AQUATIC ECOSYSTEMS AND THE SECOND LAW INEQUALITY: ESTIMATING ALPINE FISH HABITATS USING ENTROPY GENERATION MINIMIZATION

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Abstract

Conventional aquatic habitat models require statistical analysis of field data or expert knowledge of abiotic-biotic relations to assess habitat suitability. More recently, individual-based models have also emerged using bioenergetic principles to estimate organism locomotion and behavior.

The study of fish energetics and locomotion is often segregated, where energetics is quantitatively considered via 'first law' conservation approaches. Due to the complexity of the local flow field, works on fluid-body interactions during locomotion are to a large extent restricted to phenomenological investigation. This work broadens the conceptual framework by applying entropy generation minimization (EGM), allowing for the simultaneous consideration of energy quality *and* quantity. Combining hydromechanics, thermodynamics and heat transfer, EGM provides the missing link between swimming performance, metabolism, and the flow field, forming an expanded 'second law' perspective.

Here we present a new type of aquatic ecosystem model fusing abiotic-biotic metrics using principles from the thermodynamics of irreversible, finite-time, finite-sized systems.

Building upon recent advances in theoretical and phenomenological studies of fish energetics and locomotion, a model including flow pattern and water temperature is derived to assess alpine fish habitats. The model is comprehensively compared to the expert knowledge based fuzzy logic model CASiMiR-Fish on a sample of 30 alpine river reaches.

Results from this new model concept under steady conditions are found similar to CASiMiR. Differences between the two models become pronounced when the models are considered under unsteady conditions.

Introduction

The great power of thermodynamics lies in its ability to predict correlations among macroscopic observations in the complete absence of detailed knowledge of the microscopic system itself (Caplan and Essig, 1999). A biological system such as an alpine fish viewed through the lens of thermodynamics is a type of highly intricate open, or flow system. The study of thermodynamically-inspired models makes clear that the goal of obtaining a complete equation system describing the coupling between the living system and its non-living surroundings is ultimately an impossible task (Ulanowicz, 2004). Organisms are *relational* biological systems whose existence is dependent on a deep functional interactivity between animate systems within their inanimate surroundings (Mikulecky, 2000). There are truly no 'fish out of water' (Tuhtan, 2011).

Recognizing that the organism is fundamentally an open, finite-size, finite-time system allows us to describe the abiotic-biotic relations of an aquatic ecosystem in terms of its physical properties. In this work, we set our focus on alpine rivers, where a single fish is the system of interest, and the river's water provides the surroundings.

From the standpoint of thermodynamics, the first law requires that we consider the energy and mass balances of the river ecosystem, and the second law provides us the means to estimate the irreversibility introduced by friction, chemical reactions, and heat transfer.

Analysis with both the first and second laws supplies a powerful new modeling concept: that the river ecosystem is striving to increase its access to the mass and energy currents which flow through it, while fighting against imperfections which increase the overall system irreversibility. This fundamental juxtaposition of physical processes ultimately manifests itself in a system's specific configuration. All natural, spontaneous systems aim to

increase their power whilst simultaneously decreasing their losses. This was first postulated by Bejan (1997) in his general statement of the constructal law, which itself can be seen as a corollary of his earlier developed EGM theory. In this paper we illustrate how ecohydraulic fish habitat models may be improved by including the physical concepts behind EGM.

Model Concept

Even at constant flow rates, the animate and inanimate subsystems of a fluvial ecosystem are continuously evolving over a spectrum of rates which cannot be modeled explicitly. Formulations requiring the assumption of chemical, thermal, mechanical and radiative equilibrium may be of limited practical use. However via the first law, we may invoke conservation to investigate the energy and mass balances of the river ecosystem. We begin by looking at the energy change in our control volume, V by integrating over all subsystems of the alpine river ecosystem. The resulting energy balance is thus specified as a function of the mass-averaged, specific energy densities:

$$\rho \frac{du}{dt} = \frac{d}{dt} \int \left[\rho \left(u + \frac{v^2}{2} + \phi \right) \right] dV \qquad (1)$$

Where ρ is the total density (water, sediment, biota, etc.), u is the specific internal energy, v is the average velocity, and ϕ is the resultant time-independent potential of all external forces. It is possible to include the effects of non-gravitational external energy (e.g. incoming and outgoing radiation) by lumping them together as an isochoric, time-dependent forcing function evaluated over short time intervals.

