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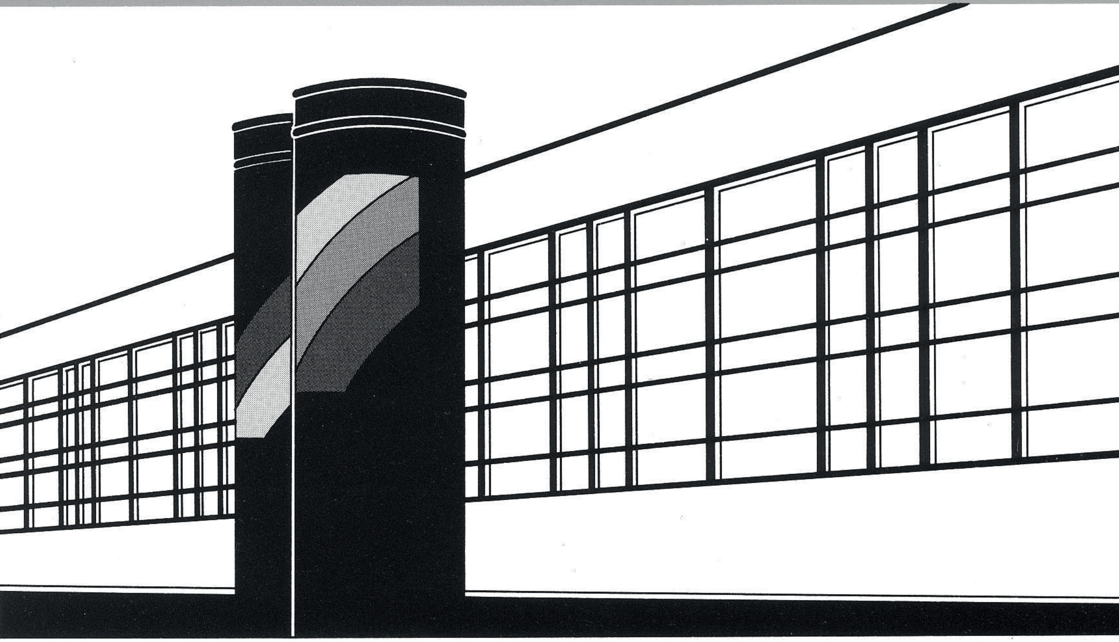

Heft 210

Jeffrey Andrew Tuhtan

A Modeling Approach for Alpine Rivers Impacted by Hydropeaking Including the Second Law Inequality

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„alle Körper der Natur, auch wenn sie vollkommen in Ruhe zu sein scheinen, befinden sich doch in der lebhaftesten inneren Bewegung“

Rudolf J. E. Clausius, Zürich 1857

$$\Delta G$$

Kurzfassung

Wegen des gestiegenen weltweiten Wettbewerbs um Rohstoffe benötigt Europa in Zukunft eine stabile und unabhängige Energieversorgung. Um diese Aufgabe zu meistern, sollen die Erneuerbaren Energien ausgebaut werden und dabei auch einen Beitrag zur Stromerzeugung leisten. Aufgrund der begrenzten Speichermöglichkeiten für Strom muss jedoch genau so viel Strom produziert werden, wie verbraucht wird, was besonders zu Spitzenbedarfszeiten eine schwierige Aufgabe ist. Gegenwärtig wird Spitzenlaststrom hauptsächlich durch Speicherwasserkraftwerke und Gasturbinenkraftwerke bereit gestellt. Zu den Erneuerbaren Energien zählen dabei jedoch nur erstere. Daher wird für die Zukunft eine Zunahme deren wirtschaftlicher Bedeutung und deren finanziellen Wertes erwartet.

Die Wasserabgabe von Speicherwasserkraftwerken zur Stromerzeugung muss an den Stromverbrauch angepasst werden, der im Laufe eines Tages starken Schwankungen ausgesetzt ist. Der daraus folgende Betrieb mit stark schwankender Wasserabgabe wird als Schwallbetrieb (Schwall-Sunk-Betrieb) bezeichnet. Wegen der hohen Unterschiede des Abflusses im Schwallbetrieb im Vergleich mit natürlichen Abflussmengen und Abflussschwankungen müssen sich unterstromige Ökosysteme an die neuen Bedingungen anpassen. Die gesamten Auswirkungen des Schwallbetriebs von Speicherwasserkraftwerken auf unterstrom liegende Ökosysteme zu quantifizieren ist jedoch keine einfache Aufgabe. Zur Beurteilung der gewässerökologischen Auswirkungen müssen eine Vielzahl von theoretischen und phänomenologischen Untersuchungen durchgeführt werden. Erschwert werden diese Untersuchungen durch die Fließgewässerökosysteme selbst, da diese keine stabilen Systeme darstellen, sondern sich fortgehend verändern, sogar unter stationären Strömungsbedingungen.

Die Benutzung Modelle zur Quantifizierung der Auswirkungen des Schwallbetriebs auf aquatische Ökosysteme befindet sich noch ganz am Anfang ihrer Entwicklung. Dabei ist die Herausforderung dieser Arbeit die Erstellung eines theoretischen Rahmens zur Untersuchung von abiotisch-biotischen Wechselwirkungen unter stark instationären Strömungsverhältnissen. Das vorgestellte Modell wird basierend auf thermodynamischen Gesetzen entwickelt. Dazu bildet die Energieerhaltung die Grundlage, insbesondere die Wechselwirkungen zwischen mechanischer, chemischer und thermischer Energie.

Die Ziele dieser Dissertation sind:

1. **Die Einbindung thermodynamischer Grundsätze/Gesetze in ein aquatisches Habitatmodell, welches auch bei stark instationären Strömungsverhältnissen effektiv eingesetzt werden kann.**
2. **Die Bewertung des Modells bezüglich theoretischer Grundlagen, Anwendbarkeit, und Leistung.**

In der vorliegenden Arbeit wird basierend auf thermodynamischen Grundsätzen ein neuartiges Fischhabitatmodell entwickelt. Dieses wird bei der Untersuchung alpiner Fließgewässer in Europa eingesetzt, die vom Schwallbetrieb betroffen sind. Des Weiteren wird gezeigt, dass ein erster Ansatz der nur auf die Energieerhaltung aufbaut, nicht ausreicht, um die Bioenergetik von Ökosystemen alpiner Fließgewässer ausreichend zu beschreiben. Daher ist es notwendig, in einem darauf aufbauenden Ansatz das Ökosystem zusätzlich bezüglich Entropie und Freier Enthalpie zu betrachten. Dieser zweite Ansatz (nach dem zweiten Hauptsatz) ermöglicht eine neue Darstellung von aquatischen Ökosystemen und stellt einen allgemein gültigeren Modellansatz dar, um die Auswirkungen auf Fische durch Schwall-Sunk-Betrieb unter realen Bedingungen abzuschätzen.

Im ersten Kapitel wird eine Einführung in die Problematik des Schwall-Sunk-Betriebes in alpinen Gewässern Europas vorgenommen. Im darauf folgenden Kapitel **"Hydropeaking in Alpine Rivers"** werden Auswirkungen des Schwall-Sunk-Betriebes diskutiert und ein Überblick zu betrieblichen und wasserbaulichen Ausgleichsmaßnahmen gegeben.

Anschließend folgt im dritten Kapitel **"Thermodynamics and the Alpine River Ecosystem"** eine Einführung in die Thermodynamik**.** Der Fokus liegt dabei auf der Beschreibung der wichtigsten physikalischen Prozesse in alpinen Fließgewässern. Es folgt eine Einführung in die Thermodynamik von irreversiblen Prozessen, welche die theoretische Grundlage für einen Hauptteil der vorliegenden Arbeit darstellt. Abgeschlossen wird das dritte Kapitel mit der Darstellung von Ökosystemen alpiner Fließgewässer als ein Spezialfall von offenen irreversiblen thermodynamischen Systemen.

Im vierten Kapitel **"Irreversible Aquatic Ecosystem Models"** wird die Anwendung thermodynamischer Konzepte auf Ökosyteme alpiner Fließgewässer behandelt. Dabei werden zwei Modellansätze entwickelt. Zunächst ein top-down Ansatz und anschließend ein bottom-up Ansatz. Die beiden entstandenen theoretischen Modellansätze zeigen, dass die Anwendung der Thermodynamik auf Ökosysteme und auf Individuen einerseits mehrere Vorteile im Vergleich mit konventionellen Habitatmodellansätzen bietet, andererseits jedoch auch eine betrachtliche menge neuer Fragen aufwirft.

Aufbauend auf Kapitel drei und vier wird in Kapitel fünf **"River+Fish Energetics"** ein Modellkonzept (Fluss+Fisch Konzept) entwickelt, in dem Fische in Bezug auf ihren Energiebedarf und die sie umgebenden hydraulischen Verhältnisse des lokalen Strömungsfeldes betrachtet werden. Die grundlegende Annahme dahinter ist, dass Fische nicht getrennt vom umgebenden Wassersystem betrachtet werden können. Am Ende des Kapitels werden grundsätzliche Fragestellungen bezüglich der Bioenergetik von Fischen behandelt.

Nachdem die theoretischen Grundlagen dargestellt wurden und ein neues Modellkonzept basierend auf thermodynamischen Gesetzen/Regeln eingeführt wurde, wird in Kapitel sechs **"Locational Entropy Model"** eine Untersuchung der Anwendbarkeit des Modells unter realen Bedingungen durchgeführt. Dabei werden 30 verschiedene Abschnitte alpiner Fließgewässer mittels des neu entwickelten thermodynamischen Modellkonzeptes und einem auf Fuzzy-Logik basierenden Stand der Technik Habitatmodell untersucht, um die Stärken und Schwächen des neuen Ansatzes zu bestimmen. Außerdem wird das neue Modell an einer Untersuchungsstrecke des Flusses Inn bei Martina (Schweiz) unter Schwall-Sunk-Bedingungen getestet. Bei dem Vergleich der beiden verschiedenen Modelle konnte festgestellt werden, dass die berechneten Dissipationsraten beider Modelle stark miteinander korrelieren. Die zwei wichtigsten Ergebnisse aus den Modelluntersuchungen sind:

1. **Das Fuzzy-Logik Modell ist auch zur Abschätzung von Dissipation/Energieverlust geeignet.**

2. **Großskalige Strömungsfeldparameter sollten in zukünftige Fischhabitatmodelle integriert werden.**

Es folgt eine zusammenfassende Berwertung des theromdynamischen Modellkonzeptes im abschließenden Kapitel **“Conclusions”.** Dabei ist festzustellen, dass das neu entwickelte Modellkonzept keineswegs einfach in einem numerischen Modell umgesetzt werden kann. Selbst wenn nur eine Abschätzung der Dissipationsraten vorgenommen werden soll, müssen die Berechnungsschritte auch bei einem Zeitraum von 24 Stunden sorgfältig vorbereitet und für jeden Untersuchungsabschnitt eines Fließgewässers einzeln programmiert werden. Weiterhin ist zu bemerken, dass die Abschätzung von Dissipationsraten mit einem 2D-Modell problematisch ist, besonders bei stark instabilen Wasseroberflächen. Außerdem gibt es noch zahlreiche offene Fragen bezüglich verwandter Themengebiete: Welchen Einfluss hat die Turbulenz (turbulente Strömung) auf den Metabolismus von Gewässerorganismenm, und vor allem von Fischen? Welche Konstellation verschiedener Kenngrößen führt zu welcher Schwimmweise von Fischen? Wie kann der Einfluss der Temperatur auf die spezifische Metabolismusrate von Fischen mit Veränderungen der lokalen Strömungsverhältnisse in Verbindung gebracht werden?

Es ist zu erwarten, dass solche Fragestellungen auch mit den neuesten 3D-Modellen nicht mit numerischen Berechnungen bearbeitet werden können, sondern ein Teil der Rahmenkonzeption bleiben.

Das vorangige Ziel dieser Arbeit ist es, für die Modellierung aquatischer Ökosysteme eine tiefere konzeptionelle Grundlage zu schaffen. Obwohl Probleme bei der Anwendung und der theoretischen Untermauerung von Teilen der Arbeit erkennbar sind, ist ohne Zweifel festzustellen, dass die Integration des Prinzips der Irreversibilität des zweiten Hauptsatzes der Thermodynamik nur zu einer weiteren Verbesserung bei der Modellierung von aquatischen Ökosystemen führen kann.

Abstract

Europe requires a growing and stable energy supply in the face of increasing competition through globalization. Electricity gained through the extraction of renewable energies is likely to be a large part of the solution. However due to storage constraints, electricity must be produced exactly as it is needed. Currently, peak power production can be generated only with gas and storage hydropower plants. Because gas belongs to the non-renewable family, European storage hydro power plants are expected to gain in both their value and importance.

An outcome of daily electrical energy consumption is that storage hydropower releases must match the changes in daily demand. These local, high intensity fluctuations are commonly called hydropeaking. Due to their large departure from natural flow rates, the river ecosystems downstream of hydro operations are forced to react. This causes a large shift in the dissipative regime of the river, affecting the entire food web from *Sparganium emersum* to *Salmo trutta*. Although the cause of hydropeaking in alpine rivers is obvious, assessing its ecological effects is not an easy task. The study of hydropeaking impacts on river ecology demands a great deal of new theoretical and phenomenological investigation. Complicating such studies is the fact that river ecosystems themselves are not stable systems but are evolving over time, even under steady flow conditions. Although ecological models of aquatic ecosystems have been present for several decades, it is currently not possible to model a fish's response to the short-term fluctuations in the flow field caused by hydropeaking with the same degree of accuracy which has been achieved under steady flow conditions.

The use of numerical models to assess the impacts of hydropeaking on aquatic ecosystems is still in its infancy. The challenge of this dissertation is to construct a theoretical framework that can be used to study abiotic-biotic interactions under highly unsteady conditions. The model is constructed through the lens of thermodynamics, by looking at system interactions in terms of the contributions of the relative equilibrium states: mechanical, chemical, and thermal.

The objectives of this dissertation are:

1. **Incorporate thermodynamic principles into an aquatic habitat model which can be effectively applied for highly unsteady flow regimes.**

2. **Evaluate the model in terms of performance, ease of application and theory.**

This work proposes a new kind of fish habitat model using thermodynamic concepts for use in European alpine rivers affected by hydropeaking. Ecosystem states may be found which allow for optimal systems in which animate components such as fish are able to participate. Furthermore, we show that a 'first law' approach which invokes only the conservation of energy is not sufficient to understand the energetics of the alpine river ecosystem. It is necessary to view the ecosystem in terms of its free energy and its entropy as well. This 'second law' methodology provides powerful insight and results in a more objective modeling approach to assess hydropeaking impacts on fish considering real-world conditions.

The work begins by introducing the problem of hydropeaking in European alpine rivers. The second chapter, **Hydropeaking in Alpine Rivers** discusses hydropeaking impacts as well as an overview of the structural and operational mitigation options currently available.

Next, an introduction to the field of thermodynamics is given in the third chapter, **Thermodynamics and the Alpine River Ecosystem.** Emphasis is given to a description of the governing physical processes common to alpine rivers. Key to this chapter is the introduction of irreversible thermodynamics, which provides the fundamental theoretical background for the main thesis of this work. The chapter concludes by sketching out the alpine river ecosystem as a special type of open irreversible thermodynamic system.

In the fourth chapter, **Irreversible Aquatic Ecosystem Models** applications of thermodynamics to alpine river ecosystems are provided first from the top-down and then from the bottom-up. These two theoretical formulations are presented to show that the application of thermodynamics to ecosystems and to individuals provides several advantages over conventional habitat model approaches, and raises new questions as well.

Following the work of chapters three and four, in chapter five, **River+Fish Energetics** the river+fish concept is developed where the fish is considered in terms of its energetic needs and the hydraulics of the local flow field which surrounds it. Key to this chapter is the illustration that the fish and water system cannot be viewed as separate entities. At the end of this chapter some fundamental questions surrounding fish energetics are addressed.

After introducing the theory and providing a new, thermodynamically-based modeling concept, a rigorous investigation of model applicability in real-world settings is undertaking in chapter 6, **Locational Entropy Model**. A collection of 30 different alpine river reaches are run using the thermodynamic modeling concepts developed in the previous chapters and are compared to the state-of-the art fuzzy logic habitat model in order to determine the strengths and weaknesses of the approach. The model is then applied under hydropeaking conditions to a single investigation reach on the River Inn at Martina. Here it is found that although there are major differences between the theories behind both models, there is a strong correlation between constant rates of energy dissipation predicted by the thermodynamic model and the fuzzy logic model. Two main suggestions for model improvement come from this modeling study: the fuzzy logic model serves as a proxy dissipation estimator, and that additional, large scale flow pattern parameters are included in future fish habitat models.

The first research objective of this dissertation is addressed in chapters four, five, and six, whereas the second objective is primarily dealt with in chapters six and in the final chapter, **Conclusions**. The thermodynamic concept developed in this dissertation is not at all easy to apply as a numeric model. In order to calculate one single 24 hour period, even when only the dissipative estimate is used, careful preparation and programming are required for each investigation reach. Furthermore, the use of a 2D model to estimate dissipation rates is problematic, especially when concerning the large surface instabilities observed on the investigation reach at Martina. Although a series of key model parameters is discussed, there remain many open questions regarding the proper derivation of conjugate relations: How is metabolism related to turbulence? What constellation of parameters results in a particular mode of swimming? How can the effects of temperature on a fish's specific metabolic rate be tied to changes in the local flow pattern? Even with the most state of the art 3D models, it is likely that such questions are to remain in the purview of the conceptual framework and are not feasible within a numerical model.

The main goal of this work is to provide a deeper conceptual basis to the field of aquatic ecosystem modeling. Though difficulties in both the applicability and theoretical underpinnings of parts of the work are identified, there can be no doubt that the inclusion of second law irreversibility can only lead to further progress in the field of aquatic ecosystems modeling.

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1 Introduction

The human species is but one of many. Viewed from a sort of universal microscope, we appear as but a vast collection of molecules in motion. In our current state we are firmly attached to an Earthly substrate, feeding off the energy gradient of the Sun. The fate of our chemical species is undeniably tied to the affinities and energies of interaction required to maintain our evolving earth ecosystem. We live in a closed system. In order to understand the nature of things, we must learn more about both our reactions and our products.

1.1 Motivation

The inspiration of this work is taken from Mauersberger's (1985) thought-provoking application of Planck's theory of dilute solutions applied to aquatic ecosystems. The bold step is taken suggesting that aquatic ecosystems follow the same physical laws as their inanimate molecular counterparts, and we can thus use the science of energy, thermodynamics as the common language in describing their roles and interactions within the ecosystem. Additionally vital is the fundamental contribution of Bauer (1920) which provides a nonequilibrium definition of animate systems. Bauer is one of the first to have the insight that organisms have a place *in* the fundamental Gibbs equation. Concepts relating thermodynamics to animate system behavior are taken from the works of Boltzmann, Clausius, Schrödinger, Jorgensen, Gladyshev, Zotin, Sterner, Elser, Morowitz, Glaser, Mauersberger, Ebeling, Katchalsky, Bejan, Ulanowicz, Mikulecky, Rosen, Elsasser and most recently Thims. These unique researchers have boldly taken chemical or thermodynamic stances when contemplating animate systems development, often inviting great controversy.

Thermodynamics presents a powerful tool for the examination of alpine river ecosystems. Considering energy and mass fluxes, the first law provides balance, the second law direction, and the constructal law design. We can now remove thermodynamics from the confines of its teleological black box, and begin to directly observe the power of design in nature. We are searching for a modeling concept not based on the limited exposition of numerical model outputs or point measurements, but one whose theory and phenomenology are valid in the rough, lumpy, viscous and imperfect world of irreversible, finite-size, finite-time processes.

1.2 Problem Statement

Modern Europe requires a growing and stable energy supply. Though the West has seen rapid growth in the quality of life in the last 80 years, a considerable portion of that success is built on releasing the free energy of bubbling crude. More than any other part of the world, the modern European civilization is looking for a way out, and fast. Electricity gained through the extraction of renewable energies is likely to be the solution. Readily transmutable into other commonly used energy forms by humans, such as heat, light, and locomotion, electricity is considered by many to be the ‘stem cell’ cure to the ills anticipated by global climate change and the impending energy crisis. Due to storage constraints, electricity must be produced *sur demande*. Currently peak power production can be generated only with gas and storage hydropower plants. Because gas belongs to the non-renewable oil family, a safe bet is that in Europe storage hydro plants are destined to gain in both their economic value and political importance.

An outcome of our unsteady circadian electrical energy consumption is that commensurate hydro releases must also be made. These local, high intensity fluctuations are commonly called hydropeaking. Due to their large departure from natural states, the river ecosystems downstream of hydro operations are forced to react. If the departure is larger than the local threshold for stability, the system changes to reflect a new dynamic stability. This occurs through a shift in the dissipative regime of the river, affecting the entire food web from *Sparganium emersum* to *Salmo trutta*. Although the cause of hydropeaking in alpine rivers is obvious, the assessment of its ecological effects is not. Their study demands a great deal of new theoretical and phenomenological investigation. Complicating such studies is the fact that river ecosystems continuously evolve over time - even under stationary flow conditions. A river ecosystem is a hierarchy of interaction between inanimate and animate components, driven to increase access to energetic currents while reducing dissipative losses.

1.3 Theoretical Approach

In applying the thermodynamic model developed in this work, the strength of the theoretical underpinnings must be tempered with the ability to utilize it. The challenge of this dissertation is to construct a theoretical framework that only a biophysicist could love, an engineer could apply, and a biologist would agree to consider. The model is constructed from first principles by looking at the physical constraints of the system in terms of the contributions of the relative equilibrium states: mechanical, chemical, and thermal. The model is tailored to available data and measurement techniques. Discrepancies between the two can be dealt with by filling the missing data with viable assumptions taken from empirical studies in the scientific literature, or based on first principles. Those areas which are potential sources of error limit model accuracy and predictive capability. We enter the modeling process recognizing the presence of its faults, but remain both persistent and optimistic in our goal of improving the approach into the future.

At the core of this work is the theorem that thermodynamically driven elements, acting in a hierarchical network serve to decrease the irreversibility at every level in the system. The individual interactions between components are capable of evolving such that the irreversibility of the system as a whole is reduced. A novel fish habitat model is proposed using this concept for use in European alpine rivers affected by hydropeaking. Ecosystem states may be found which allow for stable system configurations in which components such as fish participate. Furthermore, we show that a first law approach which invokes only the conservation of energy is necessary but not sufficient to understand the energetics of the alpine river ecosystem. It is necessary to view the ecosystem in terms of its free energy. This second law methodology provides powerful insight and results in a more objective modeling approach to assess hydropeaking impacts on fish considering real-world conditions.

1.4 Research Objectives

The goal of this work is to provide a new theoretical background for aquatic modeling in alpine rivers which can be used in even the most extreme hydropeaking conditions. The objectives of this dissertation are twofold:

1. **Incorporate thermodynamic principles into an aquatic habitat model which can be effectively applied for highly unsteady flow regimes.**

2. **Evaluate the model in terms of performance, ease of application and theory.**

In order to achieve the objectives, the dissertation work first presents the problems of mitigating hydropeaking, provides a theoretical background of alpine river enegetics, and proceeds to develop a thermodynamic conceptual model for studying the potential impacts on fish. The first objective provides a new theoretical paradigm in which we can investigate aquatic ecosystem development. A major challenge to model development is to include the effects of highly unsteady flow occurring at the river macroscale while simultaneously considering the near-body flow field and its impact on individual locomotion. This immediately brings to the forefront the determination of a suitable reference scale from which all formal description of the ecosystem is to be made. In order to determine the proper scale, we look at ecosystem dynamics first from the top down and then from the bottom up. Once the modeling approach has been stated, the second objective becomes important to the disseratation work from an engineer's perspective, as the theoretical model concept requires testing in a practical environment. Differences between the theory and practice are dealt with using examples from a wide range of previous works. Gaps are addressed as thoroughly as possible with phenomenological studies taken from the literature. Here it is also crucial to recognize that the entities in natural systems exhibit *physical semi-uniqueness*, a property which *cannot be described mathematically.* Thus our experiments and postulates may occur at a level of abstraction which may not always be suitable for direct computation in numerical models.

