velocity. All observations were undertaken during down ramping (dewatering) events, where the relevant environmental parameters observed are related to these specific conditions. In each of the investigation reaches, all benthos data was taken in the time period from November to March, when the impact of hydropeaking activity is the highest.

Compared to the frequency, it is found that the other parameters investigated to describe the presence of macrozoobenthos (biomass, number of taxa, species diversity, and number of sensitive species) were only weakly or not at all correlated to the water depth and average current velocity. Similar to the abundance was the biomass, a measure of the amount of (wet) mass of the macrozoobenthos. However, it was found that unlike the abundance, after a decrease of the velocity from a threshold value of 0.5 m/s, the biomass did not continue to decline but instead remained constant. The reason for this was found to be the presence of the relatively heavy caddis fly larvae (Allogamus auricollis), which tend to concentrate in regions of weak flow.

The highest abundances and biomass concentrations of all investigation locations were found in the sprawling right banks of the Oldis widening and on the left banks of the permanently wetted side arms of Mastrils. Both habitat regions have large spatial extents of riffles, where the high population densities were primarily due to the large numbers of black fly larva present.

Methodology

Fuzzy Logic Aquatic Habitat Model CASiMiR

The fuzzy-logic rules in this work are derived from literature values and specially tailored for use in the Alpine Rhine. Additional field studies were carried out in order to validate the rule system chosen, with positive results. The model framework itself consists of a modular structure which allows for separate observations of hydraulic and structural parameters and then combines them, resulting in the mapping of the habitat suitability for indicator organisms. The connection between the abiotic and biotic variables can be made using either univariate preference functions or via a multivariate fuzzy-logic approach, as illustrated in figure (3).

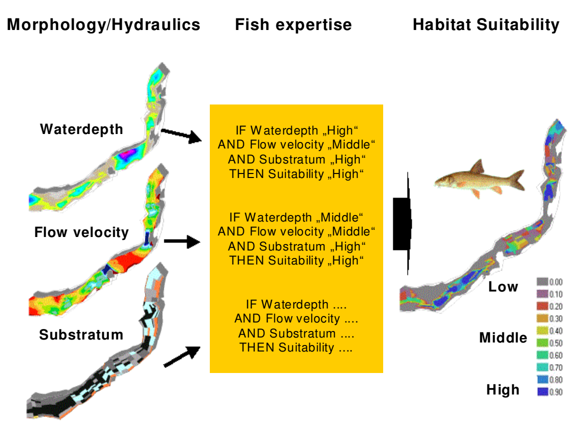

Figure 3: Fuzzy-logic concept used by CASiMiR for aquatic habitat modeling.

The CASiMiR modeling framework is unique in that aside from offering the ability to estimate habitat suitability based on the classical preference curve method, it also allows for the explicit inclusion of expert knowledge within a fuzzy-logic framework (Schneider, 2001). Inherent to the fuzzy approach is its ability to include linguistic variables in fuzzy sets, as commonly used by experts when describing the interplay of complex environmental parameters such as a 'high velocity', in conjunction with a 'low water depth'. This type of formulation is well-suited for ecological investigation since it is often not possible to strictly classify combinations of environmental parameters based on fixed ranges. Furthermore, it is often the case that field studies and literature do not cover species or new parameters of interest, but that expert knowledge does in fact exist. In such cases, the fuzzy system allows for a relatively straightforward inclusion of expert knowledge and a flexible application to various types of river environments.

Macrozoobenthos Model

In order to include the existing information on macrozoobenthos in the CASiMiR habitat model, it is necessary to formulate them according to the fuzzy-logic framework. The base requirements of the macrozoobenthos model in this investigation are the environmental variables of water depth, current velocity, dominant substrate (particle size), and inner colmation. The parameterization of the input data takes part in three steps:

1) *Determining the fuzzy sets:*
For the parameters of depth, velocity and substrate, discrete ranges are first broken down into very low (VL), low (L), medium (M), high (H), and very high (VH). The only exception is for substrate, which has the parameter range from VL-H. Afterwards, for each individual range a suitability value of 0 (low suitability), 1 (medium suitability), or 2 (high suitability) was assigned for each parameter according to the preferences of the macrozoobenthos.