Next, we apply the second law in order to estimate the entropy production rate, σ:

$$\frac{\partial(\rho s)}{\partial t} + div\boldsymbol{S} = \sigma \qquad (2)$$

Where s is the specific entropy, and $\boldsymbol{S}$ is the entropy flux. It is important to recall that unlike mass or energy, *entropy is not conserved*. Thus for any irreversible (real) process, $\sigma \geq 0$ (Kelstrup et al., 2006). Since we are specifically interested in the behavior of a single fish rather than the river at large, we narrow our focus to the analysis of a single volume element, just large enough to contain the organism in its entirety. The volume element contains a single fish and that portion of the river water in

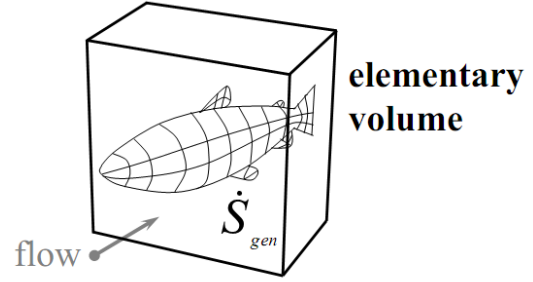its immediate vicinity. Our system is open, finite-size, and evaluated in finite-time.

Figure 1: The approach used to estimate the local entropy production inside of a volume element.

This "fish in a box" approach as shown in figure (1) allows us to describe the impact of irreversibility on abiotic-biotic relations via the entropy generation of the fish-river system, $\dot{S}_{gen}$:

$$\dot{S}_{gen} = \frac{\partial S}{\partial t} - \frac{\dot{Q}}{T_0} + \sum_{out} \dot{m}s - \sum_{in} \dot{m}s \geq 0 \qquad (3)$$

Equation (3) is the expression of the rate of entropy generation of an open system. It is always positive, and goes to zero only at the theoretical reversible limit. When the right side is multiplied through by the frontier temperature, it becomes an equivalent expression of the Gouy-Stodola theorem for lost work done over a finite period by an irreversible system. Thus the approach can be considered from an exergy perspective, where it can be said that while a fish strives to make use of its available free energy, it is subject to energetic losses due to heat transfer, internal entropy production, and fluid friction.

We consider the fish as a body of arbitrary shape with surface area A, temperature T, and average heat transfer coefficient $\overline{h}$, subject to external fluid flow at a velocity U_∞ and temperature T_∞. Fluid friction along the fish's body results in a drag force, F_D. The drag force is the sum of all distributed forces over the body, and its resultant is projected against the principle flow direction. Assuming constant and uniform body temperature over the time period of analysis, the entropy generation in the fish+river volume element can be expressed as:

$$\dot{S}_{gen} = \left(\frac{T - T_\infty}{T_\infty} \right)^2 \overline{h}A + \frac{F_D U_\infty}{T_\infty} \qquad (4)$$

The resulting formulation allows for the estimation of the entropy generation depending on the fluid-body

interactions between the fish and the surrounding flow field. The parameters of temperature, surface area, and flow velocity may be measured or estimated, whereas the heat transfer coefficient must be determined through phenomenological investigation. The drag force depends on the fish's mode of swimming in conjunction with the flow field, and is the main parameter of interest. As alpine fish are poikilothermic, we choose to neglect all terms which account for the irreversibility due to heat transfer in equation (5), resulting in the following simplified formulation:

$$\dot{S}_{gen} \sim \frac{F_D U_\infty}{T_\infty} \qquad (5)$$

The practical application of equation (6) to estimate fish habitats requires estimation of the spatial distribution of $\dot{S}_{gen}$. Local flow conditions in conjunction with the fish species and life stage provide fixed ranges of the parameter which then correspond to a fish's location. In order to estimate $\dot{S}_{gen}$, it is necessary to integrate the effects of all dissipative processes inside the control volume:

$$\dot{S}_{gen} = \int \int \sigma \, dx \, dy \qquad (6)$$

Thus in order to estimate the entropy generation in each volume element, we require a method to calculate the total irreversibility due to mechanical dissipation based on the results of a 2D hydraulic model.