1.5 Structure of the Dissertation

Chapter 2 introduces the problem of hydropeaking in European alpine rivers. The chapter discusses hydropeaking impacts and the various mitigation options available.

Chapter 3 provides an introduction to the field of thermodynamics, with emphasis on the governing physical processes common to alpine rivers. Key to this chapter is the introduction of irreversible thermodynamics, which provides the fundamental conceptual and theoretical background for the thesis of this work. The chapter concludes by sketching out the alpine river ecosystem as a type of irreversible thermodynamic system.

Chapter 4 lays out the main thesis of this work by investigating the alpine river from the top-down and from the bottom-up. Two theoretical formulations are presented to show that the application of thermodynamics to ecosystems and to individuals provides several advantages over conventional habitat modeling approaches.

Chapter 5 discusses the river+fish system concept by discussing the fish in terms of its energetic needs, and the hydraulics of the local flow field which surrounds it. Key to this chapter is the illustration that the fish and water system *cannot* be viewed as separate entities. At the end of this section some fundamental questions surrounding fish energetics are addressed.

Chapter 6 provides a rigorous investigation of model applicability in real-world settings. A collection of 30 different alpine river reaches are run using the thermodynamic modeling concepts developed in chapter 4 and compared to the state-of-the art fuzzy logic habitat model in order to determine the strengths and weaknesses of the approach. The model is then applied under hydropeaking conditions to a single investigation reach on the River Inn at Martina.

Chapter 7 provides a summary of the work, a discussion of its meaning, and provides a perspective as to how the model application may be expanded and improved.

2 Hydropeaking in Alpine Rivers

Rivers are integral parts of the valleys that they drain. Large catchment areas such as the European Alps (Fig. 2-1) can be viewed as ecosystems with both natural and cultural interactions (Hynes, 1975; Stanford et al., 1996). In West-European alpine communities, hydropower has become a locally available resource with growing transboundary value due to the increasing demand of peak energy in the European energy sector (Banfi et al., 2004). Peak energy producing hydropower operations can result in significant disturbances to the local flow regime and can be a major cause of ecological changes due to alterations in river habitat conditions (Limnex, 2004; Meile et al., 2005; VAW and EPFL, 2006).

Fig. 2-1 The extents of the European Alps. The mountain range includes territory in France, Italy, Switzerland, Monaco, Lichtenstein, Germany, Austria and Slovenia. The 1,200 km long, 192,000 km^2 region is home to some 30,000 animal and 13,000 plant species. Sources: WWF (2011a); Wikipedia (2011).

Changes to the daily discharge regime due to alpine storage hydropower facilities are particularly pronounced due to the large difference between the early morning base and the evening peak flow rates. Hydropeaking in this work is defined as extreme and short-duration ($<$ 1 hr) fluctuations occurring due to storage hydropower production. The fluctuating releases are used to cover a power network's peak electrical loading conditions on a daily basis, and to stabilize networks with considerable renewable energy (e.g. wind) contributions. Hydropeaking can result in disturbances to the hydrologic regime, river morphology and ecological condition of a river (Renöfält et al., 2010). Due to the highly dynamic nature of the phenomenon, mitigating hydropower impacts is extremely challenging. The purpose of this chapter is to introduce the hydropeaking phenomena and to lay out the case for a new theoretical basis for studying alpine river ecosystems. The chapter begins by presenting the phenomena as it relates to energy production in West-European alpine rivers, with a focus on Switzerland. Special attention is paid to the discussion of hydropeaking metrics suitable in estimating the ecological impacts of hydropeaking. The two major types of mitigation measures; operational and structural are presented along with considerations of their practicality in terms of costs and impacts.

2.1 Impacts of Hydropeaking in West-European Alpine Rivers

Human influence on river systems for flood control, irrigation, food, and energy production in West-European alpine river communities has intensified greatly since the 1950s (Pautou et al., 1997). It is estimated that some 58% of Swiss and 68% of Austrian electricity is produced by hydropower (Peter, 2010). In Switzerland, only 10% of all rivers can be considered to be in a natural or near-natural state (Schweizer et al., 2007). Furthermore, it is estimated that about 25% of the 500 ($>$300 kW) operating Swiss hydropower plants contribute to hydropeaking (Limnex, 2001). There is a growing movement calling for the alleviation of environmental pressures due to hydropeaking from both the scientific community and environmental interest groups alike (Peter, 2010; WWF, 2011b). Defining ecological impacts solely due to hydropeaking is a near impossible task because the magnitude of their effects is largely dependent on concomitant anthropogenic changes. However, there currently exists a substantial and growing body of evidence to aid in defining the anticipated local ecological impacts of hydropeaking. Limnex (2004) provides a complete list of hydropeaking impacted reaches in Switzerland along with the contributing hydropower plants. Excellent reviews of impacts and mitigation strategies in the literature are provided by Bain (2007) and more recently by Renöfält (2010). Baumann and Klaus (2003) present a literature review pertinent to the Swiss case, predominantly considering impacts and potential mitigation measures relevant to benthic invertebrates and fish. In this work fish are used as the indicator species of choice due to their sensitivity and direct response to changes in local hydraulic parameters as well as to long term changes in the river ecosystem (Landres et al., 1988).

Fish are used in many previous studies as biological indicators in assessing both short and long term ecological impacts of hydropeaking due to their sensitivity to peaking activity and their position in the trophic chain (De Jalon et al., 1994; Künzli, 2005; Pellaud, 2007). However, the impacts of hydropeaking are not limited to biota alone. In addition to the modification of the flow regime, changes to river morphology caused by hydropeaking can be pronounced, especially over decades of operation (Ibàñez et al., 1996; Osmundson et al., 2002). Hydropeaking can cause colmation, reducing the vertical connectivity between the river and groundwater. This loss of connectivity can result in severe impairments to fish spawning, the benthic community and often results in changes to the river's circadian rhythm (Berkman and Rabeni, 1987; Fette, 2005). The highly heterogeneous nature of instream structures (gravel banks, islands, refugium, etc.) often aid in reducing the negative effects of hydropeaking, but can also exacerbate conditions (Limnex, 2004). As an example, the formation of shallow pools due to changing flow conditions can provide refuge for juvenile fish during the rising limb of the hydrograph, reducing drift, but can also lead to fish stranding after the wave has passed (VAW and EPFL, 2006; Schneider and Noack, 2009).

The most noticeable effects of hydropeaking are the short term fluctuations of the river's flow rate downstream of the power plant, resulting in benthic drift, fish stranding, and a shift in the sediment transport regime (Fig. 2-2). However it should be noted that long term impacts of reservoir operations must be considered as well (Power et al., 1996). Hypolimnetic dam releases may affect the mean water temperature (Clarkson and Childs, 2000), and flow regime modification can shift the balance of sediment transport processes in the long term, causing colmation, bed armoring, and a net increase in turbidity, leading to significant changes in the fluvial morphology (Eberstaller and Pinka, 2001; Burke et al., 2006; Bruno et al., 2009).

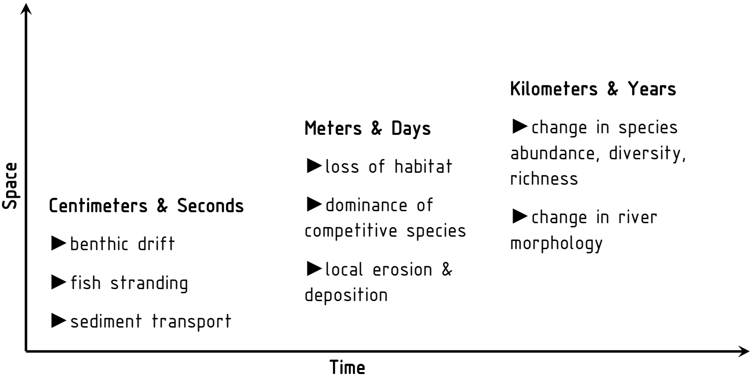


Fig. 2-2 Effects of hydropeaking over space and time.

The ecological threat posed hydropeaking when ranked by its severity follows morphological and water quality parameters. Aquatic organisms first depend on the existence of suitable physical habitat conditions constrained within chemical and physiological ranges before settlement and reproduction can occur (Arthington et al., 2006; Poff et al., 2010). Thus morphological and water quality parameters can be seen as representing necessary and sufficient conditions for the existence of an aquatic ecosystem, whereas the flow regime is often decisive in determining the extent of overall ecosystem health (Vannote et al., 1980; Power et al., 1996; Poff et al., 1997) as it provides the driving forces and fluxes within system boundaries. Accordingly, an attempt to mimic the natural flow regime of the past in a modern river valley which has undergone a high level of anthropogenic change is not likely to result in great improvement (Hauer et al., 2003). In the case of hydropeaking a more holistic approach is needed taking ecological responses, morphological characteristics, and socioeconomic interests into account (Cardwell et al., 1996; Reichert et al., 2007; Schweizer et al., 2007). Before planning mitigation measures, it is first necessary to determine metrics based on measureable quantities which couple the causes and impacts of hydropeaking.

2.2 Quantifying the Hydropeaking Problem

The literature provides a wide breadth of indicators which are applied to investigate and quantify hydropeaking phenomena and its impacts. Indicators representing operational characteristics are most commonly based on a variety of flow rate based metrics. Here the commonly used metrics are briefly reviewed in terms of their scale and utility when estimating the ecological impacts due to hydropeaking.

2.2.1 The alpine river

Alpine rivers are fed by snowmelt, glacial ice melt, groundwater, as well as from rainfall events during late spring to early autumn. Due to the variations in the individual contributions of each, alpine rivers exhibit distinctive discharge regimes and physiochemical properties, changing over temporal scales from diurnal to inter-annual (Bundi and Brittain, 2010). Although there exists a great deal of variability between individual rivers they do share common features, such as steep hydraulic gradients, high flow velocities, low water temperatures and high dissolved oxygen concentrations. Alpine rivers are often classified according to their water source and ecological class (kryal/glacial melt, rhithral/soft water, krenal/groundwater), suspended sediment concentration, hydrochemistry, channel stability, and flow variation (Ward, 1994; Brown et al., 2003). In this work, the ‘typical’ alpine river is characterized as having a gravel bed, steep bed slope, low water temperature and high dissolved oxygen concentration. Although the theoretical derivations used in this work are applicable to any aquatic ecosystem, assumptions are made throughout which require significant reformulation of many of the equations if this work is to be applied to rivers of another type. Whenever possible the assumptions have been explicitly stated as such.

2.2.2 Hydropeaking indicators on the watershed scale

At a given site, three main parameters can be readily used to identify and quantify the hydraulic properties of hydropeaking on the watershed scale (months and km) (VAW and EPFL, 2006):

- Annual mean flow rate, $\overline{Q}_A$
- Useable reservoir volume, $\forall_{\mathrm{Re}s}$
- Design discharge of the hydropower plant (may be the sum of multiple turbines), Q_d

The ratio $\forall_{\mathrm{Re}s}/\overline{Q_A}$ can be used to quantify the allocation of water from the summer to the winter months when base flow rates are typically the lowest and the effects of hydropeaking are often the most pronounced. Q_d can be used relative to a base flow rate to determine the maximum peaking ratio. The monthly mean flow rates can be used to calculate the monthly Parde coefficient, Pk_i. The coefficient can be used as an indicator of seasonality of the mean flow in month i for the year j where n is the number of years (De Michele and Rosso, 2002).

$$Pk_i = \frac{12}{n}\sum_{j=1}^{n}\left(\frac{Q_{ij}}{\sum_{i=1}^{12} Q_{ij}}\right) \tag{2.1}$$

Forstenlechner et al. (1997) used the Parde coefficient to partition the three main types of flow regimes in the alpine region as alpine, midland Jurassic and south alpine. The coefficient can also be applied to determine to what extent storage hydropower plants augment the natural flow regime. As an example, on the Rhone a decrease in Pk_i can be observed during the rainy season between May-September, and increases for all other months due to water reallocation caused by the reservoir (Meile et al., 2005). This is especially important in hydropower economics, where accurate values of the production function are very useful but often hard to come by (Førsund, 2007). Aside from the Parde coefficient, the use of monthly, seasonal or annual metrics has appeal in that they allow for an expression of hydropeaking to be presented on the large scale, where rivers or similar watersheds can be reasonably compared to each other. Such large scale reviews are performed for Switzerland’s major rivers (VAW and EPFL, 2006) for the Alpenrhein (IRKA, 2004) and in an in-depth study of hydropeaking characteristics for five investigation reaches in the Upper-Rhone catchment (Meile et al., 2010).

2.2.3 Reservoir size

Alpine peaking hydro plants have a wide range of storage volumes (Fig. 2-3), from a few hours of max daily production of up to a year of annual inflow storage. In the winter months, characteristic flow rates driven by regional hydrology are considerably lower than in the summer. This results in an effective amplification of hydropeaking effects on fish considering equivalent production due to their response to rapid temperature variation (Vehanen et al., 2000; Flodmark et al., 2004). The total reservoir volume is a useful indicator because it describes not only one of the major dimensions of the hydro system, but is in combination with the type of hydro plant directly proportional to both the costs and the magnitude of annual electricity production (Banfi et al., 2004).

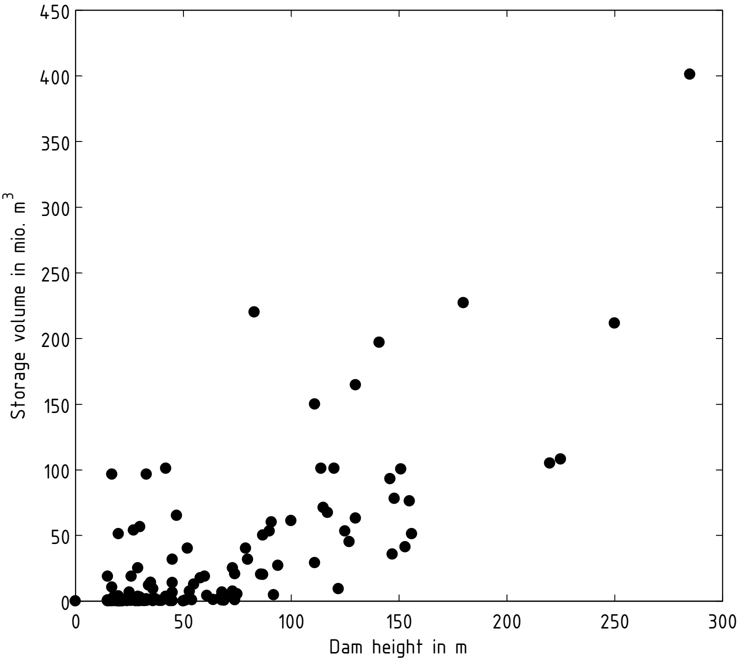


Fig. 2-3 Dimensions of Switzerland's largest 160 reservoirs. The smallest is Gietroz-du-Fond with a height of 15 m and a total storage volume of 0.02 Mio m^3, and the largest is the famed Grande Dixence with a height of 285 m and storage capacity of some 401 Mio m^3 Source: Swiss Committee on Dams (2011).

2.2.4 Type and timing of peak energy production

There are two principle reasons why the operation of storage hydropower plants is challenging: plants must keep the electricity network stable by maintaining the operating frequency within a tolerable range, on a minute-to-minute basis. At the same time, plants must cover the fractional demand which changes day-to-day and cannot be produced as needed by conventional thermal plants, which cover the base load (Zahoransky, 2008; Heuck et al., 2010). These daily events are associated with the stereotypical peaking caused by circadian demand patterns. It should be considered that seasonal peaking also exists (Fig. 2-4), caused by long term shifts in network demand, and more commonly observed in the Norwegian market. Finally, a more exotic peaking due to electric public transport such as railways or other high load systems also exists (Burri, 2009). Such peaks follow the rhythm of daily traffic patterns, but contribute globally to hydropeaking impacts to a much smaller extent. By observing the specific type of peaking produced at a given plant, tailored mitigation projects can be better assessed by engineers and biologists alike.

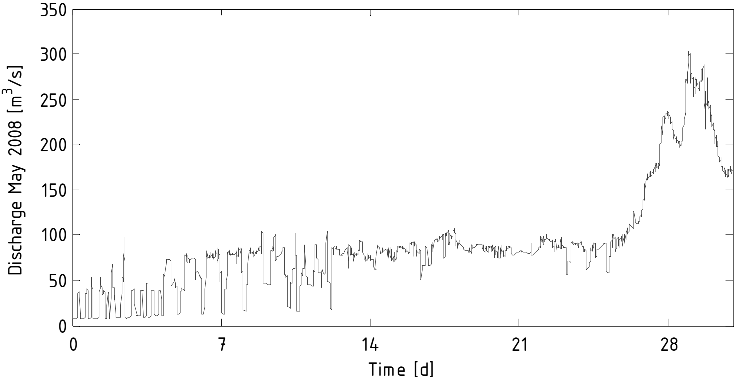


Fig. 2-4 Hydropeaking during May 2008 at Martina (CH). Note the fluctuations for the first two weeks of the month are representative of the typical $Q_{\max}/Q_{\min}$ peak ratio, whereas the remainder of the month has a much higher base flow due to seasonal rainfall resulting in peaking which is substantially less pronounced. Source: BAFU (2010).

2.2.5 Reach scale parameters

In order to study local effects of hydropeaking and to design mitigation measures at the reach scale, the use of the above mentioned watershed scale parameters are both spatially and temporally too coarse to be effectively applied. Hydropeaking metrics are developed focusing on the short term, local scale (minutes and meters) changes in the river reach.

It is clear that many possible indicators describing the hydropeaking phenomenon are available (Table 2-1). The success of mitigating hydropeaking impacts depends on tying concrete relationships between hydraulic variables (Table 2-2) to predictable environmental responses. Due to the fact that the flood wave attenuates with increasing distance from the point of discharge, and is affected at each point along the river by both the local and previous conditions, new field observation methods are required to study the hydraulics of hydropeaking. This may lead to the realization that in addition to the existing metrics, new unsteady metrics describing hydropeaking impacts are required. Although many of the currently applied flow-based metrics are intuitive, the interpretation of their expected impacts may result in a gross oversimplification of the river ecology, and often cannot provide the ability for reach cross comparison (Tuhtan et al., 2010). Successful mitigation of hydropeaking requires that the knowledge gained from one project include the specificity of the local properties of a given reach, and at the same time remain as general as possible to contain information useful in planning new mitigation projects.

Table 2-1 Common metrics used to describe hydropeaking characteristics in terms of their flow rates and the stage discharge relationship, modified after VAW and EPFL (2006).

Data Source	Parameter of Interest	Indicator used to Identify Hydropeaking
discharge hydrograph $Q(t,x)$	daily maximum, $Q_{\max}$	peak ratio, $Q_{\max}/Q_{\min}$
	daily minimum, $Q_{\min}$	peak difference, $\Delta Q = Q_{\max} - Q_{\min}$
	daily average, $\overline{Q}$	normalized peak ratio, $\Delta Q/\overline{Q}$
	peaking rate, dQ/dt	up/downramping rates and their frequencies of occurrence throughout the year, $f_i = \frac{dQ_i/dt}{\sum_i dQ_i/dt}$
stage hydrograph $h(t,x)$	daily maximum elevation, $h_{\max}$	peak ratio, $h_{\max} - h_{\min}$
	daily minimum elevation, $h_{\min}$	peak difference, $\Delta h = h_{\max} - h_{\min}$
	rate of elevation change, dh/dt	spatial distribution of rates of water surface change

Table 2-2 The physical significance of flow rate based metrics used in hydropeaking studies.

Parameter/Indicator	Physical Meaning
$Q_{\max}$	Defines upper limit of water surface elevation, the flow rate and the bed shear stress
$Q_{\min}$	Defines the minimal flow characteristics
$Q_{\max}/Q_{\min}$	Intensity of the flow events
$\Delta Q = Q_{\max} - Q_{\min}$	Related to fluctuations in the water surface elevation in the vertical and lateral directions
$\Delta Q/\overline{Q}$	Describes the relative intensity of hydropeaking on a daily scale (when compared to the daily average flow rate), and whether it occurs against a low or high background flow rate

2.3 Mitigation Strategies for Hydropeaking in Alpine Rivers

Projects attempting to mitigate the problems of hydropeaking face the same difficulties as any other river revitalization project. Historically, the planning and implementation of mitigation strategies for riparian ecosystems have largely failed to produce useful models for policy comparison and that successful experimental management plans do not reach an adequate audience to culminate in reproducible success (Hauer et al., 2003; Hobbs, 2005). Modeling efforts are hampered by difficulties in representation of the cross-scale effects needed when considering physical/chemical and ecological processes (from local rapid hydraulic changes to long-term ecological response), lack of data on key processes, and confusing causality with correlation in validation data.

Some 60% of the Swiss river network lies in alpine or high alpine regions, where rehabilitation potential is especially pronounced (Peter, 1994). In order to avoid some of the pitfalls common to river restoration projects, in Switzerland the process of systematically investigating hydropeaking mitigation began as a part of the “Rhone-Thur” project. The project aimed to define guidelines and tools for carrying out successful river restoration projects, and facilitating the transfer of knowledge between science and practice (Reichert et al., 2007; Peter, 2010).

When considering project alternatives, it should be kept in mind that *the effects of hydropeaking cannot be fully remediated but can in most cases be mitigated*. Due to the inherent heterogeneity of river systems, there is no magic bullet which can be used to unilaterally improve all sites affected by hydropeaking. Renöfält et al. (2010) provide a thorough review of the variety of alterations caused by hydropeaking related to changes in the hydrology and morphology of rivers where corresponding ecosystem responses and recommend mitigation measures from the literature. In this work mitigation measures are classified as either operational or structural. **Operational measures** involve placing constraints on hydropower production via the ramping rates, the peak ratio, and the rate of water surface elevation change. **Structural measures** involve a physical modification of the river system itself such as river widening, renaturalization and the construction of retention basins. They can be viewed as change in the flow configuration (mass and energy) of the river system. The effects of these measures can be abstracted as modifications of system fluxes. Viewing alpine rivers as open, finite, time-dependent systems points out that reference ecological states are likely to depend on both the system’s configuration and its response to fluxes. Thus structural and operational measures are likely to be most successful when synergies between the river’s configuration and its fluxes are considered.

2.3.1 Operational mitigation

Stranding constraints

The values taken must be understood as being representative for particular site conditions, not as absolutes. However, they do provide some indication as reference rates for future studies. Hunter (1992) provides an in-depth review of stranding mechanisms, and the relative rates of change between the depth and width. Ranges of values for salmonids are taken from studies and are shown in Table 2-3.

Table 2-3 Critical dewatering rates used in studies taken from the literature to reduce fish stranding and their effects when implemented.

Literature Reference	Proposed Limit (cm/min), [cm/hr]	Major Finding
Halleraker et al. (2003)	(<0.17),[10] depth	Removed the stranding risk for fish
Saltveit et al. (2001)	(0.2),[12] depth	Almost complete reduction of stranding for juvenile fish
Hunter (1992)	(0.04-0.08),[2.5-5] depth	From February 16 to June 15 no ramping should be allowed at night if salmon fry are present

Maximum allowable peak ratios

Recommended peaking limits found in the literature differ largely depending on the organism studied. In general, ramping rates for fish tend to be higher than those found for benthic invertebrates. Compounding the problem of choosing a best peaking rate for a given river is that the local flow configuration drives the distribution of local-scale hydraulic variables which determine threshold peaking rates at which catastrophic drift occurs (Gore et al., 1994; Mochizuki et al., 2006). Thus a fixed peaking ratio is likely to have highly varying degrees of effectiveness even along the same river due to its morphological heterogeneity. Because each mitigation project has a different scope, applying peaking ratios directly from the literature (Table 2-4) is a good place to start, but should not be the last word.

In 2004, the Joint Rhine Commission issued a study to assess the hydropeaking impacts on the Alpenrhine with fixed peak ratios of 4.33, 2.3, and 1.9. Estimated economic losses aggregated over all affected hydro producers due to fixed peak ratios are estimated at 0.12-1.3 Mio. €/week, based on a price of forgoing 30 €/MWh for peak electricity (IRKA, 2004). In Austria the maximum peak ratio is limited to 5:1 for small to middle Alpine rivers, and the maximum for larger rivers is to be determined based on considering downstream reaches via individual studies (Weiss, 2010). It is determined that enforcement of this regulation for a single Austrian hydro plant alone will cost a minimum of 1.3-4.5 Mio. €/year for normal years, up to a maximum of 70 Mio. €/Year for the most extreme case (Stigler et al., 2005).