2) *Including colmation effects:*
The treatment and inclusion of inner colmation is included in a second step as its importance was recognized during the project, and was not included in previous field investigations on the Alpine Rhine or in the literature. For this reason, it is included in a more simplified manner than the other parameters. The three suitability values 0, 1, 2 are included directly as part of the calculated colmation maps where 2 corresponds to a level of colmation from 0 to 9, 1 from 10 to 12, and 0 from 13 to 15. The highest level of colmation, 15 corresponds to a high degree of outer, not inner colmation, where a layer of fine material (silt, sand) is deposited directly onto the upper surface sediment. Just as the presence of inner colmation blocks entry of the interstitial pore space for retreat, the presence of outer colmation can have a strong negative impact on the habitat suitability for macrozoobenthos (see Haro & Brusven 1994; Frondorf, 2001 and references therein).

3) *Determining the rule system:*

After assigning individual suitabilities to the input parameters, the final step in the fuzzy framework is to define a rule system which calculates the overall habitat suitability index (SI) based on the combination of parameters. The SI for macrozoobenthos is calculated in steps from VH, H, M to L within each model element and for each time step. Unlike the model used for fish, the SI for macrozoobenthos is representative for a community of organisms, not just a single life stage and species. For this reason, the HSI calculation is carried out following Neary (2006) using the product of the four individual parameter suitabilities. Finally, the SI values are normalized into the habitat suitability index (HSI) which ranges from 0 (unsuitable) to 1 (ideal)

Results and Discussion

In order to evaluate the effects of both the varying bed structures and varying mitigation strategies, a series of four mitigation hydrographs (AP1-4) were evaluated over all three investigation reaches, and compared to the status quo (GL 01). A winter worse case flow regime was selected as the basis model hydrograph, and consisted of a one-week period as shown in figure (4).

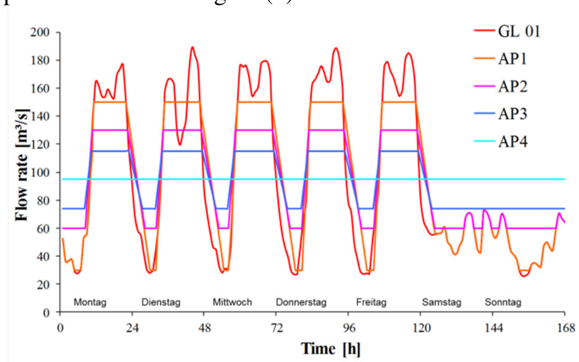

Figure 4: Hydrographs used in the investigation of hydropeaking mitigation. GL 01 represents the status quo, and AP1-4 are hydrographs with decreasing up- and down-ramping.

The results of the macrozoobenthos habitat analysis for all three investigation reaches can clearly be seen in figure (5). The most heavily modified channel, the International Reach showed an almost monotonic increase in areas of improved macrozoobenthos suitability with increasing upramping mitigation. Buchs, with its alternating gravel banks also exhibited a clear improvement from the status quo up to AP2, where further improvements are incremental but less dramatic for AP3 and AP4. The most morphologically intact reach at Mastrils also shows substantial improvement in estimated macrozoobenthos HSI with increasing upramping mitigation, where the side arm regions play an especially important role in providing regions of improved suitability. Although the total annual improvement of habitat suitability cannot be estimated based on the results of a single week, it is clearly to be seen that in all cases the remediation of hydropeaking activity is reasonably expected to improve the overall suitability.