Estimating local dissipation rates

Considering the assumptions and limitations of using a 2D model, the local entropy production due to kinetic energy dissipation in a 2D flow field $\sigma(x,y)$ is most easily expressed as the product of the ratio of two intensive properties, density ρ, and temperature T, with an extensive property; the kinetic energy dissipation rate ε:

$$\sigma = \frac{\rho}{T} \varepsilon \qquad (7)$$

The temperature is given in Kelvin (°C+273.15). Because sigma estimates are functions of the fluid density and local temperature, model outputs change along with circadian fluctuations in the river water temperature, an important parameter which is not currently included in the commonly-used fish habitat models PHABSIM or CASiMiR. In practice, the water temperature can be calculated, taken from field measurements, or set as a constant over the time interval of interest. In this work, measurements from nearby gauging stations are used. The density of water is calculated as a function of the temperature using spline interpolation; though for most practical applications it can be assumed constant.

Spatial distributions of both the kinetic energy dissipation rate ε and the local entropy production rate σ are calculated in each volume element. After Nezu (2005) the dissipation rate can be estimated in gravel bed rivers as:

$$\varepsilon = U_*^3 9.8 \xi^{0.5} exp(-3\xi) \qquad (8)$$

The relative depth is given as $\xi = y/h$, where y is the height above the bed, and h is the water depth in each volume element. This leaves a formulation which is dependent only on estimates of the local shear velocity U_* and relative depth. The relative depth is fixed at 0.6, taken to be representative of the depth at which the mean model velocity is delivered. This *does not* mean that it is representative of the optimal height in the water column at which the fish would actually position itself in the flow field. Due to the limitations of using the 2D depth-averaged modeling approach this assumption is necessary. Ideally, the model should make use of a 3D model where the dissipation rate can then be estimated directly from the calculated velocity profile.

Model Application and Comparison

Hydraulic model SRH-2D

In this work the hydraulic model of choice is Sedimentation and River Hydraulics 2D (SRH-2D), a freely-available finite volume model developed by the US Bureau of Reclamation (USBR). The model solves the 2D depth averaged diffusive and dynamic wave equations under both steady and unsteady flow conditions. Sub-, super-, and trans-critical flows can be solved (Lai, 2006). Additionally, SRH-2D allows for unstructured hybrid meshes. The advantage of using a mix of element types is that the same numerical solver can be used for a variety of mesh topologies: orthogonal or nonorthogonal structured quadrilateral meshes, unstructured triangular meshes, or hybrid meshes with mixed element shapes (Lai, 2010). The model outputs are the temporally varying water surface elevation, bed elevation, water depth, bed shear stress and Froude number. In this work, the water depth, velocity and bed elevation data are used.

Fish habitat model CASiMiR

Due to the paucity of available fish data, it is necessary to select an established fish habitat model to compare results for both steady, nonuniform and unsteady, nonuniform flow regimes. We selected the expert-knowledge based CASiMiR model due to its history of successful applications in alpine rivers. Direct comparison between the two models is challenging because the entropy model is sensitive to changes in the spatial gradients of local parameters, whereas CASiMiR relies on the averaged properties of depth, flow velocity and dominant substrate under steady conditions.

CASiMiR HSI (0-1) ■0 □0.5 ■1   Dissipation σ (W/K) ■0 ■0.5
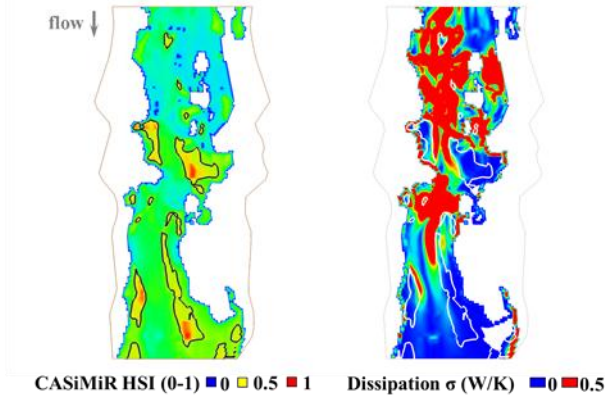
Figure 2: Comparison of the spatial distribution of the fish habitat suitability index (HSI) for the juvenile brown trout. Left: CASiMiR HSI, areas bounded by black contours have an overall HSI > 0.5. Right: Mapping of σ, where the regions inside the white contours correspond to the CASiMiR model results.