Table 2-4 Recommended peak ratios from the literature.

Reference	Limiting Peak Ratio	Location	Observed effect
IKRA (2004)	4.3:1 – 1.9	Alpenrhein	Assumed to reduce ecological impacts
Limnex (2000)	3:1 – 6:1	Sitter, Switzerland	Catastrophic drift for invertebrates reduced
Liebig et al. (1998)	10:1 v. 6:1	Oriege, Spain	The higher ratio resulted in twice as many juvenile fish being drifted
UVB (1991)	6:1 – 7:1	Poschiavino, Switzerland	No notable increase in organic drift

2.3.2 Structural mitigation

Mitigation measures involving operational constraints are often simply too expensive and lower the effective capacity of peak energy production at a given site, and thus the focus of hydropeaking remediation projects is primarily on the construction of structural measures, especially retention basins (Limnex, 2009). Volumes calculated are related to reductions of the peak ratios from 5:1-2:1. Calculating the volume depends highly on frequently a fixed peak ratio is to be held, the maximum ratio value itself, (which is to some extent a function of the retention basin's outflow), and the percentage of time at which the specified peak ratio is to be held (relative to daily, weekly, or monthly intervals). Daily basins can be constructed to dampen the effects of operation, but will result in highly fluctuating minimum and maximum flow values, depending on the natural and operational conditions in the watershed. Keeping the outflows as constant as possible requires ever larger retention basins, and basins capable of weekly storage are not likely to be feasible in narrow alpine valleys. The winter holiday from Christmas to New Year is especially problematic since inflows are low, the weather is relatively dry and cold, which often leads to very large peak ratios. In order to keep a certain regulated outflow in the winter months, a volume 100 times the size of the daily facility may be required (to increase the base flow), whereas for the weekly case, 10 times the daily facility would be sufficient. A visual depiction of the various structural mitigation measures is shown in Fig. (2-5). However, it is not feasible to construct basins which cover only this special 'Christmas peaking' scenario.

In Switzerland as of January 1, 2011 a new law has been passed which includes the requirement of reducing hydropeaking impacts via structural measures. In order to finance such measures, beginning in 2012 an additional 0.1 Rp./kWh is added to the electrical energy price (Werlen, 2011).

Reach restoration

Common to river restoration approaches is the belief that the entire bed morphology must be repaired. This type of structural mitigation falls into the field of river renaturalization and restoration, a long-standing but notoriously unsuccessful field (Kondolf, 1995; Shields et al., 2003; Whiteway et al., 2010). Literature specific to restoration of hydropeaking reaches is only beginning to emerge. However a high correlation between the fish biomass and homogeneous, monotonous morphology is described by Fette et al. (2007) when studying the effects of river rehabilitation on the River Rhone in Switzerland. One of the largest alpine restoration projects on the River Drau in Austria shows that the effects of hydropeaking were reduced due to extensive channel widening, causing a noticeable increase in the number of juvenile grayling (Muhar et al., 2008). River widening is also used to attenuate the magnitudes of hydraulic variables most affecting benthic organisms (Looy et al., 2007). The IKRA alone is currently running 16 revitalization projects on the Alpenrhine, ranging from 110,000 CHF for planning investigations in Graubünden to 25 Mio. CHF for the renaturalization of the old Rhine from St. Margrethen to Lake Constance. Although not all of the projects deal with hydropeaking, substantial general experience in alpine river restoration is expected to be gained.

In-stream structures

More recently it is suggested that in lieu of entire restoration, that local adjustments or in-stream structures, especially in near bank areas ought to be carried out (Ribi et al., 2009). The attraction here is that macroroughness elements or smaller structural components could be applied on a much lower cost basis to a larger effective number of effective reaches. The success record of local in-stream improvements based on current practice is plagued with difficulty. Pretty et al. (2003) in their investigation of the effects of instream structures as a mitigation option in 13 European lowland rivers and found that total fish abundance, species richness, and diversity are not significantly different between rehabilitated and control reaches. Similarly, Harrison et al. (2004) reported that of 13 investigation reaches included in their UK study, neither artificially constructed riffles nor flow deflectors caused any significant impact on the species richness of the benthos. Localized renaturalization using bank strips or riprap structures have been shown to improve cover conditions but are a poor replacement for natural river shore lines. Stewart et al. (2009) provide a thorough review of a wide range of in-stream structures used to increase salmonid abundance and found that the widespread use of such structures is generally not supported by current scientific evidence, especially in large rivers. However, success stories do exist: Knudsen and Dilley (1987) showed that the effects of riprap bank reinforcement on salmonids are clearly negative for small streams (< 1 m^3/s) but overwhelmingly positive for large streams (> 5 m^3/s). Bryant (1983) and Schmetterling et al. (2001) indicate that woody cover provides substantially better habitat conditions over riprap for salmonids over a variety of lifestages. Thus local refugia are more likely to be successful when a combination of riprap and woody debris are used to improve near shore habitat conditions.

Retention basins

Few existing peaking plants have hydropeaking retention basins in place constructed as part of the original design. As a type of mitigation measure, retention basins have the large disadvantage that they must be built decades after the original plants, and thus require far greater amounts of capital investment and land. Ultimately the goal is to provide the necessary alteration of the flow regime to reduce the effects of hydropeaking by raising the base flow and lowering the peak. The practical application of retention basins as viable mitigation is limited by the required storage amount and the ability to find a location which must be located close to the outfall. Basins in Switzerland are currently being investigated at Islas (Inn), Robbia (Poschiavino), and Riddes (Rhone). A thorough example of a proposed project on the Hasliaare is also described by Schweizer et al. (2008). In 1963 the first Swiss retention basin specifically designed for hydropeaking remediation was built as part of the power plant at Linth-Limmern. A comprehensive study of necessary volumes required to fix peak ratios to ecologically acceptable limits on the major Swiss rivers is provided by (VAW and EPFL, 2006). Three further potential locations on the Alpenrhine are at Rothenbrunnen (0.5 Mio. m^3), Ilanz (0.5 Mio. m^3), and Sils (0.6 Mio. m^3), however estimated costs are not included. At maximum build-out, retention basin construction in Swiss rivers is expected to cost 1-1.5 Bio. CHF (Limnex, 2009). In Austria, a retention basin has also been constructed for the powerplant Gerlos/Zillertal with a volume of 25,000 m^3 (Weiss, 2010). The basin is part of the larger 70 Mio. € project increasing the installed capacity from 65 to 200 MW (Verbund, 2005).

Bypasses

Bypass projects involve the water being carried via a pressure pipeline or side channel past the main river and into a second hydropower plant (Fig 2-5). Constructing a bypass is likely by far the most expensive option. However, compared to all other structural or operational mitigation options, it allows for a potential reuse of the water and thus an overall increase of hydropower production. Due to site constraints, the bypass may end in another peaking plant, simply carrying the problems of hydropeaking further downstream. The effect of river confluences may in many cases mitigate the effects of the downstream plant due to a higher base flow, resulting in minimal effects due to the second peaking plant. Currently, the 290 Mio. € Gemeinschaftskraftwerk Inn project at the Swiss-Austrian border (Prutz) is planning to construct a 88 MW peak power plant at the end of 22.8 km bypass. Bypasses are often not considered to be a mitigation measure *per se*, because they are the result of the construction of a new plant, and create residual flow reaches between the plant and the outlet.

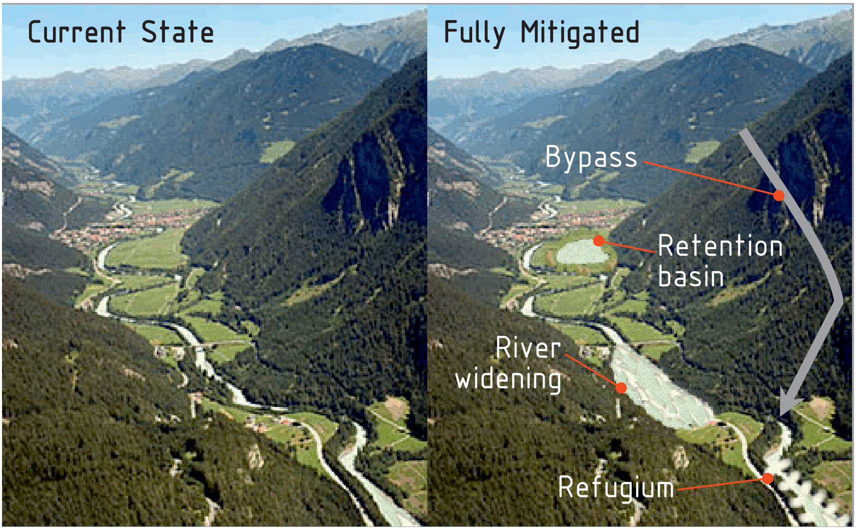


Fig. 2-5 Representation of a typical alpine river landscape with and without structural hydropeaking mitigation. Of all the options, only the bypass does not require modifying the river valley.

2.4 Modeling Hydropeaking Impacts on Fish

In many studies, important parameters are often left out when considering the ecological response such as the change of the wetted area, changes in local flow velocities, and the bed shear stress. Decisions about reach-scale river rehabilitation projects aimed at mitigating hydropeaking require a high predictive capability when considering the possible consequences of project alternatives. To provide such a capability, an integrated model is required which represents the relations between morphological, hydraulic, and ecological effects. Schweizer et al. (2007) break the necessary parts of such a modeling framework into the following categories: (1) channel morphology, (2) flooding, (3) velocity and depth distribution, and (4) riverbed siltation. Here categories 1-3 are explicitly included, and the assumption is made that the effects of erosion and deposition processes during hydropeaking activities can be neglected. Due to the complexity of the system, the model approach chosen should follow the recommendations as laid out by Bras et al. (2003) of a 'good' biophysical model:

- **Use fundamental physical principles, such as conservation of mass and energy.**
- **Depends on a minimal set of parameters having real units that can be defined as observable rates or thresholds.**
- **The model can be confirmed with observations.**

Traditionally the local hydraulic variables depth, velocity, and substrate are considered as the basic measurements and as combined indices in the development of a field known as ‘hydraulic stream ecology’ (Statzner et al., 1988) or more commonly ‘ecohydraulics’ (Newson et al., 1998; Leclerc, 2005). In order to quantify and predict the impacts on river ecology, aquatic habitat simulation tools have established a firm role in water resources management studies. The first available physical habitat model is PHABSIM (Bovee, 1982; Milhous *et al.*, 1989) as a component of the Instream Flow Increment Methodology (IFIM) (Bovee, 1982; Stalnaker, 1995) and was developed in North America in the 1970s. In the 1980s physical and statistical habitat models became an important tool for river management in the US (Bockelmann *et al.*, 2004) and developed concurrently in France (Lamouroux et al., 1998; Mérigoux et al., 2009) in sustainable management of rivers and are currently the focus of ongoing debate and research.

The habitat model CASiMiR (Computer Aided Simulation Model for Instream Flow Requirements) was developed in the 1990s at the Institute of Hydraulic Engineering at the University of Stuttgart. Its principal purpose is the investigation of fish and invertebrate habitats and their response to river discharges using a fuzzy logic based expert knowledge model. Since its inception the modeling platform has expanded to include long-term fish habitat changes in floodplain channels in the Netherlands, the effects of dam operation on physical habitat conditions in Chile. The model has also been applied to the study of the hydropeaking problem in stranding risk studies for both the brown trout and European grayling (Schneider and Noack, 2009; Tuhtan et al., 2010). Although a significant improvement over preference based models, the CASiMiR platform like it predecessors is still entirely based on a combination of best practices and phenomenological studies. Model improvements are being made which allow future versions of the model to include flood plain vegetation growth and morphological analysis.

When investigating the problem of hydropeaking in alpine rivers, it is shown that processes occur at multiple scales, are highly regional and most likely require a mixture of mitigation options. Due to past difficulty restoring rivers with less challenging flow regimes, it becomes clear that a deeper theoretical paradigm is needed to study such complex and dynamic ecosystems. Habitat models are a form of modeling tool which has performed well in the past, but which are severely limited in both predictive capabilities and in the fact that they are inherently a trade off between a purely rational Newtonian physics and the empirical. The following chapters outline a new approach in studying the hydropeaking problem, viewing the alpine river a constantly evolving open, irreversible ecosystem, first viewed from the top down and then from the bottom up. In this way, cross-scale effects can be accounted for, and a modeling framework can be tailored to studying causal relations and ecosystem behavior.

3 Thermodynamics and the Alpine River Ecosystem

Energy is the currency of action. All earth-bound processes continue to develop and energetically shape its components, whether stone or stonefly for a wide spectrum of conditions over some 4.7 billion years. Biochemical processes involve molecular interactions shaped by and derived from our planet's unique and constantly changing conditions. We are evolved chemical systems and our ancestors are the representatives of states past. However we should be careful when reducing the study biophysical systems to knowledge of the individual components alone.

That most ecohydraulics practitioners neglect thermal and chemical pathways when contemplating river ecosystem development is unfortunate since the inclusion of these additional terms provides enormous insight into the much discussed 'biotic-abiotic' relations (Power et al., 1988; Voelz and Ward, 1989; Jackson et al., 2001). The following excerpt from Newson et al. (1998) is a prime example of this regrettable situation:

> *"Ignoring major physical factors such as light and heat (they are relatively conservative and predictable), the components of depth, velocity and substrate will be considered as basic measurements and as combined indices in the development of a field known as 'hydraulic stream ecology', 'ecohydraulics' or 'habitat hydraulics.' Scientific hydraulics has a long history but is still a relatively inexact science under field conditions; whilst the physical laws controlling viscosity, turbulence and other key facts are known, the boundary conditions under which they operate are frequently too complicated for the simplistic assumptions made by practicable models, such as uniform flow."*

It will be shown that the notion of such explicit parameter separation such as light and heat from the velocity and depth may provide comfort to the practicing hydraulic engineer and biologist wishing to work independently, but is from nature's perspective clearly false. Forced cleavage in classifying natural systems, amply found in the literature and applied in practice is far more apt to hinder the development of ecology as a field of science than to help.

This chapter provides a brief introduction to the most important field in all of the natural sciences: thermodynamics. Many are familiar with the progeny of chemical thermodynamics from the popular press: nanotechnology, genetic engineering and biomimetic products are only three of the commonly-cited offshoots of the lessons learned. Many more are undoubtedly on their way. Thermodynamics provides us with the requisite analytical and theoretical tools to study the intricate and interdependent natural systems of our planet, from the Moeraki rock formations of New Zealand to the giant pandas of China. Thermodynamics is the science of energy.

For the engineer, the field of classical equilibrium thermodynamics is a comfortable entry point into the field and is the major focus of this chapter. First a brief review of the fundamentals of equilibrium thermodynamics is included, paying attention to the manifestation of the laws of thermodynamics in an alpine river. The second section introduces the base formulation of an alpine river in terms of its energetics. Section three provides a short introduction to the historically new and powerful thermodynamics of irreversible processes, critical to the observation of the rate-dependent aspects of biological organisms. Rounding out the theoretical background of this work is the presentation of Bauer's principle and the constructal law, which grant powerful insight as to why natural systems appear and react the way that they do.

3.1 Equilibrium Thermodynamics

Thermodynamics and fluid mechanics are the two most important physical sciences when investigating alpine river ecosystems. It is important to note that most hydraulic engineers are exposed to only half of the story – we are told that all of the river's energy and work is external, at the macroscale. This is an unfortunate overstatement and thus an important purview of thermodynamics, the energy at the microscale, is left out of the picture. Since all biological systems are open and we wish to investigate a highly unsteady flowing river system, it will be shown that the fundamentals of equilibrium thermodynamics can in some cases be extended to the irreversible case, offering us a way to investigate time-dependent nonequilibrium processes. This section provides a short overview of the physical laws of thermodynamics and an overview of the quantities which we will need in the biophysical model developed later in this work. Before we begin, an important statement about systems must be made: a system at *thermodynamic equilibrium* implies that *thermal, chemical, and mechanical equilibrium* is achieved, and is an expression of the *global equilibrium* state of the system. The general statement of global thermodynamic equilibrium considers the external and internal energies as well as their interactions. **A system is in equilibrium when neither its state nor its surroundings can evolve over time** (Perrot, 1998).

It should be kept in mind that *no* real system is ever truly at thermodynamic equilibrium. Processes are always abstracted into a world of the infinitely fast or slow, depending on our chosen scales of observation (Ma, 1985). This modern form of sophistic negation via minimization must often be accepted as a necessary evil when applying thermodynamics to natural systems. In this work, the term thermodynamic equilibrium is taken to imply systems which are very close to chemical and mechanical equilibrium (quasi-equilibrium), which may possess small heat flows, and where the time scale dependent temperature can be considered equivalent to the thermodynamic temperature (Cugliandolo et al., 1997).

3.1.1 Types of thermodynamic systems

Isolated

An isolated system represents the most extreme ideal case. Such systems are completely cut off from their surroundings and all processes are strictly internal. The idea of an isolated system is used frequently in the mathematical derivations of thermodynamic systems, however outside of its use as an abstraction, there are no real isolated systems. An isolated system exchanges no heat, work, or mass with its surroundings (Table 3-1). In the alpine river paradigm, no system can be considered to be isolated, *ever*.

Closed

Any system which can exchange energy as work and/or heat across its boundary, but not mass is considered a closed system. Considering the alpine river system, anytime thermal gradients without mass fluxes exist, conductive heat transfer occurs. Examples would include the thermal gradients occurring over the day in the varial zone and in the hyporheos due to conductive heat transfer, resulting from solar radiation and the conductive heat transfer from the bed material to the water body. The magnitude of these processes in an alpine river can be estimated to an acceptable degree of accuracy (+/- 10%) using diurnal changes in temperature occurring on an hourly basis at the reach scale (sub km scale). Heat transfer processes in an alpine river are discussed in further detail in the river energy balance section.

Open

The alpine river as an ecological system is open, and in fact all organisms inhabiting the system are by chemical necessity open systems, exchanging mass (food and waste) with their surroundings. When mass fluxes across the system's boundary are accompanied by work and heat transfer, a full description of the organism's interaction with its environment can be presented. Note that defining the river as an open system only requires that we recognize mass transfer across the boundaries - it says nothing about the *rates* at which this occurs. Thus an alpine river system having a constant flow rate constitutes an open system with a steady mass flow rate. In most engineering texts the energy balance of a river is derived neglecting heat transfer and the work done on its boundaries, e.g. via sediment transport.

Table 3-1 The types of thermodynamic systems classified along with the types of possible interactions with the surroundings.

	Exchange with Surroundings?		
Type of System	*Work*	*Heat*	*Mass*
Isolated	No	No	No
Closed	Yes	Yes	No
Open	Yes	Yes	Yes

3.1.2 The laws of thermodynamics as they apply to alpine river ecosystems

The first law – conservation of energy

The first law is the statement of a universal conservation of energy. It stems from the interest of the time as to how one form of energy - work, can be transformed into another form, heat. The equivalence of these two forms of energy are explicitly stated by Clausius in 1850, and can be found in his 'Mechanical Theory of Heat' (Clausius, 1867; Perrot, 1998):

In all cases where work is produced by heat, a quantity of heat is consumed proportional to the work done; and inversely, by the expenditure of the same amount of work the same quantity of heat may be produced.

The first law is widely applied because of the practicality of considering the variation of energy in the system during any transformation must be equal to the amount of energy which the system receives from the surroundings (Fermi, 1956). This accounting approach is the most beneficial result of applying the first law to engineering and physics problems. If a system is constructed such that no heat transfer occurs across boundaries then the sum of the potential and kinetic (external) energies are a function *only* of the mechanical state of the system. An example in an alpine river would be of a stone at the river bottom having the same temperature as the surrounding fluid, but which can only be set into motion via the mechanical forces of the water. If such a system is at thermodynamic equilibrium, it is thus at a state of mechanical equilibrium. The rock system cannot accelerate because all forces acting on it are in balance with one another, but it may move at constant velocity. Determining the total change in system energy is absolute, it depends only on the comparison of the energy at the initial and final states, A and B of the transformation, not on the way in which the transformation has taken place. In most cases of interest, the quantities of work and heat exchanged *during* the process path are of interest. Because the work done in relation to the total amount of heat exchanged from A to B is *path-dependent,* it is determined by the system's material consituents, configuration, and the resulting useful work needed to overcome reducing imperfections. Making use of the laws of thermodynamics in this biophysical theory of alpine river systems depends on knowing *how* work and heat are exchanged *in relation to* the total change in system energy.

Energy is the ability to do work. To the engineer, the most familiar forms are kinetic, potential, thermal, chemical, electromagnetic, and nuclear. Energy has the further benefit in that its precise mathematical definitions have clear physical implications. Energy can be quantified. If an external force is applied to a body, the energy can be found as the product of the force and the resulting displacement of the body. Work can be used to change the kinetic and potential energy of the system, and even to change its chemical composition. The total energy of a system, minus its (external) macroscopic kinetic and potential energies whether turbulent eddy, fish or rock can be described in terms of its internal energy U :

$$U = E - E_{kinetic} - E_{potential} \tag{3.1}$$

the rate of change of the total system energy dE is given as the sum of the change in energy due to internal processes of the system, $d_i E$ and the change in energy due to its exchange with its environment, $d_e E$ (Jørgensen and Svirezhev, 2004):

$$dE = d_i E + d_e E \tag{3.2}$$

We are now equipped with two powerful equations, the first describing the energy of the system in terms of the individual contributions, the second telling us about the *interaction* between the system with its surroundings (Fig. 3-1). Conceptual aids in determining relevant energy fluxes are found in the three types of thermodynamic systems discussed above. Defining the type of system to investigate provides a convenient level of abstraction as we set out to derive mathematical relations of the energy balance of an alpine river.

The first law constrains our description of the energy balance by further telling us that because energy cannot be created or destroyed, $dE = 0$. This further simplifies our understanding of the rates of energy change in both the system and surroundings. The description of interactions between the system and its surroundings as described in terms of the rates of change of both the path-dependent work done on the system by the surroundings δW , and the heat gained by the system from the environment, δQ . Because heat and work are inexact differentials, their derivatives are often denoted using δ rather than d . It can be seen that a fish by moving its caudal fin does work on the surrounding water by some amount $-\delta W$, and through heat transfer along its gills and via its excrement it loses an amount of heat energy $-\delta Q$. For any real, open thermodynamic system such as an alpine fish+river system, there is no simple relation between the work done and the variation in energy because the exact quantities of energy exchange are constantly fluctuating between the system and its environment as heat transfer, chemical work, work on the fish due to drag in turbulent flow.

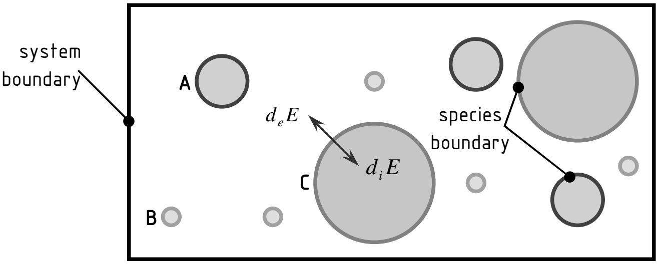


Fig. 3-1 Closed idealized ecosystem containing 3 closed, animate species (A, B, and C) with a total population of 10 individuals. Energy transfer can only occur between the surrounding ecosystem and the individuals embedded in it through an exchange of work and heat, no mass is exchanged in a closed system.

$$d_e E = \delta W + \delta Q \tag{3.3}$$

This allows for transformations of the system to occur while it remains in thermal and/or mechanical contact with the environment. The change of work δW may be larger or smaller in magnitude than the corresponding change of energy of the surroundings, depending on how the system absorbs or releases heat to its environment. Here it is interesting to point out that nature has divided organisms into two groups of thermal control: *poikilotherms* where $T_{org} \approx T_e$ and *homeotherms* where $T_{org} \approx const$. Fish such as the grayling or brown trout are poikilotherms, thus when observing the energy exchange of a fish system over a short time interval, $T_{fish} = T_e$ and thus $\delta Q = 0$. The energetics of a fish over short time spans (minutes) can be estimated by looking at the work exchanged by an approximately adiabatic fish system with its watery surroundings.