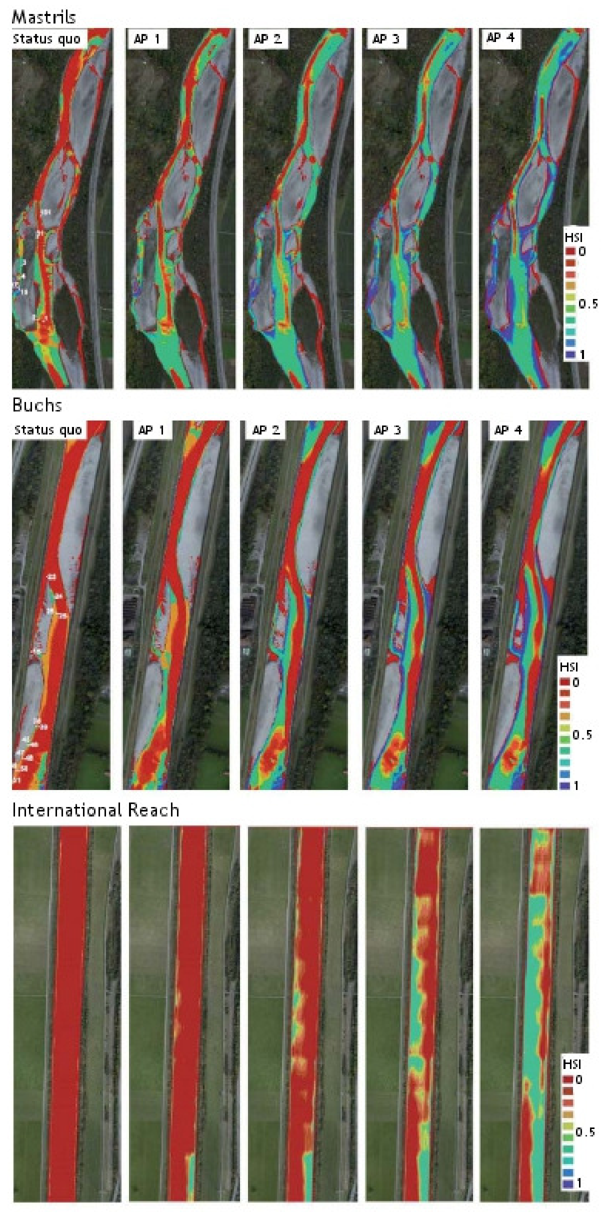

Figure 5: Model results of the integrated base habitat suitability index (HSI) for the macrozoobenthos. The status quo (left) along with each of the four flow scenarios AP1, AP2, AP3, and AP4 are shown. For each of the three reaches, increasing peaking mitigation (left to right) results in larger regions of higher HSI. For the Mastrils and Buchs reaches, field sampling locations are shown superimposed on the results of the status quo model results.

Conclusions and Recommendations

Most peak energy generated in the Alps is produced by storage hydropower plants. Increasing the renewable energy mix reduces the production of greenhouse gasses, but will increase hydropeaking activity. Furthermore, the uncertainties introduced by climate change may act as a force multiplier when considering future ecological impacts on Alpine river ecosystems. Thus the development of investigative tools to assess and quantify environmental changes to fluvial ecosystems is essential.

Next to morphological degradation, hydropeaking is believed to be one of the major reasons for the decline in both biodiversity and abundance of organisms in Alpine river ecosystems. The main difference between hydropeaking and natural flood events is that hydropeaking is a persistent phenomenon, in contrast to naturally occurring seasonal fluctuations in the flow regime.

In many studies the peak-base ratio is used as an indicator of hydropeaking. It should be noted that the ratio alone is not a sufficient indicator of ecological impacts on fluvial ecosystems, especially when considering differences in morphology. (Baumann & Klaus, 2003; Tuhtan et al., 2012).

Based on the results of this study, it can clearly be seen that there is a net positive effect on the available habitat in relation to the available mitigation. The volume of such a required detention basin would depend on seasonal considerations and must be operated based on limiting ecological conditions not only for macrozoobenthos, but on additional species and their seasonal, life stage specific habitat requirements as well.

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