To make an initial comparison between the two models, a reference reach on the river Olivone, Switzerland is chosen due to the presence of available fish observation data for adult and juvenile brown trout during a constant flow rate of 900 l/s.

Table 1: Summary information of the investigation reach Olivone used to compare the local entropy to CASiMiR.

No. Nodes	10,803
No. Elements	10,620
Width (m)	20
Length (m)	41
Slope (m/m)	0.03
Total Area (m^2)	648
Resolution (node/m^2)	16.7

The qualitative assessment of the spatial distribution of regions having a high habitat suitability index (HSI ≥ 0.5) as shown in figure (2) indicates that a relationship exists between the two approaches. It thus appears that at steady-state, CASiMiR may be operating as a type of proxy dissipative estimator. In order to further test this hypothesis, a more comprehensive comparison of the models under steady-state conditions is necessary.

Comparison with 30 alpine river reaches

The previous sections introduce a simplified isothermal model for fish habitats based on EGM theory. Focusing on the local dissipation rate, the model is then compared to CASiMiR, and found to have significant spatial correlation. In order to observe possible trends when comparing the two approaches, the parameters of 30 individual alpine river reaches are collected. An overview of the sizes of the models is provided in Table (2).

Table 2: Summary statistics on a sampling of the 30 investigation reaches used in the model comparison. Reaches having the largest value of the total dataset are shown in bold, reach 20 was statistically average.

Reach ID	No. Nodes	Width / Length (m)	Slope (m/m)	Area (m^2)
6	**120,473**	94 / 402	0.002	30,845
14	7,996	**207 / 572**	0.002	**83,477**
20	10,800	31 / 50	0.04	1,565
27	25,529	16 / 35	**0.07**	420

Largest reach:
No. 14
207 m wide
572 m long

Smallest reach:
No. 24
6 m wide
12 m long
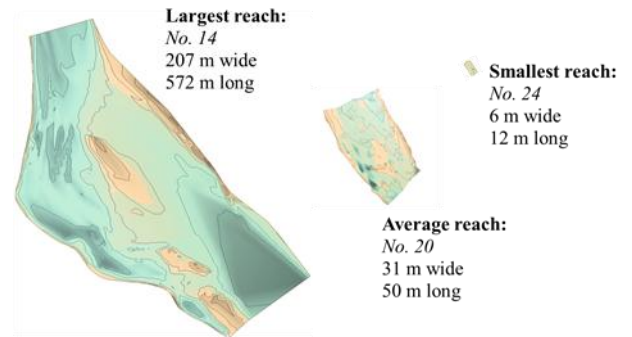
Average reach:
No. 20
31 m wide
50 m long

Figure 3: Graphical illustration of the wide range of sizes encompassing the 30 investigation reaches. Not to scale.

After running the hydraulic model for multiple flow rates per reach, both the dissipative and CASiMiR models are used to calculate the fish habitat suitability. In order to test our hypothesis that CASiMiR in the steady-state is a proxy dissipative estimator, we look to see if there are fixed values of σ which correspond to areas having high habitat suitability (HSI ≥ 0.8) across all flow rates and model reaches. Both the juvenile and adult brown trout are investigated in order to see if a significant difference in σ could be observed across life stages.