We describe the amount of work required to move an animate system to a new equilibrium state, A as equal to the amount of work performed during this transition:

$$U_A = -W \tag{3.4}$$

However, this condition only holds for the case in which we have an ideal or reversible system. In reality the system is riddled with imperfection; roughness and friction at the system boundaries, etc. The effects of these imperfections manifest themselves as unavailable work, or entropy.

The second law – real systems are imperfect and irreversible

Due to system imperfections, there is always a difference between the available work and the lost work, depending on the path chosen by the system as it transforms from A to B. For all real processes the path really does matter, not only because they are inexact differentials, but because there is an underlying physical meaning to path dependence: different paths require differing contributions of entropy and work to get to the same end state. During the transition, some of the energy goes into internal molecular motion. We can imagine this in an alpine river as we start with bed roughness caused by the small stone: due to viscous effects, the flow around the stone generates a small vortex; this vortex stretches as it flows downstream, moving smaller and smaller eddies of water until the last tiny amounts of kinetic energy are transferred as heat to the molecules themselves. When reaching the smallest scale, the scale of molecular motion, it is observed that the molecules themselves are not interacting as perfectly round points. Molecules have internal degrees of freedom: they can rotate, translate, or vibrate. Each of the particle interactions results in some energy being transferred to internal molecular motion instead of contributing to maintaining the mean properties of the bulk (temperature and pressure). Some the energy is used during the transformation from vortex to heat, for example the bulk molecular kinetic energy in the internal degrees of freedom. This portion of the energy is called the entropy. Thus a hot coffee cup never stays hot forever, and as Rudolf Clausius stated in 1879 (Kunz, 1907):

The entropy of the universe is increasing.

Entropy only exists as the conjugate to heat, a result of microscopic interactions, and we are most commonly interested in the study of its manifestation at the macroscale. The entropy of a system changes only in relation to heat transfer. Thus we can measure the temperature change due to chemical reactions and friction, monitor changing heat fluxes across a surface to determine if entropy is produced and how it is transferred. The entropy can be envisaged as the ‘end the line’ energetic quantity.

The third law – establishing a thermodynamic datum

The use of the first two laws allow for useful applications of thermodynamics to systems which are at equilibrium. This means that we need to have well-defined states A and B which are measurable. The first law tells us how to budget the system energy, and that it cannot be created nor destroyed, only changed. The second law tells us that the system configuration and the path chosen as we travel between the two states A and B determines how much work is used to get to the path, and how much work is lost to entropy along the way. However it is still not possible to compare systems against each other effectively because thermodynamic potentials are defined apart from a universal constant. In 1905 Nernst postulated his heat theorem, stating that at sufficiently low temperatures the internal and free energies of reactants undergoing a chemical transformation become equal in magnitude (Barkan, 1999). The third law of thermodynamics is born:

It is impossible to reach absolute zero temperature in a finite number of steps, and the entropy change between system states connected by a reversible process vanishes at absolute zero. Thus at absolute zero matter attains a perfectly ordered state.

The third law thus provides us with a crucial thermodynamic datum. Relating the entropy to the temperature now makes much more sense, as we now see that a value of absolute zero means that the system can no longer increase its entropy. Furthermore, temperature has a real meaning in that it can be used universally when discussing energy at the microscale.

The zeroth law – connecting systems through temperature

The zeroth law allows us to use measurements of temperature of a system in a practical manner. We are able to determine the temperature of systems through equivalence:

If two bodies are in contact with a third body, and if they are in equilibrium with it, then they are also in a thermal equilibrium with each other.

Recall that thermodynamic equilibrium requires that heat is not exchanged between a system and its surroundings. Because many of the biophysical properties of fish, metabolism, respiration, muscle efficiency, dissolved oxygen content, etc. are temperature-dependent, the temperature plays a significant role in developing a thermodynamic theory of alpine ecosystems.

3.1.3 A crash course on entropies – phenomenological vs. statistical

Before continuing on to a more rigorous treatment of the energetics and thermodynamics of alpine rivers and more particularly to fish, it is important to cross a major hurdle which has tripped up many over the years: when we discuss entropy, what *exactly* are we talking about? In this section, a brief introduction to the most common entropies discussed in thermodynamics, accompanied by the exact definition of entropy in this work is presented to avoid confusion.

Thermodynamic entropy is probably one of the most misunderstood and abused concepts in all of the physical sciences. In this work, we define it explicity at the molecular (micro) scale, though other more fundamental definitions do exist:

Entropy is the energy of a system, unavailable to do useful work, trapped in the molecular degrees of freedom.

Clausius entropy – the price of doing work

In his groundbreaking 1857 presentation on 'The Nature of Heat compared to Light and Sound' Clausius laid out the connections between the energetics of heat, light, and sound for the first time. Clausius illustrates heat as a form of energy used by plants and animals alike, related to light, and required for all earth-bound chemical reactions (Clausius, 1857). As mentioned previously in the description of the first law, he also recognized that work and heat are interchangeable quantities, that is, they are both forms of energy. Due to the conservation of energy which had been recognized from both practical experience and observation, they are exactly equal. He noted that:

Work may transform itself into heat, and heat conversely into work, the quantity of the one bearing always a fixed proportion to that of the other.

However, heat and work are not measured using the same scale. Work is calculated using the product of force and distance, whereas the measurement of heat is related to the increase of temperature of a fixed volume of water. Thus Clausius further stated that for practical purposes, heat and work can only be related in proportion to one another, hence his use of the terms *mechanical equivalent of heat*, and the *thermal equivalent of work*.

Joule set out to precisely determine if work and heat are equivalent by measuring the heat generated via friction and comparing it to the work done (Joule, 1850). He did so by spinning a paddle and rubbing cast iron plates inside containers filled with water or mercury and determining the increase in temperature due to the mechanical work performed.

Clausius then used the concept of a *cyclical process* to break down heat transfer into a series of steps. He related the changes of volume of an isothermal system containing an ideal gas to the changes in heat Q_1, Q_2 between two successive volume dilations. He defined heat transfer *to* the system *from* the surroundings as positive, and from the system to the surroundings as negative.

$$Q_{in} = Q_1 = RT_1 \log \frac{V_1}{v_1} \tag{3.5}$$

$$Q_{out} = Q_2 = RT_2 \log \frac{V_2}{v_2} \tag{3.6}$$

Observing the total heat transfer over one reversible cycle (Fig. 3-2) results in the relation:

$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} = 0 \tag{3.7}$$

Clausius shows that this formulation can be extended to more complicated cyclical processes at which heat is exchanged at n number of temperatures:

$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} + \frac{Q_3}{T_3} + \frac{Q_4}{T_4} +,\dots,+ \frac{Q_n}{T_n} = 0 \tag{3.8}$$

Simplifying leads to:

$$\sum \frac{Q}{T} = 0 \tag{3.9}$$

This can be further extended to processes of any type, each broken down into infinitesimally small quadrangular strips (Fig. 3-2), made up each of two adjacent isentropic curves, and two isothermal curves relating in the above formulation but in a the more general integral form:

$$\oint \frac{dQ}{T} = 0 = S \tag{3.10}$$

This formulation in its time provided groundbreaking insight in showing that there is a mathematically tractable description of the processes governing heat engines. Furthermore, Clausius is able to prove that Carnot's observations did indeed provide an upper limit for the extraction of mechanical work from reservoirs at different temperatures, effectively killing the idea of a *perpetuum mobile*. As previously mentioned, heat and work are path-dependent processes which require the use of non-trivial mathematical formulations. As an example, the difference in the internal energy can be expressed in terms of the net change in energy between the two states A and B, where there are many possible combinations of work and heat which could have provided us with the final state. That is, the sum of the individual contributions of heat and work form the *exact differential* of a system's internal energy, dU. Since there is no way to differentiate between heat and work knowing only the change in internal energy, heat and work are *inexact differentials*.

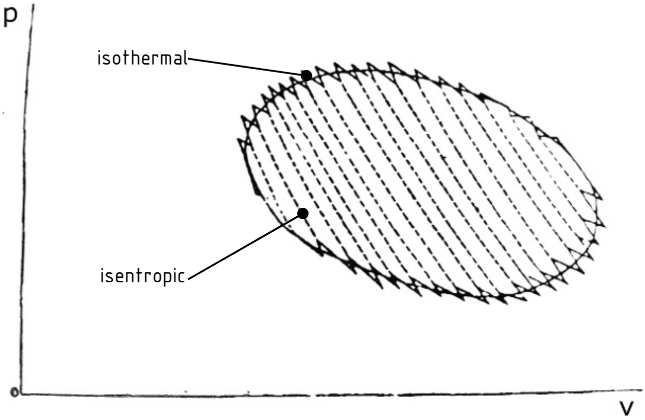


Fig. 3-2 Reproduction of Clausius' original diagram of the cyclical process used to define the concept of entropy. The area of the closed curve represents the total external work consumed. Isentropic curves are shown as dotted lines; isothermal lines are shown in solid, cutting the process curve. Source: Clausius (1867).

Clausius' expression, Eq. (3.9) forms an exact differential and provides us with the definition of a new state function of quantity S, the entropy. More conveniently, the entropy can be written in terms of the heat transferred.

$$dQ = TdS \tag{3.11}$$

Clausius recognized from the experimental works of Joule and others that real processes are not completely reversible; that friction causes heat, air provides resistance, and heat transfer between bodies can never perfectly achieved. He thus revised the reversible statement to recognize that a net sum zero entropy represents the limit or ideal case. Thus the expression for the Clausius entropy is born:

$$-\int \frac{dQ}{T} \geqq 0 \tag{3.12}$$

The Clausius entropy tells us how much energy goes into lost work, that is, how much energy is irreversibly dissipated into the microscale, but manifests itself at the macroscopic scale as lost work. We would like to apply Clausius' formulation, as it is extremely useful in telling us what entropy is, gives a hint at the scale in which it inhabits, and even provides us with a theory of time's arrow. At the same time we would like to know more about the local changes of entropy, especially if we wish to improve the efficiency of our processes by reducing lost work. We need another mathematical definition of entropy, preferably one which can be interpreted at the molecular scale, providing a better idea as to how the entropy of our system is created and finally, how it may be partitioned. This is precisely what Boltzmann set out to do.

Gibbs/Boltzmann entropy – a statistical measure of configuration

In order to get a clear picture of what entropy is, not just *that* it is, it became necessary to more closely investigate Clausius' phenomenological and mathematical descriptions of the entropy. As it turns out, entropy is related to the specific *configuration* of molecules in the system. Due to the huge number of molecules involved and their possible degrees of freedom: translation, rotation, and vibration, configurational entropy is most often only viewed statistically for simple systems such as monotomic gases. As stated by Schrödinger (1989), there is really only one problem to be dealt with in all of statistical thermodynamics: *how to determine the distribution of energy over a large number of particles.* Statistical thermodynamics tell us that an increase in the Clausius entropy is due to the kinetic energy of a huge number of molecules. This increase in entropy is only actualized if the process makes available a larger number of arrangements for the system's energy, providing a final state involving the most probable distribution for that energy under its final conditions (Lambert, 2007).

The probability of each phase space location in classical mechanics corresponds to the positions and momenta of all the molecules in the system. We must recognize that even in a tiny volume of substance, there are an infinite number of states of molecular motion corresponding to a given thermodynamic state (Fermi, 1956). Henri Poincaré went so far as to prove that it is *not possible* to directly calculate the entropy at the microscale even with perfect knowledge of the coordinates, velocities, and masses of all the molecules in a system (Ebeling et al., 1992), effectively slaying Laplace's demon (Ulanowicz, 2009). Thermodynamics relies on the use of the *average ensemble properties* of the macroscopic system where detailed knowledge of the microscale becomes unnecessary.

Planck is actually the first to have used the well-known formulation for entropy $S = k \log W + const$, in his 'The theory of heat radiation' (Planck, 1906). Here we follow the much shorter derivation of the Boltzmann distribution after Glaser (1976) and are thus able to look at the physical meaning of thermodynamic entropy at the microscopic level as we go. It is first important to indicate that the system under investigation consists of discrete components such as atoms, ions, molecules, etc., and that the energy exchange between all components is possible. Furthermore, we allow for the distinction that each element of the system can be sorted by their *finite quantized* energy levels. The thermodynamic probability of a given particle at particular quantized energy levels is:

$$W = \frac{n!}{n_1! \cdot n_2! \cdot n_3! \ldots n_m!} \tag{3.13}$$

and $n! = 1 \cdot 2 \cdot 3 \cdot 4 \cdot \ldots \cdot (n-4) \cdot (n-3) \cdot (n-2) \cdot (n-1) \cdot n$ where n is the particle count and $n_1, n_2, n_3, \ldots, n_m$ are the numbers of particles in each class, and m the total number of classes.

The total system energy can be found by summation over the energies of the individual particles. For a given system with a constant energy having a large number of particles, there becomes an almost infinite number of combinations. Each of the possible configurations is thus given by its thermodynamic probability. In this example, we wish to find the most probable configuration of a given system. Knowledge of this configuration is crucial because the system is subject to stochastic fluctuations. The importance of the fluctuations is that they allow a system to transform from the current state to a more probable one. Hence the universal observance of the second law by a system always involves some type of change, often referred to as 'time's arrow'. *For the case of the ideal, isolated system, the most probable state is the state of thermodynamic equilibrium.* At equilibrium, fluctuations only cause indistinguishable changes in the thermodynamic probability of the system.

Important to understand is that the fluctuations *do not* contribute to a change in system entropy. They are only *statistical fluctuations* at the molecular scale. These fluctuations cause molecular motion and contribute to individual exchange processes between molecules. Thus chemical equilibrium, in which the number of products and reactants is constant, can occur in the presence of such fluctuations.

If we divide up the total amount of energy into the minimum finite amounts, or quanta which are required to enact change in our system, and allow a single quantum of energy in our system to move from one class to another, we see that a molecule must move down from class 2 to class 1, whilst another moves up to class 3. The total energy the system remains constant, but it's thermodynamic probability changes from W to W_1:

$$W = \frac{n!}{(n_1+1)! \cdot (n_2-2)! \cdot (n_3+1)! \cdot n_4! \cdot \cdots \cdot n_m!} \tag{3.14}$$

We can see the change of probabilities as the ratio W_1/W :

$$\frac{W_1}{W} = \frac{n_1! \cdot n_2! \cdot n_3!}{(n_1+1)! \cdot (n_2-2)! \cdot (n_3+1)!} \tag{3.15}$$

Recalling the definition of $n!$ allows for further simplification to:

$$\frac{W_1}{W} = \frac{(n_2-1) \cdot n_2}{(n_1+1) \cdot (n_3+1)} \tag{3.16}$$

If our system is composed of many molecules, it can be assumed that $(n-1) \approx n \approx (n+1)$, further allowing us to simplify the relation to:

$$\frac{W_1}{W} = \frac{{n_2}^2}{n_1 \cdot n_3} \tag{3.17}$$

As mentioned previously, the change in the system's energy due to fluctuations near the equilibrium state are small, so that we can further assume that $W_1 \approx W$ giving:

$$\frac{{n_2}^2}{n_1 \cdot n_3} = 1 \tag{3.18}$$

Expressing the ratios of the number of particles in each of the changed classes leaves:

$$\frac{n_1}{n_2} = \frac{n_2}{n_3} \tag{3.19}$$

If we repeat this excercise again and again, each time choosing a different set of classes in which one quantum of energy is exchanged, we find the general relation holds for any system:

$$\frac{n_1}{n_2}=\frac{n_2}{n_3}=\frac{n_3}{n_4}=\ldots=\frac{n_{m-1}}{n_m} \tag{3.20}$$

This simple but powerful set of relations describes the structural relations of any system in its state of highest probability - its equilibrium state. Graphically this can be expressed as an exponential function. If we wish to calculate the number of molecules as a function of the system energy level, $n(E)$ we use the following relation:

$$n = n_0 e^{-qE} \tag{3.21}$$

where n_0 and q are system-dependent constants. The relation between the numbers of molecules n_i corresponding at energy level E_i to the total number of molecules is provided by the *Boltzmann distribution*:

$$\frac{n_i}{n_{total}}=\frac{e^{-qE_i}}{\sum_{i=0}^{\infty} e^{-qE_i}} \tag{3.22}$$

where $q = 1/kT$. In our case, we wish to know how a change in the system energy from one state to the next ($\Delta E = E_i - E_j$) affects the number of particles in a given energy state.

$$\frac{n_i}{n_j}=e^{\frac{-(E_i-E_j)}{kT}}=e^{-\frac{\Delta E}{kT}} \tag{3.23}$$

The preceding formulation in Eq. (3.23) is exceedingly important. First, it shows from first principles that there *is* an optimal state at thermodynamic equilibrium, and that this state is the *most statistically likely*. Furthermore, it introduces a distinction between the *energy as it is distributed over a given configuration*. We now differentiate between the disordered molecular energy; thermal noise, also known as ‘heat chaos’ and the ‘orderly’ energy which can be used to do useful work. As an example, this relationship exists due to the change in useful energy in the system due to the presence of a changing electrical field ΔE. The quantity $e^{-E_i/kT}$ can be seen as a relative measure of the frequency of occurrence of particles having energy E_i when the system is at thermodynamic equilibrium. We can use this knowledge in order to define the physical basis of entropy in our system.

Taking all molecules in our system together, we form the *canonical ensemble*. Crucial to this definition is also the recognition that this is only correct when the energy of each individual particle has exactly a single state. We can imagine this in the case of an idealized system of perfect spheres which only possess kinetic translational E_{iT}, vibrational E_{iV}, and rotational E_{iR}, energies:

$$E_i = E_{iT} + E_{iV} + E_{iR} \tag{3.24}$$

Unfortunately we come to the conclusion that our system has infinite possible combinations of the given system energy. We do however recognize that there is *only one* most probable outcome at equilibrium. Thus we use the concept of *degenerate* energy levels; that is that at a given energy level, multiple combinations are equally possible. This leaves us with a relation of the relative frequency of occurrence of such degenerate states as:

$$g_i e^{-\frac{E_i}{kT}} \tag{3.25}$$

where g_i is the degeneracy, and corresponds to the number of levels having an energy of exactly E_i. From the degeneracy and the measure of frequency of occurrence, we can update our definition of the partition function as the sum of all possible configurations of our system.

$$Z \equiv \sum_{i=1}^{n} g_i e^{-\frac{E_i}{kT}} \tag{3.26}$$

The partition function tells us that the frequency of a given quantized energy level is not the end of the line. In fact, degeneracy allows for complimentary arrangements on the microscale, further increasing the number of possible combinations of particles at a given energy level. This is a very important finding in quantum theory as it points to the fact that thermodynamic systems can theoretically have more than one equally optimal configuration. Thus at the microscale we need not concern ourselves with a search for the perfect configuration for two reasons: the first is that there may be multiple equally optimal solutions due to degeneracy, the second is that no real system is isolated. All real systems, animate or inanimate will face perturbation, and contain some imperfection. Degeneracy allows for stable systems, even with all the seemingly chaotic motion at the molecular level. It allows the system to remain flexible at equilibrium; a system at equilibrium is still a system in microscopic motion. But the most important quality of degeneracy is that it does not place the requirement on the physicist that all particles are identical, just that the system configuration is energetically equivalent.

The probability of a particle occurring in the energy level E_i including degeneracy is:

$$p_i = \frac{n_i}{n_{tot}} = \frac{g_i e^{-\frac{E_i}{kT}}}{Z} \tag{3.27}$$

Therefore in order to determine the probabilities, we need to have the canonical ensemble to normalize the frequencies of occurrence of each E_i, including degeneracy. Recalling that the total system energy of our particle system can be further broken down into translation, vibration and rotation, we find:

$$E_i \equiv e^{-\frac{1}{kT}(E_{Ti}+E_{Vi}+E_{Ri})} \tag{3.28}$$

and thus:

$$Z = Z_T \cdot Z_V \cdot Z_R \tag{3.29}$$

In any well-defined system, the entropy S is defined as the probability P of the physical system being in a particular state:

$$S = f(P) \tag{3.30}$$

Most commonly, the above formulation is found in statistical mechanics, and is referred to as the *Boltzmann entropy*:

$$S = -k_B \sum_i p_i \ln p_i \tag{3.31}$$

where k_B is the Boltzmann constant, and p_i is the phase space probability of a system being in a given microstate given by the Boltzmann distribution, as previously given. The maximum value of this function occurs when $p_1 = p_2 = p_3,...,= p_n$ that is, when all probabilities are equipartitioned. This can only occur under the assumption that all molecules in the system are acting independently, that is to say that the trajectories and velocities of the particles are not correlated before collisions. When considering an ideal gas system, the Boltzmann entropy is thus found to be identical to the Clausius entropy. It cannot however, be used to calculate the actual entropy of a real, complex condensed matter system as it represents an ideal mathematical case. Schrödinger (1989) however does show that the Gibbs distribution becomes equal to the Boltzmann distribution as the number of equivalent systems goes to infinity.

The nature of the partition function tells us something more than Clausius' phenomenological approach to entropy. In determining the partition function, we see that we must account for the individual contributions of the quantum energy levels of the different types of energies. As it turns out, the translational energy is some 16 orders of magnitude smaller than the thermal energy at room temperature ($18^{\circ}C$) needed for a 'quantum leap' to occur. The rotational energy of a molecule is some 400 energy levels below the thermal energy (energy relative to absolute zero), and the vibrational energy is just about twice the thermal energy (Glaser, 1976). Thus it is clear that the molecular modes have very different contributions to the total internal energy of a system. In such a case it is useful to define the degrees of freedom (DOF) of a system as the number of independent coordinates relative to a fixed reference needed to fully describe a particle. A simple monoatomic ideal gas particle has only 3 DOF (translational x,y,z), and a diatomic molecule has 5 DOF (2 rotational, 3 translational). More complicated molecules, such as the huge macromolecules found in biological systems generally do not have straightforward geometric methods for deriving the exact DOF, and instead depend on statistical representations of their geometries. As an example, an entire database has been developed for protein researchers alone (Berkholz et al., 2009). In all real physical systems the total energy is the sum of the translational, vibrational, rotational, and ground state energy of the particle, plus the energy due to electric excitations. The entropy of statistical mechanics tells us three new things about the entropy which Clausius' phenomenological entropy could not:

1. **Entropy is manifested at the molecular scale and is related to microscopic configuration**
2. **The molecular configuration changes because the probability of a given state increases**
3. **The entropy of a particular configuration is the energy of the system which is 'busy' inside the molecular DOF and which cannot be used for work**

This tells us that if we wish to lower the entropy of a system, we must allow for an exchange of energy or mass with the surroundings. For this to occur, we need systems which are at least closed and exchange energy or better yet, open and allow the exchange of both energy and mass. From the second law, we know the only way this can be accomplished is by incorporating flows of energy and mass into the system such that it can replace the entropy generated in the system with lower entropy inputs (Bailey, 1990).

All spontaneous processes occur with a corresponding decrease in free energy as they are driven towards the equilibrium state. Thus any real system will manifest a configuration depending on molecular interactions leading to the most probable configuration. We will see in the next section why we needed such a precise understanding of the entropy, and why it is so important in the context of our energetic balance in the Alpine river.

3.2 Energy Balance of an Alpine River

In a purely mechanical system such as an alpine river, an incremental external work δW performed during a transformation is equal to minus the variation in the internal energy δU. Following Tribus (1961) we begin first by investigating the energy balance of a closed system

$$d_i E = \delta W + \delta Q \tag{3.32}$$

where $\delta Q, \delta W$ and dE are the incremental contributions of heat added to, work done by, and the increase in energy of the closed system over the time interval dt. The time rate of change of system energy over a finite interval can be given as the difference in energy at $t_0 + dt$ and t_0. Important to keep in mind is that the changes in work and heat transfer are inexact differentials, denoted by δ. That is work and heat transfer processes are inherently path-dependent, whereas the change in total system energy is not.

Extending this principle to the open flowing river system requires the addition of the mass flux. For convenience, the specific energy, e_{tot} or energy per unit mass of the system is used. If dm_i is the change in the mass flowing into the system and dm_o is the mass flowing out:

$$-de = e_{tot,o} dm_o - e_{tot,i} dm_i \tag{3.33}$$

This total specific energy can be considered as two parts:

> *External* – energy associated with the motion and position of the center of gravity with respect to the fixed reference frame. Here it is further broken down into the separate contributions from the kinetic energy $mv^2/2$ and the gravitational potential energy mgz.
>
> *Internal* – energy of the particles in the system themselves.

The internal energy is the part of the energy of the system which depends only on its microscopic parameters and is the energy of interest from the viewpoint of thermodynamics. The change in internal energy by a system during a transformation is the sum of the energies exchanged with its surroundings excluding effects due to external forces (Perrot, 1998), and can be expressed as:

$$dU = \sum X_j dx_j \tag{3.34}$$

The relative contributions can further be broken down as:

$$dU = T\left(dS - d\sigma\right) + \Gamma d\wp - PdV + \sum \mu_i dn_i + \ldots \tag{3.35}$$

$T\left(dS - d\sigma\right)$ is the heat quantity dQ, $\Gamma d\wp$ is the work of surface tension, $-PdV$ is the work of pressure forces, and $\sum \mu_i dn_i$ is the work related to the change in amount of chemical species i.

The internal energy can also be expressed in terms of the entropy produced by irreversibility:

$$dU = -Td\sigma + \sum X_j dx_j \tag{3.36}$$

Where from the second law:

$$dS = \frac{dQ}{T} + d\sigma \tag{3.37}$$

$d\sigma$ is the system internal *entropy production* due to irreversibility of the transformation process. A formulation of the above expression more commonly found in the literature on environmental thermodynamics (Jørgensen et al., 1992) is:

$$dS = d_e S + d_i S \tag{3.38}$$

where $d_e S = d\,Q/T$ is the familiar flux term previously described by Clausius, accounting for the reversible external exchange of entropy due to heat exchange by the system with its surroundings. $d_i S = d\sigma > 0$ is therefore the *internal* contribution to the change, a source term describing the net entropy creation relative to the universe at large. The entropy content of the system can be seen as the contributions which can be exchanged reversibly with the surroundings (Fig. 3-3), and the local irreversible generation. The field of entropy generation minimization first developed by Bejan (1996a) is used extensively in both chemical and mechanical engineering for a wide variety of complex engineering problems, but likely due to its deep roots in thermodynamics has not found resonance in the field of civil engineering, where system energy balances are often simplified as being purely external (macroscopic potential and kinetic energies).

For the river system, the external energy in form of the potential and kinetic energy terms are very familiar macroscopic forms of energy to the hydraulic engineer. The *internal energy* however is not usually considered in river hydraulics. It represents the sum of microscopic energies in the form of molecular rotation, vibration, translation and interactions between molecules. In this work it will be shown that although often neglected, the consideration of the internal, molecular energies of the individual system components (e.g. fish) is required if we are to begin to view entire river ecosystems and not just the energetics of the water flowing through them. Here the view is taken that the biotic or animate matter in the system can be modeled as a proxy or equivalent degenerate system component. Such components persist inside the system by decreasing the available free energy, and can change their internal system configuration in response to external forcing from their environment.

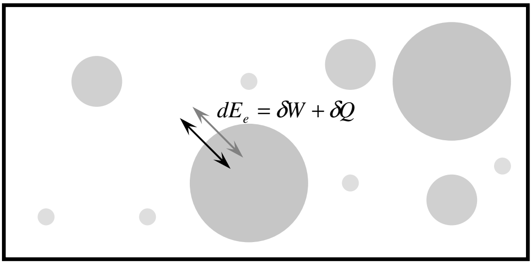


Fig. 3-3 Closed ecosystem with 3 species of open organisms. Each species is an open system and exchanges work, heat and mass with its surroundings. Note that mass fluxes can also be part of chemical reactions such as feeding, waste excretion, etc.

Rewriting the expression for a theoretical open, reversible river system whose energy balance is broken down in terms of its microscopic energies, heat and work, and macroscopic potential and kinetic energies gives:

$$\delta Q - \delta W_s - \delta W_{\exp,i} - \delta W_{\exp,o} = \dot{m}_o \left(e_o + gz + \frac{v_o^{\ 2}}{2g} \right) - \dot{m}_i \left(e_i + gz + \frac{v_i^{\ 2}}{2g} \right) \tag{3.39}$$

Although this formulation leaves a relatively simple energy balance equation, we shall see that most of the terms are *highly coupled*. Furthermore, this formulation only considers the river water, and does not include terms describing the mass flow of chemical components, or the energetic contributions of reactions.

The equation can be used to describe a hydropeaking wave, its driving feature as the change in the mass flow rate. The waves cause a local expansion of the river's control volume. A portion of this energy is stored as pressure-volume work in the surrounding air. Other portions of the energy are transformed into heat due to friction at the river bed and in the water column due to turbulence. Energy is also transferred as work done on the moving sediment. In most civil engineering texts, this coupling complexity is ignored and the energy equation is simplified by removing all terms with the exception of the average cross-sectional velocity and gravitational components. Mays (2001) also provides a similar thermodynamically based derivation for open channel flow.

3.2.1 Heat transfer in an alpine river

The water temperature is a critical ecological parameter in mountain streams (Vannote and Sweeney, 1980), and is affected by a multitude of factors (Fig. 3-4). Temperature affects growth, metabolism, reproduction, emergence, and species distribution (Wieser, 1973). In alpine rivers, flow resistance in steep streams with step-pool morphology is due to both form drag and skin friction (Lee and Ferguson, 2002). Due to lower average flow depths, mountain streams tend to be highly sensitive to changes in their energy fluxes (Table 3-2) as compared to their lowland counterparts. Viscous shear in alpine rivers is the driving factor in thermal gradients (Meier et al., 2003).

Table 3-2 Comparison of Calculated Energy Fluxes in summer for three streams.

Energy fluxes W/m²	**Meier et al. (2003)**	**Evans et al. (1998)**	**Sinokrot & Stefan** (1993)
Short-wave radiation	221	525	76
Long-wave radiation	-25	-109	-63
Heat exchange with sediment	-48	-49	12
Evaporation	-37	-75	-18
Convection	48	2	-5
Dissipation	52	1	-
Sum	211	22	2

Following Evans et al. (1998) the mechanical dissipation of energy which is converted into heat can be estimated for rivers can be simply expressed as:

$$Q_{diss} = \rho g S_0 \frac{Q}{w} \tag{3.40}$$

where Q_{diss} is the heat flux per unit surface area of the river, ρ is the density of the water, g is the gravitational constant, S_0 is the average slope of the river bed, Q is the volumetric flow rate of the river, and w is the wetted perimeter. This quantity can vary substantially. For alpine rivers, Meier et al. (2003) found that for rivers which had slopes steeper than 5 to 10%, viscous dissipation *is the dominant heat source*. If the stream is shaded, or solar radiation is found to be small, the dissipation can also dominate in rivers with more gradual slopes. In alpine rivers, they also derived the following equation converting the potential energy of the water ($mg\Delta h$) into heat ($mc_p\Delta T$). It can be used to estimate the temperature increase, ΔT due to dissipation from the simple difference in bed elevation Δh:

$$\frac{\Delta T}{\Delta h} = \frac{g}{c_P} = \frac{0.235^\circ C}{100m} \tag{3.41}$$

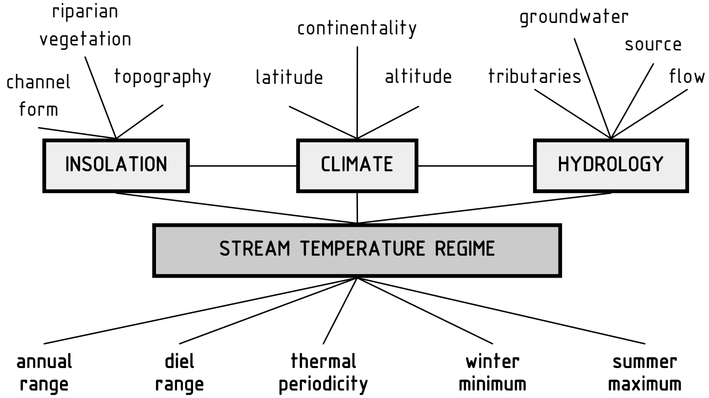


Fig. 3-4 Major factors determining the temperature regime of a natural stream. After Ward (1985).

The natural heat fluxes which drive water temperature in alpine rivers are solar radiation, energy exchange with the atmosphere, heat exchange with the stream bed, heat influxes from tributaries, internal generation, and groundwater in- and exfiltration. An excellent overview of an entire river's heat balance by BUND (2009) has been performed on the river Rhine. However, because temperature gauging stations are often not available, statistical models correlating the local air temperature to the river water temperature are used (Stefan and Preud'homme, 1993). In cases when knowledge of specific physical forcing and heat exchange processes are important, deterministic models are required because they can effectively quantify the relative contributions of the individual heat fluxes (Caissie et al., 2007).

In some cases it may be advantageous to account for additional heat transfer terms describing the groundwater-surface water heat transfer, as well as diurnal temperature fluctuations caused by solar radiation, shading from an overhanging tree canopy, etc. We also assume that during the time period under investigation, the river system is in thermal contact with its environment at constant temperature T throughout. This is not unreasonable, since temporal fluctuations between the river substrate and the air-water interface (Fig. 3-5) are typically of a larger time scale. The heat balance equation of is simplified as:

$$\delta q_R = q_o - q_i + q_{\text{int}} \tag{3.42}$$

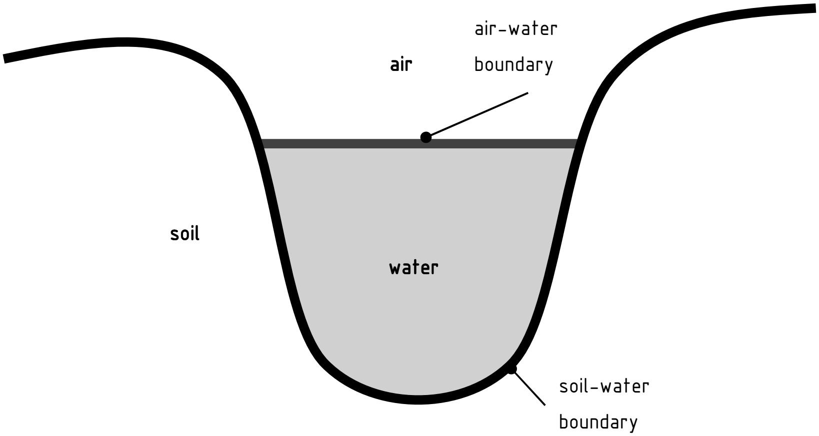


Fig. 3-5 Cross sectional view of an alpine river section showing the system boundaries.

where δq_R is the change in the specific heat flux of the river, q_O, q_i are the heat flows out and into the river, respectively, and q_{int} is the contribution of heat due to internal changes in the river such as groundwater interactions, viscous dissipation, etc. Because the focus of this work is on the effects of hydropeaking, we can only investigate the local hydraulics on relatively short river sections (< 250 m), and over time intervals of minutes. In this range of length and temporal scales it is therefore reasonable to use the gauging data as the only temperature gradient in the system and assume that the difference between the in and outflow of heat, as well as the internal heat production is balanced over the temporal and spatial scales considered. However, *local* heat exchange is still possible.

$$dQ_R = m\delta q_R \approx 0 \tag{3.43}$$

Hydro power operations affect the water temperature both directly and indirectly. In the case of peak energy production it is called 'thermopeaking' (Zolezzi et al., 2010). An example of the Swiss case can be found in the investigations of Frutiger (2004) on the Ticino. There it is found that hydropower operations resulted in much less annual variation in water temperature than in the natural case, where the effects of cold hypolimnetic releases could clearly be seen. Because the potential energy is transformed into electricity, water temperature in rivers with hydro operations differ from those without discharges, and can be warmer or colder. Minimum flow reaches downstream of hydro installations tend to have a larger heat exchange due to increased surface to volume ratios. This can result in a net increase of summer temperatures, and a decrease in the winter (Meier et al., 2003).

It is also important to recognize that all real systems are subject to nonlinearities. In cases where the heat capacity and thermal conductivity are temperature dependent, where large changes in temperature due to surface radiation occur, or when the boundary conditions rapidly vary (e.g. melting or freezing ice in the river), heat transfer processes can no longer be considered with simple linear relations (Biot, 1970).

3.2.2 Work done by an alpine river

From the standard definition of work as the product of force and time, we can see that determining the work done by a river on its surroundings must involve forces and displacements along its boundary. Because the work done by shear at the air-water interface is small relative to the boundary shear at the bed, we neglect its contribution in this work and define the work done by an alpine river only in terms of the work performed on the sediment and internally by the working fluid itself. The work done by an alpine river outside of hydraulics is not always obvious to the hydraulic engineer, but several studies have shown the importance of considering inanimate-animate process coupling when studying river ecosystem development.

Sediment transport is also strongly affected by the presence of vegetation (Lopez 1997), and the presence of flow sediment biota relations is also gaining in interest (Osmundson 2002) and it is noted for instance, that Salmon redds can significantly impact the insitu character of the bed sediment distributions (Gottesfeld 2004). Moore et al. (2007) show that salmon can control on a river scale the flow of nutrients and matter via physical modification of their habitat. Such findings have spawned ecological theories such as the subsidy hypothesis, and have indicated how aquatic and terrestrial ecosystems are interrelated via emerging aquatic insects. Thus even fast-flowing alpine rivers are not subject to upper and lower boundaries of the river bed and water surface, and must be considered as a sort of leaky control volume in our model estimates.

The forces acting on an ideal spherical particle at the river bed of an open river channel can be expressed in terms of the hydrodynamic drag acting on it (Yang, 2003):

$$F_D = C_D \frac{\pi d^2}{4} \frac{\rho}{2} V_d{}^2 \tag{3.44}$$

where C_d is the drag coefficient at velocity V_d, ρ is the density of water, and d is the distance above the river bed. Because the number of particles is far too high to calculate force balances for all individual particles, a vast number of phenomenological studies have been undertaken in the field of sediment transport to determine estimates of incipient motion (Buffington and Montgomery, 1997), fluvial geomorphology (Stott, 2010), and transport (Turowski et al., 2010).

The rate of energy dissipation in a river can be expressed in terms of the stresses acting on a fluid element (in a numerical model this would correspond to one volume element). Over each element the specific rate of work done or power, is the product of the velocity component with the gradient of the stresses acting on it (Julien, 2010):

$$w = v_x\left[\frac{\partial \sigma_x}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}\right]+v_y\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \sigma_y}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}\right]+v_x\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \sigma_z}{\partial z}\right] \tag{3.45}$$

This formulation can be simplified for incompressible Newtonian liquids to include viscous dissipation in terms of (I) the linear $\partial v/\partial x$ and (II) angular deformation Θ:

$$w = \underbrace{2\mu_m\left[\left(\frac{\partial v_x}{\partial x}\right)^2+\left(\frac{\partial v_y}{\partial y}\right)^2+\left(\frac{\partial v_z}{\partial z}\right)^2\right]}_{I}+\underbrace{\mu_m\left[\Theta_x^2+\Theta_y^2+\Theta_z^2\right]}_{II} \tag{3.46}$$

In order to succinctly illustrate how sediment transport can be considered as work in the alpine river paradigm, we follow the minimum dissipation approach after Yang and Song (1986). Taking uniform flow in an alluvial channel with velocity V ,water depth h, and channel width w, the continuity equation can be written as:

$$Q = whV \tag{3.47}$$

The bed material concentration can be expressed as a function of the velocity V , slope of the energy grade line S , the water depth h , median sieve diameter of sediment particles d , the kinematic viscosity ν , and terminal fall velocity ω:

$$C_t = f(V,S,h,d,\nu,\omega) \tag{3.48}$$

The theory of the minimum rate of energy dissipation states that when the river reaches its dynamic equilibrium (steady, uniform flow conditions) the rate of energy dissipation (entropy generation) is at a minimum. This minimum depends on the flow configuration (boundary conditions). For the simple case of uniform flow where dissipation between particles is neglected, the rate of dissipation per unit weight of water is equal to the unit stream power:

$$\frac{dY}{dt}=\frac{dx}{dt}\frac{dY}{dx}=VS \tag{3.49}$$

where Y is the potential energy per unit weight of water. The above formulation shows that a river in dynamic equilibrium does work on its surroundings at a minimal rate corresponding to the movement of particles at the water-sediment interface. In this work, in order to keep the evaluation of the river model at a reduced level of complexity, we will consider the river bed to be immobile (the energy balance for sediment transport is a stationary state). However, there is no theoretical problem including the work done by the river on the sediment, including local entropy production due to adiabatic viscous dissipation. Such a formulation can be input into the energy equation, Eq. (3-39) as a term for work done on the surroundings W_s.

Following the thermodynamic principle of minimum energy expenditure (entropy generation minimization), it is proposed that the spatial organization of river basins follow basic physical principles. This theory links energy dissipation, the three dimensional imperfections of the landscape, and the spatial organization of drainage networks. There is much empirical evidence to support this theory, such as Horton's laws, the spatial distribution of river reach lengths, and the fractal properties of drainage networks. Networks which drain a given watershed with minimum total energy expenditure are called optimal channel networks (OCN).

Alpine rivers can be seen as a particular class of OCN, where bed slopes are higher and mean water temperatures are lower than in lowland rivers. Leopold and Maddock's (1953) paper revealed that simple power law relations can be used to transfer the average properties of highly variable local hydraulic characteristics (width, depth, velocity, suspended sediment load and discharge) to reach-scale measures of a river's hydraulic geometry. This work is followed up by Leopold and Langbein's (1962) publication 'The Concept of Entropy in Landscape Evolution' in which a more general recognition that dissipative processes both on the local and global scale are driving factors in determining river morphology. Bagnold's (1966) work on dissipation in rivers, and Yang's (1986) theory of minimum rate of energy dissipation are now used in conjunction with the unit stream power concept to successfully model sediment transport. More recently, works on the watershed scale have recognized that entire river basins themselves can be viewed as OCN (Ijjász-Vásquez et al., 1993) under the following three assumptions:

1) **the network minimizes the energy expenditure in each reach**
2) **the rate of energy dissipation per unit area of channel bed is equal throughout the network**
3) **there is a minimum energy expenditure in the network as a whole**

Following these assumptions, Ibbitt (1997) and others (Molnár and Ramírez, 1998; Gurnell et al., 2009; Chanson, 2011) have shown that minimizing the energy dissipation in a river holds both on the watershed scale, and can be used in the design of optimal hydraulic structures themselves. It has been shown that the effect of imperfections in the landscape forced the network to rearrange and correct energy intensive defects, and that unstable landscapes moved quickly to lower levels of energy when perturbed (Ijjász-Vásquez et al., 1993). Thus practitioners of river hydraulics have had considerable experience in the application of dissipative concepts stemming from thermodynamics, which over the last four decades have found functional use both on the regional and local scales.

Sediment transport is also strongly affected by the presence of vegetation (Lopez 1997), and the presence of flow sediment biota relations is also gaining in interest (Osmundson 2002) and it hs been noted for instance, that the Salmon redds can significantly impact the bed sediment distributions (Gottesfeld 2004). Furthermore, Moore et al. (2007) show that salmon can control the flow of nutrients and matter via physical modification of their habitat on a river scale. Such findings have spawned ecological theories such as the subsidy hypothesis, and have indicated how aquatic and terrestrial ecosystems are interrelated, e.g. via emerging aquatic insects. Thus even fast-flowing alpine rivers are not subject to truly fixed boundaries at the river bed and water surface, but must be considered as a sort of leaky control volume in our model estimates.

3.2.3 Free energy balance of an alpine river

The energy transformations at the river's boundary can be shown to have definite terms for both the heat transfer and work. Furthermore, the energy balance equation is formulated using the traditional focus on the external energies (kinetic and potential). However, in order to estimate the effects of hydropeaking on the organisms within the river control volume, we need a formulation which allows us to differentiate between internal processes as well. For this we need a description of the free energy.

Of great importance in any physical study is the concept of free energy. Energy is the ability to do work, however not all work is equal in it's usefulness to a particular animate system or process. Depending on the perspective of utility, energy has a hierarchy. The Helmholtz free energy F is the standard thermodynamic potential describing the difference between the qualities and quantities of energy in a given system and is a metric of the total amount of a system's useful, available free energy. It is defined as:

$$F \equiv E - TS \tag{3.50}$$

However, it is standard practice that the effects of macroscopic, bulk energy and the effects of external fields are removed from the definition of the Helmholtz free energy resulting in the expression:

$$F \equiv U - TS \tag{3.51}$$

where U is the system's internal energy at temperature T and entropy, S.

The Helmholtz free energy is most commonly applied when operating at constant temperature T and volume V and determines when a process is spontaneous. Such processes can only occur if the net effect is to reduce the system's free energy. If a system's free energy is already at the minimum, its entropy (Table 3-3) is at the maximum, and *no spontaneous change can occur* (Nelson et al., 2008). All chemical processes use the currency of free energy, *not* the total energy to get reactions moving. Bioenergetic models using empirical formulations of metabolic 'energy' as a generic metric (Cuenco et al., 1985; Elliott et al., 1995; Hayes et al., 2000) often overlook the decisive factor in determining the amount of *useful* energy which the animate system has access to: the decrease in its free energy.

Table 3-3 Comparison of the amount of energy versus the corresponding entropy given off for a range of universal processes. Source: Haynie (2008).

Form of energy	Entropy produced per unit energy used
Nuclear reactions	10^{-6}
Internal heat of stars	10^{-3}
Sunlight	1
Chemical reactions	1-10
Terrestrial waste heat	10-100

The expression of the rate of change of Helmholtz free energy can be expressed for any system as:

$$dF = dU - TdS - SdT \tag{3.52}$$

As an example, if an alpine fish is observed as a constant volume system on a time scale small enough such that it is not affected by temperature or pressure fluctuations due to interactions with its surroundings, then we may write the expression of the change in the isothermal fish system's free energy as:

$$(dF)_{T,V} = dU - TdS \tag{3.53}$$

Recalling that the fish is poikilothermic, (neglecting heat exchange with the surrounding water), we can approximate of the rate of change of internal energy being only dependent on the work done: $dU \approx -dW$.

The net change in internal energy of the fish can be expresses as the work done on the surrounding water plus the increase in entropy:

$$-(dF)_{T,V} = dW + TdS \tag{3.54}$$

Thus the total reversible work performed by the isothermal fish system at constant pressure and volume can be seen to be equal to the decrease of the fish's free energy. The next chapter will show the general validity of this formulation through empirical studies, and provide more insight as to the conditions under which this expression is truly representative of the alpine fish energetics.

When a system evolves from one well-defined initial state to another, we can use a second description of the free energy of our system, the Gibbs free energy, ΔG. This difference is equal to the work exchanged by the system with its surroundings minus the work done by pressure forces during a reversible transformation of the system from identical initial and final states (Perrot, 1998). G is the most widely used thermodynamic potential because it removes the boundary work done by changes in pressure and volume from the free energy calculation, and most commonly assumes an isothermal process.

$$G = U - TS + PV \tag{3.55}$$

Under conditions of constant temperature and pressure, which are valid on the small time scales (meters and minutes) we wish to observe, the expression can be written as a rate equation following the fundamental Gibbs relation:

$$(dG)_{T,P} = dU - TdS - PdV \tag{3.56}$$

The sign and magnitude of G can tell us something about the environment as a whole. From basic thermodynamics, we know that if $G < 0$ the reaction is spontaneous (or 'natural'), if $G = 0$ the system is in equilibrium, and if $G > 0$ we need to put energy into the system in order to force the reaction to occur ('unnatural'). Ecosystems which are devoid of 'life' (chemical evolution) will either be at equilibrium, or have positive values of G. By strict definition, an organism at equilibrium is 'dead' (no longer capable of chemical evolution).

The second advantage of using G is that from an ecosystems perspective, it gives us an idea of which factors are driving the system under observation through the interplay of enthalpy and entropy terms. Systems with high enthalpies can have a large amount of heat transfer, chemical potential, and/or work done by the organism on the surroundings. Essentially, high enthalpy systems have either a large amount of internal energy, of pressure-volume work done, or both. Earth-bound processes tend in the former category, since most living creatures are not large enough to enact large changes to the ambient pressure surrounding them. Systems which are highly entropic however, tend to spread or dissipate the energy throughout different levels of the ecosystem on a much wider scale, and may also have high levels of mechanical (adiabatic) energy dissipation as they move matter from one location to another. In the following chapter we will derive the theoretical local entropy production rates using a combination of the river's external energy balance and the concept of internal energy.