As shown in figure (4), the pattern of high HSI locations is found to be similar to specific values of σ. A summary

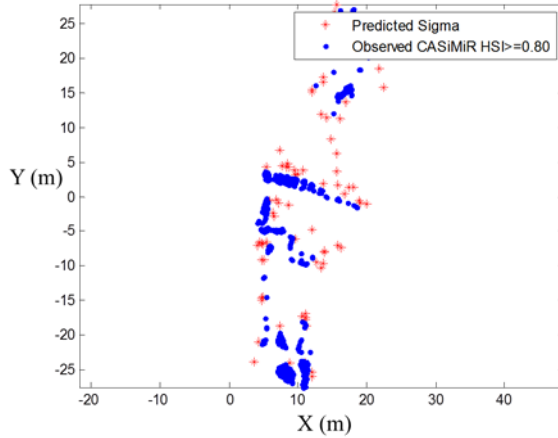of all reaches is shown in figure (5), where a clear distinction can be found between juvenile and adult.

Figure 4: Results from reach 7, $Q = 0.5$ m^3/s comparing the spatial distributions of HSI ≥ 0.8 to $\sigma = 2.75$E-04 for the adult brown trout.

The results shown in figure (5) indicate that not only does it indeed appear that there is a direct relationship between local σ estimates, but that distinct values for both the adult and juvenile can be found. Differences between life stages of a single fish species are well-founded using the entropy generation minimization approach since it has been found that aging creates a decrease in the specific rate of entropy production in mammals, birds, fish and insects (Lamprecht and Zotin, 1978). Since the rate of entropy production is proportional to the rate of respiration, it should be possible to determine species and life stage specific estimates for use in future numerical models.
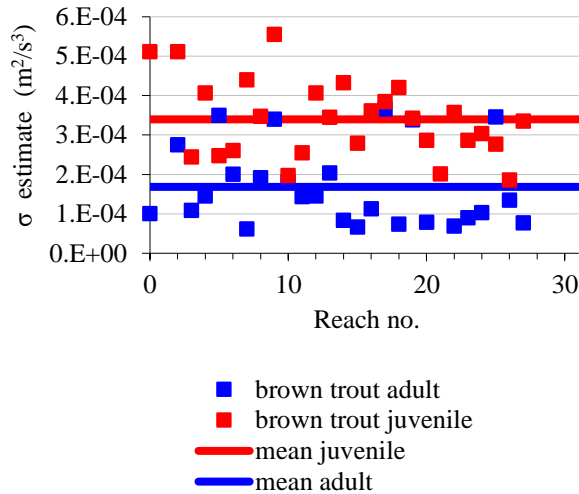

Figure 5: Results of the 30 reach comparison for constant values of σ and HSI ≥ 0.8.

The results show that over the possible spectrum of σ found in all reaches a correlation exists between the EGM

and CASiMiR model results with high habitat suitability. A noticeable difference between mean σ estimates for the adult ($\sigma = 1.69$E-04) and juvenile ($\sigma = 3.4$E-04) can be observed.

The results of the 30 reach comparison study thus suggest that CASiMiR may actually be acting as a proxy estimator for dissipation rates under steady flow conditions. This relationship was found in 27 of the 30 reaches investigated, where missing data in figure (5) is due to lack of any regions of HSI ≥ 0.8 for the flow rates investigated. It is also worth noting that dissipation rates may be determined empirically from the analysis of the respiration intensity of the fish at different life stages. Thus it may indeed be possible to provide physical estimates of σ for different modes of behavior for each species and life stage, and model them in an improved 3D EGM based approach. However, the comparisons thus far have only included analysis of the two modeling approaches under steady-state conditions. Due to the importance of highly unsteady flows on alpine river ecosystems (e.g. seasonal flood events and hydropeaking), it is crucial that the EGM model will also be evaluated under highly unsteady conditions as well.

Unsteady analysis

In order to investigate the effects of unsteady flow on the estimation of habitat distributions using the EGM approach, a case study is carried out on the river Inn at Martina, on the Swiss-Austrian border. The investigation reach is located 3.25 km downstream of the hydropower outlet. The reach chosen for analysis is generally representative of the Inn in the Alpine region, with wide, flat cross sections and a rough, rocky bed. Gauging data for the discharge hydrographs are provided by the Swiss Federal Office for the Environment's (BAFU) station 2067 for the years 2000-2010 for both the water elevation and flow rate in 10 minute intervals. The data is broken down into monthly datasets, statistically and visually inspected, and individual days of interest are then selected for further statistical analysis and used as boundary conditions for the hydraulic model.

Table 3: Summary information on the Martina Inn (CH) investigation reach.