3.3 Irreversible Thermodynamics

Although the principles of equilibrium ('ideal systems') thermodynamics are well known and considered standard fare in any engineering curriculum, the updated and exceedingly more useful principles of irreversible ('real systems') thermodynamics have remained the purview of a small number of specialists in heat transfer, process engineering, biochemistry and applied physics. It is the hope of the author that the flexibility and high practicality of irreversible thermodynamics begin to extend further into the fields of engineering and ecology. It is worth noting that limnologists are some of the first in the wider scientific community to apply thermodynamic principles to aquatic ecosystems, but today few practitioners of their original ideas remain. Notable exceptions are Bauer, Mauersberger, Ebeling, Glaser, Gladyshev, Ulanowicz, Bejan and Thims who have done much to further the field through their research efforts showcasing the thermodynamic nature of all systems, inanimate or animate.

An important consideration in the use of irreversible thermodynamics is the concept of the stationary state. The **stationary state** of a thermodynamic system occurs when irreversible processes are proceeding at a constant rate such that the macroscopic parameters, including the entropy of the system, remain constant over time (Zotin, 1990). Thus unlike the thermostatic approach used in equilibrium thermodynamic, irreversible thermodynamics allows the introduction of time as a variable (Kjelstrup et al., 2006). This allows for the formulation of entropy production in the system, compensated by an outflow of entropy:

$$\frac{dS}{dt} = \frac{d_eS}{dt} + \frac{d_iS}{dt} = 0 \tag{3.57}$$

and for the stationary state the entropy production is compensated by the entropy flow:

$$\frac{dS_i}{dt} = -\frac{d_eS}{dt} \tag{3.58}$$

This concept of the stationary state is not a trivial one. Prigogine and Glansdorf (1965) recognized the concept of a local equilibrium based on Boltzmann and Einstein's work on the probabilities of microscopic fluctuations. They related local potentials to non-equilibrium fluctuations of macroscopic quantities near equilibrium. Furthermore, systems are described as either being beholden to the laws governing *individual events,* as described by classical mechanics, or those laws dealing with *average values.*

Irreversible thermodynamics describes transport processes in systems which are not at global equilibrium (Kjelstrup et al. 2006). The field resulted from the efforts of a large number of scientists searching for a formulation of the second law which would function when investigating non-equilibrium systems. The field began in 1856 by Thomson's studies of thermoelectricity, followed by Onsager's 1931 formulation of reciprocity relations (for which we won the 1968 Nobel Prize in chemistry) and made popular in the physics community due to Prigogine's 1973 award of the Nobel Prize for his work on describing dissipative structures. The study of entropy generation in thermomechanical and biological systems under non-equilibrium conditions has also resulted in Bejan's general statement of the constructal law, contributing design to thermodynamic systems (Bejan, 1997).

3.3.1 Onsager reciprocity relations

Key to understanding the difference between ideal and irreversible thermodynamic processes is the reformulation of the second law in terms of local entropy production. Onsager (1931a, 1931b) showed that the entropy production of the system is given by the sum product of conjugate fluxes, J_i and thermodynamic forces, X_i. Entropy is the result of imperfection in the flow system and can be thought of as the product of "across" (e.g. pressure, temperature, concentration, voltage) and corresponding "through" (e.g. mass flow, heat, molar flux, current) variables. The rate dependent expression of the second law can be written as:

$$\dot{\sigma} = \sum_i J_i X_i \geq 0 \tag{3.59}$$

and each flux is taken as a linear combination of all forces:

$$J_i = \sum_i L_{ij} X_j \tag{3.60}$$

Assumming microscopic reversibility (time symmetry) Onsager proved the relations:

$$L_{ji} = L_{ij} \tag{3.61}$$

The meaning of the Onsager relations can be summed up as the following general statement:

Energy exchanges in irreversible systems close to equilibrium are linearly related, where the relations may change over time and in their proportions, depending on the system configuration.

Note that due to the requirement that the system is close to equilibrium, strict linearity cannot always be assumed. However, there exist ways of keeping the linearity of the reciprocity relations mathematically whilst including some nonlinearity. As an example Pagonabarraga et al. (1997) view chemical reactions as a diffusion process through an energy barrier in order to keep the linear law relating the local reaction rate and a fictive gradient of the chemical potential acting as the thermodynamic force in the internal space. Difficulties in applying irreversible thermodynamics also surface when the scales of study become so small that the notion of the thermodynamic limit may no longer apply. Reguera and Rubi (2001) also provide an interesting example by showing how problems can arise when it becomes necessary to determine the translational-rotational degrees of freedom in their study of nucleation phenomena.

3.3.2 Conjugate variables – describing thermodynamic forces and fluxes

The energy of a Newtonian particle can be described in terms of the force F and an infinitesimal motion produced by that force, dl. Similarly the mechanical energy due to volume dilation is equal to the pressure P and the infinitesimal change in volume dV. Note that the combinations (Table 3-4) are in terms of an intensive thermodynamic property (force, pressure, temperature, chemical potential, charge potential, etc.) and a corresponding extensive property (distance, volume, entropy, number of molecules, electric current, etc.).

Table 3-4 Conjugate intensive and extensive variables.

Intensive variable	**Extensive variable**	**Energy**	**Formula**
Pressure	Volume	Pressure-volume work	pdV
Temperature	Entropy	Internal work	TdS
Chemical potential	Particle number	Species transfer work	μdN
Force	Length	Elongation/contraction work	fdL
Electromotive force	Charge	Electrical work	εdZ
Gravitational potential	Mass	Gravitational work	$mgdH$
Surface tension	Surface area	Surface work	γdA

3.3.3 Local entropy generation of irreversible systems

There are three possibilities of the system entropy balance:

$$\begin{aligned}
&\frac{dS}{dt}=\frac{d_eS}{dt}+\frac{d_iS}{dt}>0\\
&\frac{dS}{dt}=\frac{d_eS}{dt}+\frac{d_iS}{dt}<0\\
&\frac{dS}{dt}=\frac{d_eS}{dt}+\frac{d_iS}{dt}=0
\end{aligned}\tag{3.62}$$

The only case in which the total entropy can decrease is the second. Only this second case fulfils the criteria, thus in order for a system to decrease its entropy, it must be associated with a greater flux of entropy out of the system then into it. All animate systems must be open or at least non-isolated (Jørgensen and Svirezhev, 2004). Investigating the stationary case for the internal energy balance and the entropy balance sets the rate of change of internal energy to that exchanged with the surroundings (Ebeling et al., 1992):

$$\frac{dU}{dt} = \frac{d_eU}{dt} = -\frac{d_iU}{dt} = 0 \tag{3.63}$$

The same balance is reached for the entropy flux:

$$\frac{dS}{dt} = \frac{d_eS}{dt} = -\frac{d_iS}{dt} = 0 \tag{3.64}$$

In our system, processes of interest occur under isobaric and isothermal conditions over the scales of interest. In this semi-idealized case, the internal entropy generation can be described as being driven by a decrease in the Gibbs free energy of the surroundings:

$$\frac{d_eG}{dt} = -T\frac{d_iS}{dt} < 0 \tag{3.65}$$

We can see that Boltzmann (1925), Schrödinger (1956), Ostwald (1996) and many others have therefore been correct in stating: *life cannot exist without the input of free energy.*

3.4 The Thermodynamics of Animate Systems

3.4.1 Energetics of biophysical systems

This chapter has thus far shown that all physical systems act according to the first and second laws, which fix and decrease the overall ability of incoming energy, establishing new energy gradients and thus disequilibrium. This is accomplished by increasing throughput and degrading the useful, free energy content of the mass and energy flows through the system. Considering earth-bound processes, the largest ecosystem consists of the earth+Sun system (Fig. 3-7). The overall thermodynamic direction of evolution is to dissipate and degrade energy quality flowing through the system. This free energy reduction is accomplished via the development of evolving, nature-designed structures. The cornerstone of this thermodynamic theory of the animate is to view these systems as evolving solutions to the thermodynamic problem of increasing the effective degradation of the incoming solar energy while persisting in a changing and often unpredictable environment.

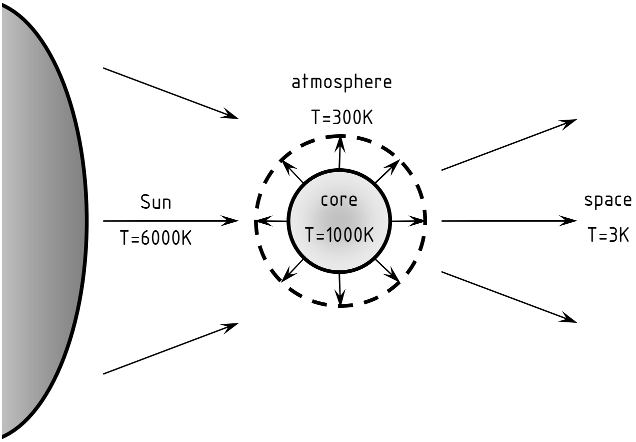


Fig. 3-6 The earth as a closed thermodynamic system. After Ebeling et al. (1992).

We view this as the development of systems (biochemical factories) which are joined together in a supersystem (ecosystem). The supersystem degrades the incoming energy by producing and then breaking down molecular structures. These biochemical factories (Fig. 3-8) have four common traits: self-construction and death, reproduction, evolution, and adaptation. Ecosystems at steady states synthesize biological compounds (anabolism) at rates which are in balance with their decomposition (catabolism) (Jørgensen and Svirezhev, 2004). In mature ecosystems, developing over long periods of growth and decay, energy tends to flow whereas matter tends to cycle (Morowitz, 1979).

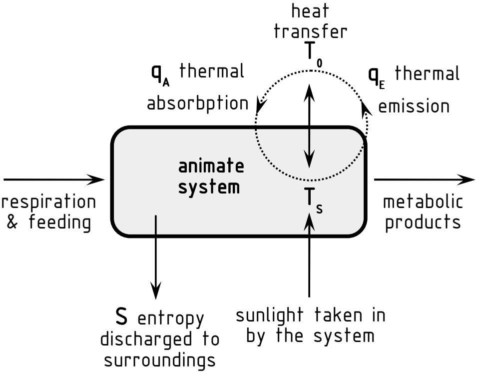


Fig. 3-7 The organism as an animate thermodynamic system. After Ebeling et al. (1992).

Let us for a moment consider a sort of biochemical soup of the kind investigated by Miller, and include the influence of the Sun, which is constantly bombarding the soup with solar energy (Miller and Urey, 1959). Following up, we find that the second law predicts the emergence of microscopic “chemical factories” in this primordial soup (Wicken, 1978, 1980). However, this is a wholly earth-centered view of these processes. The beginning of this process, if it can be stated as such, began at the time the universe first came into existence. Such factories would degrade the high-quality solar energy of the soup, creating structure along the way. Such degradation would be accomplished along a thermodynamically determined hierarchy of complexity, where low level unstable molecules are energetically bootstrapped using primarily solar energy to form new higher level, stable supramolecular substances, structures, and eventually entire organisms (Gladyshev, 1997). The formations of these new molecules degrade the available potential (free) energy by transforming it on the microscopic level into bond, translational, and vibrational energies, manifested at the macroscopic level as waste heat. A magnificent variety of natural (in terms of Gibbs free energy) processes and molecular forms should then emerge, and the larger their number, the more degraded the incoming solar energy becomes. On a chart of ‘ecosystem inhabitants’, this exhibits itself as species diversity in the vertical and species richness horizontally (Schneider and Sagan, 2006).

The stored potential energy of the primary producers can be further degraded if accessible to other chemical factories, which then use them to fuel even more production of molecules of growing complexity. Simple chains develop into vast works of systems, each feeding on the stored potential energy of another system. They themselves emerge over time into larger networks of chains. The characteristic of these chains is that they degrade as much of the incoming energy as possible per unit production of complex molecules. On the scale of microorganisms, such autocatalytic reactions can be found which echo the concept that energy flows and matter cycles, an excellent example being the Krebs cycle taking place in the matrix of the mitochondria (Campbell and Farrell, 2006). Thus the chemical reactions in animate systems often use self-reproducing cyclic systems, e.g. the Calvin cycle to synthesize carbohydrates from carbon dioxide, and the Krebs cycle which oxidizes organic compounds to carbon dioxide, releasing energy (Gánti, 2003). Fundamentally, such complex reactions form energetic pathways along which electrons are exchanged via an electron and hydrogen translocation system. Electron transport systems in mitochondria are chemiosmotically coupled to reversible ATPase systems in biological membranes which serve to separate two aqueous phases, the matrix and intermembrane spaces (Mitchell, 1961). The cell membrane is only one type of biochemical system boundary, separating the animate system from its inanimate surroundings.

The macroscopic manifestation of relations between animate autocatalytic cycles is well-known in aquatic ecology, and is referred to as the trophic web. More commonly, the transfer of chemical energy from the source in plants through a series of organisms with repeated stages of eating and being eaten is known as the food chain. In complex natural communities, organisms whose food is obtained from plants (heterotrophs) by the same numbers of steps are said to belong to the same trophic level. Green plants (autotrophs) occupy the first trophic level, herbivores the second. Trophic specification is one of function, not of species; as given species may occupy multiple trophic levels according to the sources of energy (Ulanowicz, 2000). Each transfer of energy from one organism to the next results in a part of the energy being degraded into heat. The shorter the chain, or the closer in proximity the organism is to its beginning, the greater the available food energy (Chhatwal, 1988).

Due to the phenomenological nature of ecology, considerable effort has been undertaken in the study of energy fluxes through individual biological and ecological systems (Schneider and Kay, 1994a; Jørgensen and Svirezhev, 2004; Haynie, 2008; Nelson et al., 2008; Jørgensen, 2009). There is no reason to expect the emergence of only a few simple chains, made up of energy degraders and chemical decomposers. Rather, the systems are interconnected in a complex food web. The path length and cycling rate are used to gain effective measures of an ecosystem's energy flow. Looking at the range of sizes of studied ecosystems is alone a monumental task. As an example, the total number of pathways from primary producer to predator in one coral reef in the Virgin Islands is estimated to be larger than 107,000 (Christensen et al., 1993). Schoener (1989) also provides conclusive evidence that the maximum chain length (maximum number of pathways between basal prey and top predator) is directly related to ecosystem constraints. Sterner and Elser (2002) further used the concept of ecological stoichiometry to define specific material constraints to interacting biological systems, greatly limiting the combinations of chemical elements and their interactions. The precise bonding between atoms means that elements must occur in fixed proportions in biological substances, whereas the hallmark of the inanimate world can be viewed as stoichiometric variability. The fundamental work done by Sterner and Elser provides conclusive evidence that all biological systems have consistent stoichiometric patterns of chemical formation. Investigations of consumer versus resource stoichiometry may therefore improve predictions of mathematical models wishing to more clearly define food webs, at least in terms of their mass balances. But we still need to include energy in the overall ecological picture.

Kooijman (2000) rewrote the mass fluxes of biological systems into comparable energy terms in the development of the dynamic energy budget (DEB) theory. DEB aims to quantify the energetics of individual organisms as they develop over their life history (Nisbet et al., 2000). Key processes are feeding, digestion, storage, maintenance, growth, development, reproduction and aging. Kooijman also provided a useful thermodynamic definition of homeostasis: "The term homeostasis is used to indicate the ability of most organisms to keep the chemical composition of their body constant, despite changes in the chemical composition of the environment, including their food." The strength of invoking homeostasis in ecology can thus be seen as a resistance to fluctuations in the mass balance of the food web. In this work, alpine fish are viewed as organisms from the Sterner and Elser point of view:

> **"…organisms are what they first eat but then do not digest, egest, defecate, excrete, lactate, exhale, or otherwise release back to the external world."**

We will see that the active regulation of matter and energy within the ecological system as a whole (top), and at the level of the individual organism (bottom) is an important thermodynamic characteristic when considering the persistence of an alpine river species under hydropeaking conditions.

Studies of the physiochemical and energetic properties of biological organisms are far from new. In the seventeenth century, R. Boyle, R. Hooke and J. Mayow are some of the first scientists to relate respiration to combustion. In 1779 A. Crawford, and A. L. Lavoisier made the first measurements of animal heat production, and in 1780 P. S. Laplace is the first to relate heat production to oxygen consumption and the production of carbon dioxide (Kooijman, 2000). To this day the metabolic rate of animals, including that of fish is measured as their oxygen consumption rate (Bejan and Lorente, 2011). Thus ‘the fire of life’ is indeed real, but only from a chemical perspective.

3.4.2 The Bauer principle

The previous sections of this chapter have laid out a concise overview of the thermodynamics required in the study of alpine rivers. Integral to the question surrounding the effects of hydropeaking on fish habitats is a conceptual separation of the animate and the inanimate. In order to distinguish between the two, it is necessary to invoke the Bauer principle of biology (Grandpierre, 2011), one of the first known works applying the thermodynamics of Gibbs to animate systems (Bauer, 1920). The principle states:

> **“The living and only the living systems are never in equilibrium, and, on the debit of their free energy, they continuously invest work against the realization of the equilibrium which should occur within the given outer conditions on the basis of the physical and chemical laws**.” (Bauer, 1935)

Before continuing we must first recognize the fundamental importance of this statement, as it provides the *only* known description of biological, animate systems which can be considered as *universally valid*. Secondly, we wish to remark that the notion of ‘living-nonliving’ in this work is taken only to reflect levels of evolution when comparing physical systems, thus rock and fish systems are recognized according to a more contemporary scientific viewpoint as inanimate and inanimate systems, respectively.

Bauer’s principle states that biological systems must be open and exist in a state of unstable dynamic equilibrium. These animate systems possess configuration; chemical and physiological structures which allow them to resist the pull of equilibrium. Maintenance of the unbalanced state in open systems is only possible at the expense of creating flows of matter and energy. Through these interactions the system and surroundings, as well as regulation through internal processes are indelibly coupled (Bauer, 1928; Bauer and Tschukitschewa, 1930; Korotkov et al., 2004).

As an example, it is shown in Fig. (3-8) what would happen if we are to throw a bird and a rock from the tower of Pisa. The rock, falling to the ground would come to equilibrium in a predictable, Newtonian manner. Invoking the second law, we could further increase the accuracy of our calculations by including the effects of the air molecule's drag due to friction on the rock during its fall, and its inevitable inelastic collision with the ground. The bird however, presents a bit of a problem. We see that the bird, as an animate system following Bauer is predicted to resist equilibrium, it simply flies away. Furthermore, we do not have a simple physical law which tells us how fast, how far, or in which direction the bird is going to fly once it is released. But we do recognize that the bird is made of the same atomic constituents as the rock, it is also a subject of nature's laws, and it too must be going to equilibrium. Thus by focusing on *how* the bird goes to equilibrium, we find that it is functionally different as to *how* a rock does.

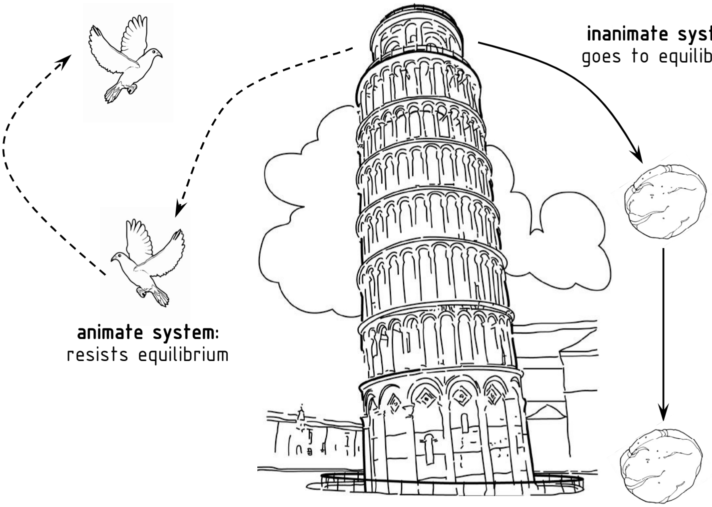


Fig. 3-8 Graphical depiction of the Bauer principle: animate systems are those whose internal flow configurations allow them to *resist* equilibrium, whereas inanimate systems possess forms which are *incapable of resisting* equilibrium. Both systems are however subject to equilibrium as an attractor.

Looking at the entropy balance of a given system as a function of time, we see that the entropy generation is expressed as the sum of the entropy exchanged with the environment and the internal entropy production (Jørgensen, 2008). Recalling that at equilibrium, $dS/dt = 0$ and is a maximum. We also recall that all spontaneous processes occur at the expense of free energy. Energy exchange in animate systems result in energy returned to the environment in a less useful state then when it was consumed (Haynie, 2008). The formulation of Eq. (3.62) points out that the total rate of entropy change of the system can be positive or negative depending on the relative contributions of the changes in interaction entropy, d_eS and the internal entropy, d_iS. Following the second law for finite, irreversible systems we know that the total entropy of the universal ecosystem can only increase (Myrvold, 2011). Thus at least one of the terms on the right side must always be larger and more positive than the other. Taking the alpine fish system example, we find that all internal processes relying on spontaneous chemical reactions (respiration, digestion, muscle contraction, sensory systems, reproduction, etc.) occurring must do so at the expense of changes in the system's Gibbs free energy (Tytler and Calow, 1985; Jobling, 1994; Perry and Tufts, 1998). Thus the internal entropy of the fish must be increasing as a result. In order for the fish to retard the onset of equilibrium (death), it must expel high-entropy waste and take in new, low-entropy chemical compounds whose free energy can be used for catabolic and anabolic reactions allowing it to persist (Fig. 1-10). All animate systems are open thermodynamic flow systems which depend on their interactions with the surroundings. There are no 'fish out of water.'

The above formulation is simple but provides deep meaning when we consider that the evolution of animate systems and their flow architecture provides a goal and competing interests: The Bauer principle tells us that the persistence of the system (its immediate goal is not to die) depends on its ability to repel equilibrium. At the same time, the animate system is pulled towards equilibrium by generating entropy. Entropy is generated in either its interactions with its surroundings, or by internal regulatory processes. The fact that the interactions are coupled points out an invaluable piece of knowledge: there can be no separation in the study of animate-inanimate interactions, as the evolution of all animate systems is a result of balancing persistence with participation. The result is the animate system's design pattern, rhythm, form, morphology, structure: its flow architecture.

3.5 The Constructal Law and Flow Architecture

The law of stable equilibrium is way to describe the sum total of the laws of thermodynamics in their entirety (Schaefer, 1997; Perrot, 1998):

A constrained system, evolving in such a way that the surroundings remain unmodified, can reach one and only one state of stable equilibrium.

Accompanying this law is a series of six corollaries, where a rigorous and complete discussion of the law can be found in Hatsopoulos and Keenan (1965). It can be shown that the four laws of thermodynamics together can be viewed as a coupling of the system's constraints with the properties of the matter (for biological organisms, their stoichiometry) which make up the system itself. However, in the alpine river paradigm considerations of irreversibility and openness are a must. We require a formulation which allows for a more robust description of our river system under the vast array of flowing, fluctuating, and heterogeneous constraints imposed upon it.

It can be seen that an individual investigation reach of an alpine river ecosystem is just a part of the larger flowing watershed system. Conversely, each organism in the river can be also be viewed as a component of the larger reach system, just as we view the neuron in the brain, an eddy in a turbulent river, or a leaf on the branch of a tree. Nature fills systems with components in a myriad of reoccurring patterns of shape, structure, configuration, rhythm, and similarity (Bejan and Merkx, 2007). That the flow architecture of blood vessels and river basins are so similar in shape and form is no coincidence. The constructal law as formulated by Bejan and Lorente (2006) explains why:

For a finite-size flow system to persist in time (to live), its configurations must change in time such that it provides easier and easier access to its currents.

When considering the constructal law for systems which contain both animate and inanimate subsystems, the general statement of Bejan and Lorente is rephrased by Tuhtan (2011) to clarify the constructal law from the point of view of the animate system:

Persistence comes at the cost of participation.

The four laws of thermodynamics are powerful tools which have lead to great insight into the behavior of physical systems. However, the first and second laws discuss only a black box. The use of constructal theory allows us to look at the direction of development of the flow configuration of our system, be it the Earth or an alpine river (Fig. 3-9). Because these systems have developed and evolved over billions or millions of years, we can never gain a perfect abstraction, but we can guess where it is going. The constructal law tells us to focus on a simple but powerful concept: that equilibrium flow architectures can develop when all possibilities of increasing morphing freedom are exhausted (Bejan and Merkx, 2007). This architecture is a result of the system striving to optimally distribute system imperfections.

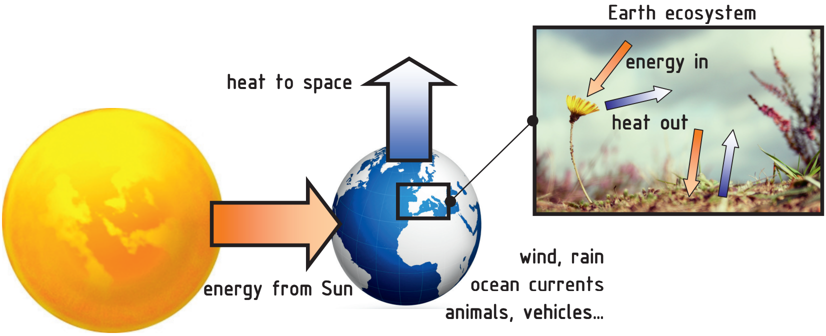


Fig. 3-9 The earth as a constructal flow system. The system contains innumerable tiny 'heat engines', e.g. the flower, soil, etc., interacting with large-scale phenomenon such as wind currents, and also provide energy and matter for additional levels of hierarchy, e.g. animals and machines. After Bejan and Lorente (2011).

The constructal law plays a significant role by explaining why we can view the fish in an alpine system from both the top-down and from the bottom-up: from the perspective of the river's energy balance, the individual fish can be seen as a mere energetic component, a sort of idealized chemical lump. At the same time from the bottom-up, we see the fish now as a complex and slender form gliding between vortices induced by the local flow patterns resulting from a single boulder. The fish as a component must continue to be optimized, to evolve, if it is to persist. This is huge clue as to why the fish is streamlined, and not a cube, why it is poikilothermic and not homoeothermic, and most importantly why we can use the laws of thermodynamics in conjunction with the constructal law to determine the importance of local and global entropy production to anticipate what the fish should do next. The next chapter provides the theoretical framework of fish in alpine rivers, and discusses the difficulties, implications and potential uses of irreversible thermodynamics in improving the study of the hydropeaking problem.

This chapter has provided an overview of the necessary physical properties required to form an improved 'second law' conceptual model for alpine rivers. First it is shown that the river must be considered as an open system, one in which both heat and work are exchanged. Next, the concept of irreversibility and entropy is presented where it is found that the entropy represents the amount of energy in the system which cannot be used to do work, manifested as disorder on the microscale. It is then shown that the entire earth ecosystem is fundamentally based off of the degradation of energy gradients from the Sun, where this can be conceptually scaled to an individual river using a combination of the Bauer principle and constructal theory. The Bauer principle states that any animate systems in our river require non-equilibrium conditions to persist, and the construcal law states that the configuration of these systems (e.g. their position in the river) ultimately determines their ability to persist (to live). Thus in order to improve our modeling capabilities, we must consider both the irreversibility in the river both as an integral part of our modeling the energy quality of the system, and keep in mind that the location and configuration of animate systems have a role to play in the overall evolution of the ecosystem itself.

4 Irreversible Aquatic Ecosystem Models

The fields of thermodynamics, biochemistry and biophysics have evolved to aid in explaining the seemingly unending intricacy of natural systems. Indeed, 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 universal insight is that physical systems cannot differentiate between the animate and the inanimate when it comes to finding the most direct route subject to global constraints (Bejan and Merkx, 2007). Furthermore, a point which is often left out when treating animate systems as autocatalytic networks (Gánti, 2003) is that nearly all of the catalysts used by organisms are themselves products of the organism themselves (Stelling et al., 2002; Cornish-Bowden and Cárdenas, 2008). Compounding these issues is the fact that all biological systems must be open in order to survive (Jørgensen and Svirezhev, 2004), where the development of a mathematical model to describe an ideal deterministic coupling between the living system and its non-living surroundings is an impossible task (Ulanowicz, 2004). Organisms are relational biological systems whose existence is dependent on a deep functional interactivity with their inanimate surroundings; they are fundamentally not machines (Mikulecky, 2000). There are no ‘fish out of water’ (Tuhtan, 2011).

The alpine fish cannot be considered isolated from the surrounding ecosystem because its presence is synonymous with a state of the global flow architecture. The aim of the river, like that of all flow systems is to minimize and allocate imperfections in the system under the given finite-size, finite-time constraints (Bejan and Lorente, 2006). This energy dissipation is primarily mechanical occurring due to viscous shear, a function of a river’s flow rate and bed morphology (Meier et al., 2003). We find that fish are seen as *possible* components of the river ecosystem whose natural utility is measured by their ability to increase the ecosystem’s access to currents. Deterministic models of living systems are not possible because complex systems contain by definition, nonsimuable models (Mikulecky, 2001). The participation of a given fish species is dependent on a specific range of system configurations, because their ability to persist at any given location in the river is limited by their evolved physiological constraints. It is no coincidence that fish are svelte.

Stressed ecosystems, such as an alpine river subjected to hydropeaking can be expected to become more open, where internal cycling is reduced (Odum, 1985). The job of a fish in the river ecosystem is to provide greater access to the energy and mass currents that flow through it. Utilization of energy sources in the food web, the transduction of free energy, occurs via feeding, metabolism, and reproduction all whilst striving to lower the global flow resistance of the river (Fig 4-1). All systems, whether animate or inanimate can be viewed in the constructal paradigm as a type of engine with a brake (Lorente and Bejan, 2010):

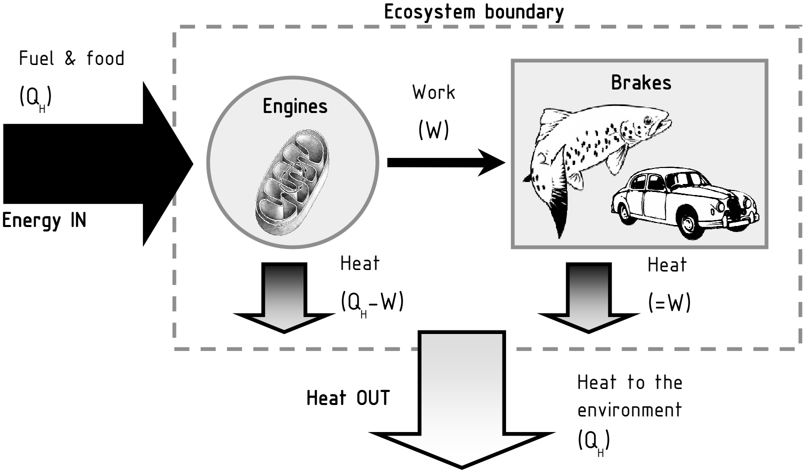


Fig. 4-1 Diagram of the "engine+brake" concept used in constructal theory to describe the balancing act between power generated from the engines (e.g. mitochondria and muscles) and dissipation from the brakes (e.g. energetic losses due to the motion of animals and machines). Regardless of the system type, animate or inanimate, high-quality free energy is always transduced into low-quality heat. After Lorente and Bejan (2010).

According to constructal theory and theoretical biology, "fish+river" systems are continuously and mutually evolving, albeit at varying rates and over periods of time which we cannot explicitly model. In improving our limited modeling capability, we should focus on methods which allow improved estimation of the fish's anticipated response to hydropeaking events in terms of its interaction with the *local* flow field, while keeping the *global* constructal view of the river as a flow system and the engine+brake concept in mind. In order to better understand animate systems, emphasis needs to shift away from rigid, Newtonian notions towards a focus on the description of processes (Ulanowicz, 2009). This chapter provides two thermodynamic viewpoints of the alpine river ecosystem: the first is a view of the entire aquatic ecosystem from the top-down; the second considers only a single fish, from the bottom-up. The chapter concludes as the locational entropy principle is presented, providing the theoretical basis for the hydropeaking model.

4.1 Top-Down: An Irreversible aquatic ecosystem

Any attempt in developing a thorough ecosystem model must obey the second law of thermodynamics (Mauersberger, 1979; Schneider and Kay, 1994b). Fundamentally, the second law provides us with only the direction of a process, but our study of finite time, finite size irreversible systems require that we also investigate the *rates* at which these processes occur. The use of irreversible thermodynamics assumes that the second law remains valid locally, and introduces functional relations which we can use for rate estimation (Kjelstrup et al., 2006). Although second law causality gives direction to time's arrow (Fig. 4-2), they do not point ever downwards to particle physics, but rather to a networked mutualistic system, the food web. This mutualism in conjunction with natural selection manifests itself as the result of environmental forcing and organism evolution via genetics (Ulanowicz, 2009). The addition of entropy into our modeling framework allows for a semi-causal, top-down description of this mutualism (food web) by including terms describing the interplay between both internal and external energies (environmental forcing). This leads to a complete expression of irreversible physical, chemical, and biological processes in the river ecosystem.

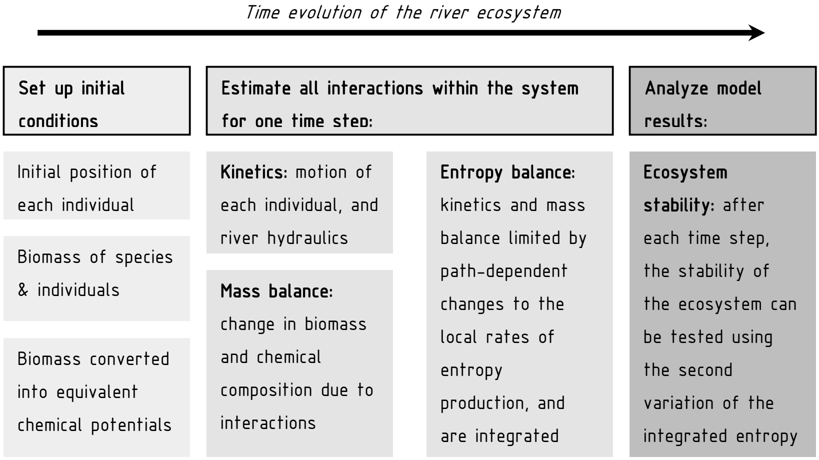


Fig. 4-2 Model framework of the top-down approach.

In developing our top-down thermodynamic model of aquatic ecosystems, we follow the original works of Mauersberger et al. (1978, 1979, 1982a, 1982b, 1987; 1987; 1991, 1996), Ebeling and Feistel (1981; 1992), as well as more recent works by Jørgensen et al. (1992, 1999, 2000; 1999; 2004; 2008, 2009). The original formulations and adaptations have since evolved into a top-down, 'eco-exergy' formulation (Jørgensen and Svirezhev, 2004). A full description of these works is far too involved to be presented in its entirety here, as it ranges from the ecosystem response to external environmental forcing to aspects of cybernetics and genetics. Instead, what we endeavour to do is to distill the basic ideas of the top-down approach into a simplified formulation, appropriate for the investigation scale of an alpine river reach. The focus here is on the relevant processes needed for the study of hydropeaking phenomenon. We then critically review its applicability to the investigation of hydropeaking on alpine fish.

4.1.1 Stability Criteria

Mitigating the hydropeaking problem for fish requires establishing stable (homeostatic) conditions, and subsequently the stationary state needs to be defined even if stability can only occur locally. Accordingly, we need to define ecologically relevant stability criteria which can be assessed, preferably using one or more of the hydropeaking indicators presented in the second chapter. We must consider that small fluctuations in space or time of hydraulic, chemical and biological parameters can give rise to a transition of the ecosystem to a new stationary state, or bifurcation. The effects of hydropeaking, though most pronounced on the large scale (daily hydrograph) can be best viewed as the sum of local phenomena from a resident species' point of view. The hydropeaking surges are the *driver* of *local* changes. The sum of these local unsteady effects may cause a shift in the global state and or flow configuration of the ecosystem as a whole. As shown in Fig. (4-3), all ecosystems proceed through a succession of state transitions from one stationary state to another (Vannote et al., 1980); the question in the hydropeaking case is whether or not these transitions create new states which preclude the participation of fish in the ecosystem. Stability criteria play an important role in the investigation of aquatic ecosystems (Mandal et al., 2006). However, we must remain vigilant in distinguishing between biological, mathematical, and numerical stability (Mauersberger, 1979).

An example of ecosystem development in terms of predator-prey relations and population development is shown in Fig. (4-3). The vertical axis indicates the number of prey in the ecosystem (prey population) as a response to its interaction with a predator. Horizontally the stage of development over time is shown. Within the fixed physical constraints of a given ecosystem (size, nutrients, rate of growth etc.) we can first capture all possible development in terms of upper and lower bounds. Due to the finite constraints, in this case the total population of the prey (x-axis) levels out after some critical developmental stage has been reached. This can be seen in the flattening of both the lower and upper bounds. During ecosystem development, and depending on intial conditions, there are a multitude of possible trajectories within the lower and upper bounded regions. An example trajectory of a prey population inside our fictive ecosystem is shown, with two regions in which the population has remained stable during ecosystem development. For an alpine river, we can imagine such a scenario as that presented in Fig. (4-3) when we consider the mitigation of a river reach, where over time the population stabilizes within some bounds but remains even at the lower bound significantly higher than before mitigation has taken place (the graph's origin).

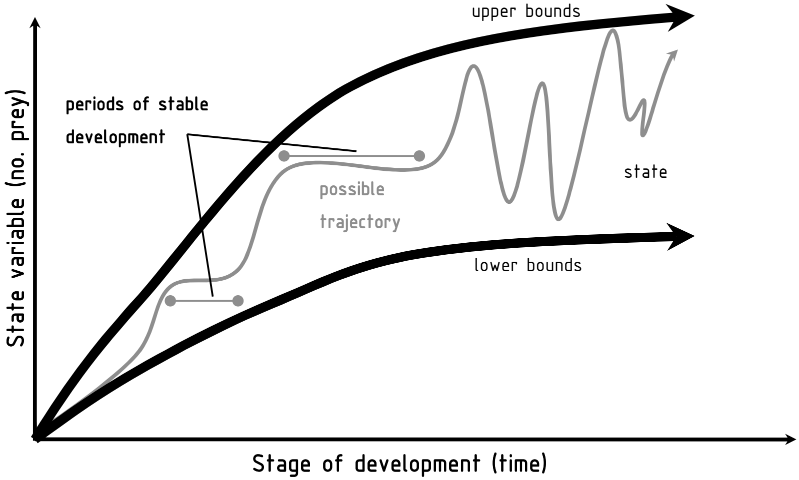


Fig. 4-3 A generalized model of development trends of ecological state variables (e.g. population), considering stability and an attractor (e.g. number of prey). Uncertainty and instability direct the system toward a range of possible states. After Jørgensen and Müller (2000).

In this work, estimates of the local entropy of the ecosystem serve as the indicator of stability, the product of irreversible processes. In both the top-down and bottom-up approaches, the stability estimate of the local entropy production σ is calculated in a single volume element $\forall$:

$$\delta^2 \sigma_{\forall} = \sum \delta \mathrm{J} \delta \mathrm{X} \tag{4.1}$$

where $\delta^2\sigma$ is the *second-order variation* of the specific entropy and $\delta \mathrm{J} = \mathrm{J} - \mathrm{J}^*$ and $\delta \mathrm{X} = \mathrm{X} - \mathrm{X}^*$ are the *variations of excess* thermodynamic fluxes and forces from a stationary reference state denoted by *, respectively. In the case of hydropeaking, it immediately becomes clear why the use of entropy as the stability criteria is invaluable: as a result of the combination of the forces and fluxes, it provides a single indicator of an otherwise intractable system. Stability of the whole river reach can be estimated by integrating the local variations over the water body (Mauersberger, 1987):

$$\int_V \delta^2 \sigma_{\forall} dV \tag{4.2}$$

There is a mathematical upper limit as to the degree of abstraction which can be taken in models using the top-down approach. Studies of the mathematical roots of population dynamics are investigated by May (2001), where it can be seen that with increasing system complexity, the characteristic equation determining stability increases in degree, and the greater the probability of an instability at a given stationary state. Further compounding the problem is that even at a specific level of resolution, for the top-down model the addition of a single new parameter may cause the previous stationary solution to become unstable. Such problems would arise when applying the top-down approach to the behavior of the river ecosystem after the introduction of a new species, in estimating climate change scenarios, or the effects of hydropeaking after a long period of stable flows.

4.1.2 The organism as an equivalent chemical potential

Here we recall that the strict definition of any thermodynamic potential must follows Gibbs' original statement: if we add an infinitesimal quantity of any substance to our system mass, leaving its state (gas, liquid, solid, plasma) intact, and not inducing any change in the system entropy or modifying its volume, the increase of energy divided by the quantity of the substance added is the potential of that substance in the system mass considered. The **chemical potential** can thus be defined in terms of the change in internal energy at constant entropy, volume, without contraction work, charge transport, or a change in the mole number of all other n_j substances than the substance i in question (Gibbs, 1906):

$$\mu_i = \left(\frac{\partial U}{\partial n_i} \right)_{S,V,l,q,n_j} \tag{4.3}$$

This definition of the chemical potential also applies to substances in an open system. Here it is applied to represent the potential of an animate species participating in the alpine river ecosystem (Fig. 4-4). The chemical potential is an intensive variable with the characteristics of partial system energy. It has the advantage of being independent of the ecosystem size, but can fully include dependencies on all other parameters of the fundamental Gibbs equation. Changes in the chemical potential are related to either positive or negative contributions to the system work (Glaser, 1976). The top-down approach thus views each animate subsystem, each individual in terms of its mean, or expected chemical potential.

Since we are interested in creating a top-down model approach including all organisms in the alpine river, we view the entropy of the biomass as a whole. The critical assumption is that an approximation of animate subsystem potentials can be achieved by assigning unique chemical potentials to different species of biomass. In this idealized model, trophic interrelationships (the food web) are expressed only as differences in energy contents (Feistel and Ebeling, 1981).

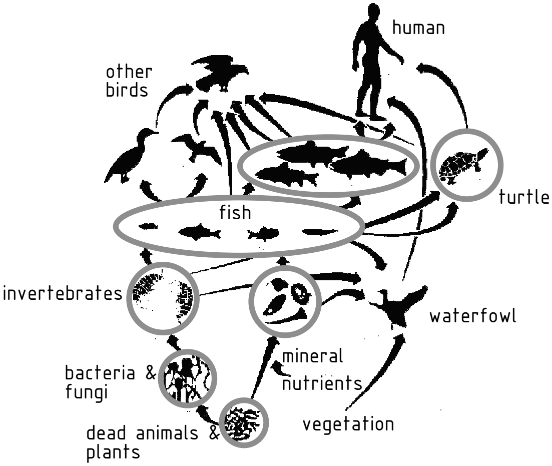


Fig. 4-4 Simplified representation of the food web of a river ecosystem. Arrows indicate the direction of free energy transduction (higher to lower). The driving force of the food web begins at the bottom, where the Sun's energy is utilized by vegetation, sourcing material from dead animals, plants, and mineral nutrients. Source: EPA (2011).

4.1.3 Energy balance

We begin by looking at the distribution of the energy density of all subsystems of the alpine river ecosystem (Table 4-1). The energy balance is specified as a function of the specific densities (mass-averaged):

$$\rho\ \frac{du}{dt} = \frac{d}{dt}\int_{V(t)}\left[u_e + \rho\left(u + \frac{v^2}{2} + \phi\right)\right]dV \qquad (4.4)$$

Where u_e is the electromagnetic energy, ρ is the total density (water+biota), u is the specific internal energy, v is the average velocity, and ϕ is the resultant time-independent potential of all external forces. Following the second chapter, we lump the electromagnetic energy (incoming and outgoing radiation) and all other non-gravitational external forces (electromagnetic fields, etc.) together as an observed, time dependent forcing function, evaluated over a short time interval at constant volume. This leaves us with only the specific internal energy u, and the external kinetic $v^2/2$, and gravitational potential energies ϕ_g for explicit further consideration:

$$\rho\ \frac{du}{dt} = \left(\phi(t)\right)_V + \frac{d}{dt}\int_{V(t)}\left[\rho\left(u + \frac{v^2}{2} + \phi_g\right)\right]dV \qquad (4.5)$$

Table 4-1 Energy distribution in living cells. After Haynie (2008).

Kinetic energy	Potential energy
Heat or thermal energy – energy of molecular motion in all living organisms.	*Bond energy* – energy of covalent and non-covalent bonds, for example a σ bond between two atoms.
Radiant energy – energy of photons, used during photosynthesis.	*Chemical energy* – energy of a difference in concentration of a substance across a permeable barrier. The greater the difference, the greater the energy.
Electrical energy – energy of moving charged particles, for example reactions involving electron transfer.	*Electrical energy* – energy of charge separation, for example the electric field across two lipid bilayer membranes.

4.1.4 Mass balance

The mass balance equation for the animate components is also taken as relative to that of the water:

$$\rho \frac{dB_k}{dt} + div\boldsymbol{J}(B_k) = 0 \tag{4.6}$$

where $B_k = \rho_k / \rho$ is the mass fraction of the biomass of animate subsystem of type k, and J is the mass flux term $\boldsymbol{J}(B_k) = \rho_k(v_k - v_R)$ taken relative to the center of mass velocity of the river water $v_R = \sum_i \rho_i v_i / \rho$. This formulation certainly lacks practicality, as it is not possible to model all animate subsystems inside our model boundaries with sufficient resolution in order to determine explicit values of their equivalent mass fluxes and relative velocities. Instead, it becomes necessary to look at the *causes* of instability in the system. Assuming that over the time period in question, the mass flux through the system is constant, we are only left with internal exchanges of biomass, either between species and/or between the species and water. There is no accumulation or reduction of biomass in our river in this steady state. The formulation leaves us only the convective term, which would still be extremely unwieldy to evaluate since it requires the breakdown and evaluation of the mass flux term for each system component as partial derivatives in three dimensions:

$$div\boldsymbol{J}(B_k) = \frac{\partial[\rho_k(v_k - v_R)]_x}{\partial x} + \frac{\partial[\rho_k(v_k - v_R)]_y}{\partial y} + \frac{\partial[\rho_k(v_k - v_R)]_z}{\partial z} = 0 \tag{4.7}$$

Calculating the relative velocities for each system would require explicitly solving relations to obtain velocity estimates. For a fish this would include balancing drag forces, buoyancy, thrust, etc., even under stationary flow conditions. One benefit in this formulation is that if the animate components are considered stationary (at mechanical equilibrium) and at constant volume and atmospheric pressure over the time period of investigation, than any change in the internal energy of the ecosystem is solely due to the external forcing function at constant volume. Note that this relation can hold even for unsteady flow conditions:

$$\rho \frac{du}{dt} = (\phi(t))_{V,P} \tag{4.8}$$

Thus far we have simply reformulated our description of the river system to include animate systems, and stated that the total change in internal energy considering stationary behavior is only due to external forcing. Recalling the definition of Gibb's chemical potential from Eq. (4.3), it becomes clear that the response of the animate subsystems to external forcing comes from a change in their chemical potentials. Thus we have clearly shown *where* the energy of individual organisms or species is: its chemical energy (Haynie, 2008). This is an important statement because the standard abiotic-biotic relations in habitat models view the organisms as a sort of particle, whose external energies (kinetic and potential) play the largest role. This is unfortunate since we know that changes in external forcing will cause an organism to react, perhaps even mechanically (swimming away), but the source of this mechanical motion is *always* chemical (Eisenberg and Hill, 1985). We will see later that alpine fish make use of the surrounding flow field in order to lower their energy expenditure during swimming, but that maintaining position still requires basal metabolic activity.