Width / Length (m)	Slope (m/m)	Substrate composition
56 / 188	0.006	90% stones 12-20 cm 5% small stones 6-12 cm 5% rocks >20 cm

The mesh is constructed using quadrilaterals having approximately equal side lengths, with an average element

size of 1.75 m^2. The model is calibrated using field measured water surface elevation data for a series of steady flow rates ranging from 5-200 m^3/s. The hydrograph was run as a 24 hour unsteady simulation, where model results are saved at 10 minute intervals. The upstream boundary conditions are supplied by the 25.10.2005 hydrograph taken from unmodified data from the BAFU gauging station at Martina-Pradella (ID 2067). Downstream boundary conditions are input as rating curves based on measured field data. Manning's roughness values are assumed constant over the hydrograph and range from 0.013-0.083 depending on surface conditions. Estimates of the water temperature are taken from BAFU station ID 2617.

After running both CASiMiR and the EGM under unsteady conditions, it is found the unlike the steady case, large differences in both the temporal and spatial distributions of suitable habitat areas for both the juvenile and adult life stages can be found. The results of both models are shown in figure (6).
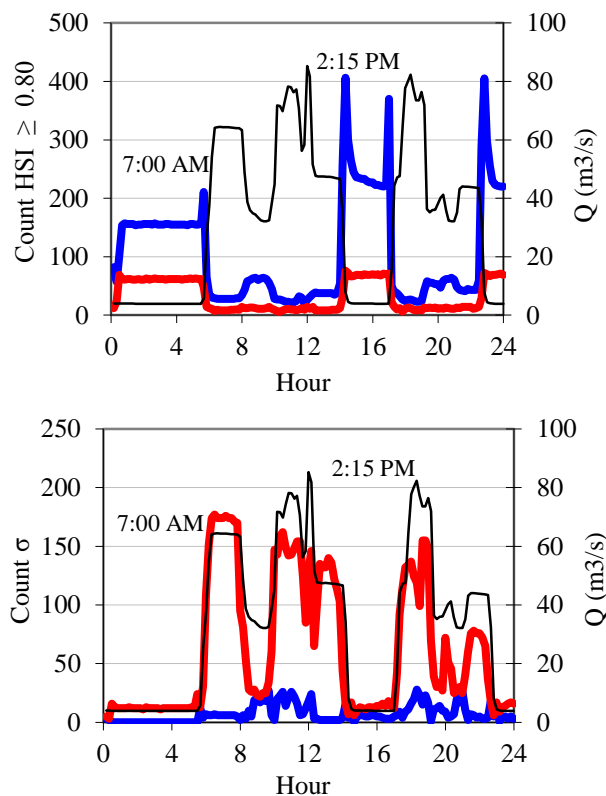

Figure 6: Results from the unsteady analysis. Above: CASiMiR HSI distributions for juvenile (**red**) and adult (**blue**) brown trout as a function of the flow rate (**black**). Below: the model nodes count of suitable σ locations.

Conclusions and Recommendations

All flow systems, including alpine river ecosystems strive to maximize access to their currents whilst minimizing the dissipation and are subject to finite-time, finite-size constraints. In alpine rivers, energy dissipation is primarily mechanical, and occurs due to viscous shear as a function of the river's flow rate and bed morphology. The existence of a fish at a particular location in the river ecosystem is dependent on specific ranges of physical parameters such as depth, velocity, and water temperature. This is because the ability of the organism to persist at any given location is fundamentally limited by their interaction with the surroundings, primarily governed by their evolved physiology.

In this work we introduce the concept of EGM and apply it to the study of alpine fish. Our results indicate that when comparing the EGM approach to the established steady-state CASiMiR model, the results are strongly correlated, both for juvenile and adult brown trout. However, when considering unsteady flow events, large differences are observed between the two approaches, regardless of the life stage modeled. This is due to the fact that the EGM approach fundamentally uses spatial gradients of hydraulic variables to determine dissipative estimates, whereas the CASiMiR model uses mean flow properties such as water depth and flow velocity. In order to determine the sources of these differences, it is necessary to carry out further research on the changes in local hydraulic variables due to highly unsteady, nonuniform flow regimes.

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