4.1.5 Entropy balance

Thus far we have provided equations for the energy and mass balances for the river. We now include the entropy balance equation to our derivation of the top-down theory:

$$\frac{\partial(\rho s)}{\partial t} + div\mathbf{S} = \sigma \tag{4.9}$$

Recalling that s is the entropy density (per unit mass), $\mathbf{S}$ is the entropy flux, and σ is the local entropy production. Note that **entropy is not conserved**. Thus for any irreversible (real) process $\sigma > 0$. For an irreversible process, the (average) total entropy production dS_{irr}/dt over the finite time interval ΔT is (Kjelstrup et al., 2006):

$$\left(\frac{dS_{irr}}{dt}\right)\Delta t \equiv \Delta S_i + \Delta S_e \tag{4.10}$$

Where ΔS is the entropy change of the river ecosystem and ΔS_e is the entropy change of the river's surrounding environment. Having an expression for the local entropy production, we can also calculate the entropy production as the integral over the total system volume:

$$\frac{dS_{irr}}{dt} = \int \sigma dV \geq 0 \tag{4.11}$$

Although the base concept of an entropy balance guides the derivation of both Eqs. (4.9) and (4.10), they are describing the system in slightly different ways. Equation (4.9) uses the material derivative formulation where excess entropy production S_{irr} at the steady-state would show up in the spatial change $div\ \boldsymbol{S}$. During unsteady conditions, this is not the case and S_{irr} may have contributions due to the changes of entropy flux at its boundaries, through the temporal change $\partial(\rho s)/\partial t$. As far as the entropy balance is concerned, steady-state conditions refer only the situation in which entropy fluxes in and out of the system are balanced. Even as the time derivative goes to zero at steady-state conditions, entropy is not conserved, and we are left with the relation:

$$div\boldsymbol{S} = \sigma \tag{4.12}$$

This leads to the following relations using a simplified, equivalent form:

$$S = \sigma + \frac{Q}{T} \tag{4.13}$$

From the above definitions we arrive at a description of the total system entropy in terms of the internal production plus entropy fluxes in and out of the system, S_i and the external contribution due to heat exchange with the surroundings, S_e:

$$S_i = \frac{\partial(\rho s)}{\partial t} + div\boldsymbol{S} \tag{4.14}$$

$$S_e = \frac{Q}{T} \tag{4.15}$$

and thus at the steady state:

$$dS_i = -dS_e \tag{4.16}$$

combining Eqs. (4.14) and (4.15) at the steady-state provides a simplified formulation:

$$d\sigma = \frac{dQ}{T} \tag{4.17}$$

Thus at the steady state, the internal entropy produced is proportional to the heat exchange at the system boundaries in the case that entropy is only exchanged with the surroundings via heat transfer mechanisms (e.g. not via chemical reactions). This finding tells us that if we can calculate either the heat flux or the entropy production (energy unavailable to do useful work) of our system, we can estimate the departure from the steady state, and thus retain an estimate of our ecosystem change. If direct measurements of the heat fluxes are not available, we are forced to return to the left hand side of the equation and calculate estimates of the entropy production. In our case, experimental data of a river during hydropeaking events is not available.

So far, we have described the energy, mass and entropy balances of our river ecosystem at the large scale, using a top-down approach. However, in investigating the effects of hydropeaking on alpine fish, in order to get a picture of population dynamics, we need an expression of the entropy per individual, or at least per species. Although neglected by conventional environmental models, the individual contributions of heat energy by organisms are astoundingly high. Calculating the heat transfer per species and if possible, per individual should be possible using modern equipment, and can provide at least an order of magnitude estimate of the entropy.

Assuming that the amount of water far exceeds that of the biota, we assume after Planck (1964) that animate subsystems can be viewed as an equivalent solute in a dilute solution. This results in the following formulation for the animate portion of the ecosystem entropy $\tilde{S}$ of an ideal mixture:

$$\tilde{S} = \sum N_i \left[s_i(p,T) - k \ln\left(\frac{N_i}{V}\right)\right] \tag{4.18}$$

Where $s_i(p,T)$ is the characteristic entropy of species i as a function of pressure and temperature, k is the Boltzmann constant, and N_i is the number of individuals of each animate species. The second term in brackets is equivalent to the more commonly seen expression $RT\ln c_i$. We also define the chemical potential of a subsystem in the ideal dilute solution under conditions of constant temperature, pressure, and number count of additional substances (Katchalsky an0d Curran, 1967):

$$\mu_i = \mu_i^0 + RT\ln c_i \tag{4.19}$$

Where μ_i^0 is a constant of integration, R is the gas constant and T is the temperature. The entropy per species in the ecosystem can be estimated after Feistel and Ebeling (1981) as:

$$\frac{\tilde{S}}{N} = \sum q_i s_i - k\sum q_i \ln q_i - k\ln\left(\frac{N_i}{V}\right) \tag{4.20}$$

where $q_i = N_i / N$ is the relative frequency of species i. This formulation considers three different sources of entropy: $\sum q_i s_i$ is the average contribution of a given species, $k \sum q_i \ln q_i$ is the entropy due to system configuration related only to the probability of occurrence of each species, and $k \ln(N_i / V)$ is the internal entropy production, S_{irr} due to chemical reactions within the ecosystem. For practical applications, where the rate of local entropy production due to a known chemical reaction (changing the chemical potentials) can be determined directly, this term can alternately be expressed in terms of De Donder's **affinity of reaction,** A (Perrot, 1998):

$$\frac{d\sigma}{dt} = -\frac{1}{T} \sum v_i \mu_i \frac{d\xi}{dt} = \frac{\mathrm{A}}{T} \frac{d\xi}{dt} \tag{4.21}$$

where the extent of the reaction varies by $d\xi$ and v_i is the reaction rate. Similarly, the fundamental Gibbs equation can be invoked to derive the expression for the time rate of change of the total biological energy of the river ecosystem, $\tilde{U}$ (Ebeling et al., 1992):

$$\frac{\tilde{U}}{dt} = T \frac{d\tilde{S}}{dt} - \tilde{p} \frac{d\tilde{V}}{dt} + \sum \tilde{\mu}_i \frac{dN_i}{dt} \tag{4.22}$$

Interesting to observe is the fact that the second term of Eq. (4.20) is *identical* to the **Shannon index**, a commonly used indicator in systems ecology to determine species diversity (Samson and Knopf, 1996):

$$H = -\sum p_i \ln p_i \tag{4.23}$$

Where p_i is the proportion of individuals of the i^{th} species. Mauersberger and Ebeling's formulation for the top-down approach seems to have some direct support in applied ecology. Though it is important to note that the use of the Shannon index alone appears only to account for the ecosystem's configurational entropy.

We should keep in mind that describing the interactions of a single species or individual using the top-down approach requires a complete description of the coupling between external forcing and the response expressed in terms of energy transduction through its various internal chemical processes. These processes are determined by metabolic pathways, evolved chemical processes which are set up to reduce the available (usually) Gibbs free energy. In the case of a fish, the twitch of a single muscle in response to a change in the local flow field would have to be described along its metabolic pathways (Eisenberg and Hill, 1985). A full description of the pathways requires a mathematical description of metabolic closure (Letelier et al., 2011), a topic in theoretical biology about which little is understood.

In principle a complete description encompasses a total of six intensive thermodynamic variables; force, temperature, chemical potential, electrochemical potential, pressure and electromagnetic radiation (Urry, 1997). Thus the consideration of a single pathway would require invoking Onsager reciprocity to describe interactions between six conjugate relations, assuming transduction occurs sufficiently close to equilibrium so that the linear laws hold.

4.1.6 A possible application of the top-down approach

How may the top-down approach be used realistically? We believe that it may indeed have some practical use. Due to the fact that most internal entropy production in animate systems comes from mechanochemical processes, the generated heat is often either internally utilized to drive coupled (endothermic) scalar (temperature) and vectorial (mass transport) processes (Caplan and Essig, 1999). For this reason, a deterministic heat balance approach is not feasible, and is also not possible when scaling from the individual to the reach scale. However, another option using remote sensing data having sufficient resolution may provide greater insight (Fig. 4-5). Recalling that entropy is the conjugate to temperature we can employ the following equation to tease out entropy production estimates:

$$-\frac{\partial q_x}{\partial x}-\frac{\partial q_y}{\partial y}-\frac{\partial q_z}{\partial z}=-div\ \boldsymbol{q} \tag{4.24}$$

and recalling that Fourier's law for heat conduction provides a simple relation between the scalar temperature field T and the thermal conductivity λ:

$$q_i=-\lambda\frac{\partial T}{\partial i} \tag{4.25}$$

this can also be rewritten in vector form for each time step as follows:

$$\boldsymbol{q}=-\lambda\ grad\ T \tag{4.26}$$

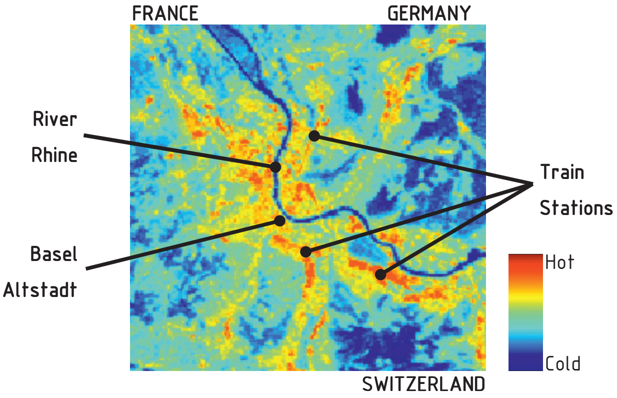


Fig. 4-5 Thermal imagery taken from Band 6 data sensed using Landsat-7. Obvious features include the hot settlement areas, as well as several train stations, which appear as elongated regions of higher temperature. Cooler areas seen are forested regions and the river Rhine. Values of the temperature data are not available. Source: NASA (2011).

If reasonable estimates of the river's temperature field could be taken over time, Eq. (4.26) could be applied using GIS to estimate the conductive heat flux along the river corridor. This estimate, divided by the ambient (local) temperature could then serve as a proxy for estimating the entropy production, (due to sensible heat transfer) over finite time. It would certainly be interesting to monitor two similar river reaches, one with and without hydropeaking to determine what differences in the global estimates of entropy production would be observable. The next step would then be to observe the hydropeaking affected system at a reference steady-state, and determine second order fluctuations of the entropy production estimates during hydropeaking. This can be done by using high resolution remote sensing equipment to measure temperature changes. Such a system will allow for stability criteria to be developed with significantly reduced field effort. Improved estimates of heat transfer along the river corridor could be obtained by adding convection (evaporative) and radiation terms into the entropy production calculations. Heat flux balances in rivers have to a limited extent already been carried out (Mackey and Berrie, 1991; Webb and Zhang, 1999).

4.1.7 Critical assessment of the top-down approach

It has been shown that the local rate of entropy production, in combination with the energy and mass flows has the potential to deliver important information about our alpine ecosystem. Ecosystem stability may be estimated using the second order variation of the entropy production, which can be estimated at the steady state by integrating heat transfer estimates over the river control volume.

Estimating the individual or species-specific entropy production requires solving the mass balance, Eq. (4.6) where organisms are considered as being in a dilute solution. Once the biomass balance is determined, it is then converted into equivalent chemical potentials, a function of its internal energy. Assuming stationary organisms over each model step, the energy equation provides a functional relationship between the application of external forces and the internal energy of the system, Eq. (4.5). Finally, the entropy balance of the system allows for the path-dependent behavior of the organisms to be described in terms of the changes in their chemical composition, Eq. (4.21).

Assuming that the above approach is possible to model, we would require full descriptions of both the mechanical and chemical interactions of all model components in order to tease out the response of a single subsystem. As most animate-animate and animate-inanimate interactions (environmental forcing) are nonlinear processes the consideration of simplified linear interactions quickly becomes mathematically impossible (Jørgensen and Svirezhev, 2004).

Further difficulty in applying the top-down approach becomes apparent once we see that we have not only the requirement of high model intricacy, but are also forced to make three sets of calculations in order to estimate future system trajectory, and each carries with it a set of unsecure assumptions. Aside from the difficulty in obtaining the large number of estimates of the initial conditions, the balance of forces requires us to obtain relative velocities for the organisms, and further demands the application of several upscaling procedures. Once the kinetics is solved, we are still left with determining an astoundingly huge number of chemical reactions, all which should occur via highly interconnected metabolic pathways.

However, even if we choose to ignore the extreme difficulty in getting through the first two steps, we find that the third step provides us with the real problem: **entropy production is a *path-dependent* enterprise**. There may be more than one equally viable solution at a steady state! The top-down approach, even with its assumption of stationary organisms still carries with it the ‘curse of degeneracy’. There may be 15 equally suitable locations for our fish to be in, all things considered equal. But when we carry out field work, we surely find that a single fish is at only one location.

Understanding the basics of our river system from the top-down, the model approach shows that open systems including animate subsystems perform work originating from chemical reactions, where the work is dissipated into heat due to local entropy production. This is in substantial agreement with experimental studies of individual organisms and ecosystems (Tolman and Fine, 1948; Lamprecht and Zotin, 1978). Taking the lessons learned from the impracticality of the top-down approach, we now approach the problem from the bottom-up.

4.2 Bottom-up: Local entropy estimates

The previous section showed that local estimates of energy transduction and dissipation are crucial in determining ecosystem trajectory via path-dependent, irreversible processes, and stability, viewed in terms of the second-order variation in entropy. In this section we focus on a single volume element containing a single animate subsystem – an alpine fish (Fig. 4-6).

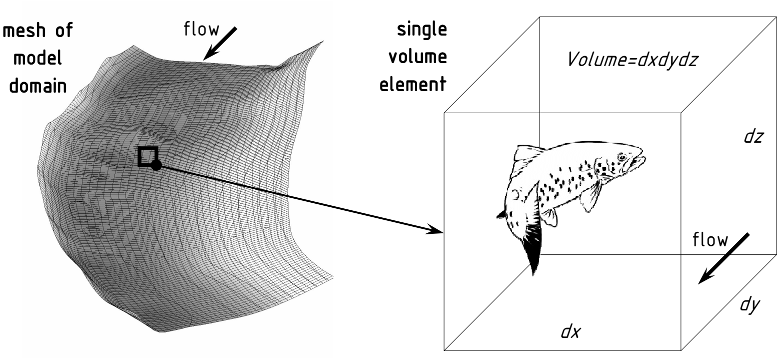


Fig. 4-6 Graphical representation of the bottom-up scheme: a three dimensional volume element with fixed dimensions dx, dy, dz is taken from the mesh of a hydraulic model. The element size must be chosen large enough to contain at least one individual organism in its entirety. The boundaries of the control volume define one elementary "river+fish" system.

4.2.1 Entropy generation

The bottom-up approach borrows from the thermodynamic-hydraulic concepts developed by Bejan as a self standing field of research in his 1982 book *Entropy Generation through Heat and Fluid Flow.* Since then, the principles of entropy generation minimization (EGM) have held a prominent place in modern engineering design (Bejan and Lorente, 2001). These designs represent finite-time, finite-size systems for which analytical solutions and equilibrium conditions often do not exist. EGM (Fig. 4-7) is the method of thermodynamic optimization of real systems owing their thermodynamic imperfection to heat transfer, fluid flow, and mass transfer irreversibilities and can be best understood as the confluence of thermodynamics, heat transfer, and fluid mechanics. By virtue of its interdisciplinary nature, EGM can be considered distinct from each of the three more classical disciplines (Bejan 1996).

While biologists tend to attach importance to variations on a theme, engineers have a need to simplify. This requires that the variations are limited, and that the resulting product is robust in its application. The bottom-up modeling approach using concepts of EGM leaves plenty of room for both.

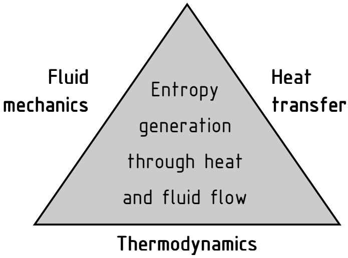


Fig. 4-7 The interdisciplinary triangle covered by the method of entropy generation minimization. After Bejan (1982).

When evaluating the degree of reversibility of engineered systems, the second law inequality can be written as an expression consisting of two terms: The first is a *transfer* term which contains the in- and outflows of the specific entropy and heat transfer across the system boundaries. The second term accounts for the net *change* in entropy as a function of time. At the steady-state, this term goes to zero:

$$\underbrace{\sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \frac{\dot{Q}}{T_0}}_{transfer} \leq \underbrace{\frac{\partial S}{\partial t}}_{change} \tag{4.27}$$

Rearranging the expression leads us to the definition of the entropy generation $\dot{S}_{gen}$:

$$\dot{S}_{gen} = \frac{\partial S}{\partial t} - \frac{\dot{Q}}{T_0} + \sum_{out} \dot{m}s - \sum_{in} \dot{m}s \geq 0 \tag{4.28}$$

Equation (4.28) is thus the general expression of the rate of entropy generation of any open system. It is always positive, and goes to zero only at the theoretical reversible limit. When the right side is multiplied by the frontier temperature, Eq. (4.28) becomes an equivalent expression of the Gouy-Stodola theorem for the lost work done over a finite time period by an irreversible system (Kjelstrup et al., 2006):

$$w_{lost} = w - w_{ideal} = T_0 \left(\frac{dS_{irr}}{dt} \right) \Delta t \tag{4.29}$$

Alternately, using Eq. (4.28), Gouy-Stodola can be expressed as the *rate* of lost work:

$$\dot{w}_{lost} = T_0 \left(\frac{\partial S}{\partial t} - \frac{\dot{Q}}{T_0} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \geq 0 \right) \tag{4.30}$$

We now continue by applying the concept of entropy generation to the case of our alpine fish, submerged in a single volume element. Consider a body of arbitrary shape with area A, temperature T, and average heat transfer coefficient $\overline{h}$ subject to external flow at a velocity U_∞ and temperature T_∞. Fluid friction along the fish's body results in the 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 uniform body temperature, the entropy generation $\dot{S}_{gen}$ in the fish+river volume element is (Bejan, 1996a):

$$\dot{S}_{gen} = \left(\frac{T - T_\infty}{T_\infty} \right)^2 \overline{h} A + \frac{F_D U_\infty}{T_\infty} \tag{4.31}$$

We have now derived a general description of the irreversibility of a single volume element containing a fish. However questions remain regarding the definition of our system boundaries, and the type of system to choose. In order to solve this problem, we need to investigate the fish+river system in terms of the biophysical concepts previously discussed focusing on how the system *with* the fish differs from the system *without*.

4.2.2 Determining system boundaries considering nonequilibrium conditions

A system can only reach equilibrium when it is left with no external disturbances. At equilibrium the internal properties are fully determined by the external properties. There are no thermodynamic forces acting within the system. During small perturbations, the system can spontaneously return to the state of equilibrium, because short-range intermolecular interactions resist thermodynamic forces. Equilibrium systems are therefore at least conditionally stable. The alpine river ecosystem even inside a single volume element is not at equilibrium, and considering hydropeaking it is certainly not stable.

Following the extremum principle, the entropy of an isolated system attains a maximum at the expense of its free energy, which reaches a minimum at equilibrium. However this principle is of little help in our investigation, as many real physical and biological processes of interest occur in nonequilibrium, irreversible and above all, open systems. For systems like our fish+river elementary volume, classical thermodynamics is only able to provide us with a guiding set of inequalities. When considering only simple systems, kinetic equations and statistical mechanics can be applied to describe the transport of matter, energy and charge. Such analyses can also work well in a limited range of biological systems, such as muscle contraction and basic autocatalytic reactions (Demirel, 2007).

Comparing our understanding of equilibrium with the Bauer principle from the previous chapter, we are compelled to follow the results of this comparison to the end of its logical conclusion: if animate systems are those which repel the equilibrium state, and if the equilibrium state is one in which there are *no* external disturbances, then animate systems cannot be at equilibrium. Furthermore, animate systems can actively participate and induce external disturbance in order to maintain their departure from the equilibrium state. Considering the deep interactivity between the animate system and its surroundings, we must ask: where may we draw the system boundaries when considering the fish as a unique thermodynamic entity (Fig. 4-8)?

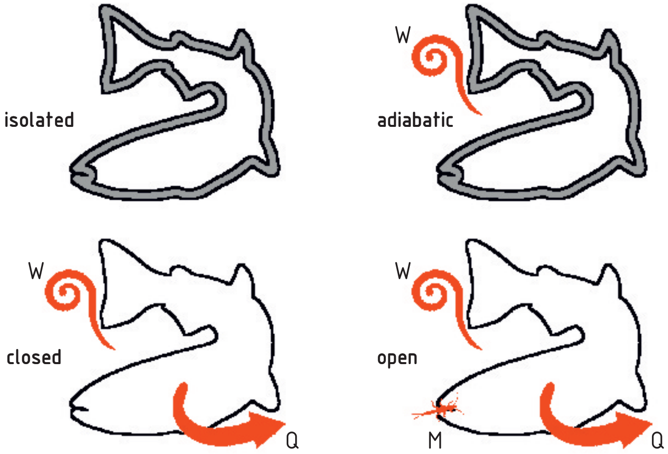


Fig. 4-8 Representation of the alpine fish as either being isolated, adiabatic, closed or open. W is the work, Q the heat, and M is the mass exchanged with the environment.

The notion of isolating and studying a single fish system and its specific interaction with its watery surrounds becomes fuzzy and blurred once it becomes clear that the presence and utilization of Lagrangian coherent structures (LCS) is ubiquitous in aquatic propulsion and feeding systems. LCS were first discovered through the particle tracking analysis of real unsteady flow, where physically meaningful, fluid-fluid boundaries acting as barriers to transport are found (Haller and Yuan, 2000; Green et al., 2007; Lekien et al., 2007).

LCS can be thought of as a post-processing technique which can be used to reveal coherent structures (manifolds) in a flow field (Fig. 4-9). The flow field data can be the result of a hydrodynamic model, or from PIV data. In either case, it is necessary to calculate the finite time Lyapunov exponent (FTLE) field at a collection of points in the model space:

$$\sigma_{t_0}^{T}(x) = \frac{1}{|T|} \ln \sqrt{\lambda_{\max}(\Delta)} \tag{4.32}$$

where t_0 is the finite time interval for each calculation step, T is the integration time, x is the position vector, and $\lambda_{\max}(\Delta)$ is the maximum eigenvalue of the finite time deformation tensor Δ. In order to calculate the FTLE, the flow field is seeded with passive tracer particles and advected from t_0 to $t_0 + T$. The final particle positions are used to estimate Δ over the total time of interest, and finally the FTLE field is calculated (Lipinski and Mohseni, 2009).

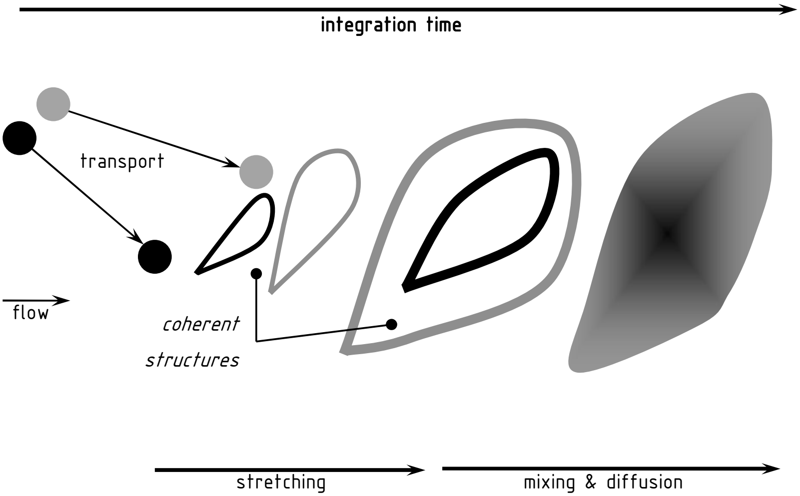


Fig. 4-9 Transport of two tracer particles in a flow field, followed by diffusive mixing. Macroscopic patches which remain stable over time are considered as coherent structures (manifolds). However, at increasingly longer time scales, stirring and diffusive effects take over, mixing the particles irreversibly. After Lekien and Coulliette (2007).

This ‘skeleton of water’ (Peacock and Dabiri, 2010) is shown (Fig. 4-10) to play significant roles in studies of propulsion at low and high Reynolds numbers, and is also utilized in fish feeding (Peng and Dabiri, 2009; Tew Kai et al., 2009; Vétel et al., 2009; Wilson et al., 2009). The use of LCS in studying complex unsteady flows is a new field of fluid mechanics, which and will no doubt deliver startling new insights into fluid body interactions of a great deal of animate systems, including alpine fish such as the trout.

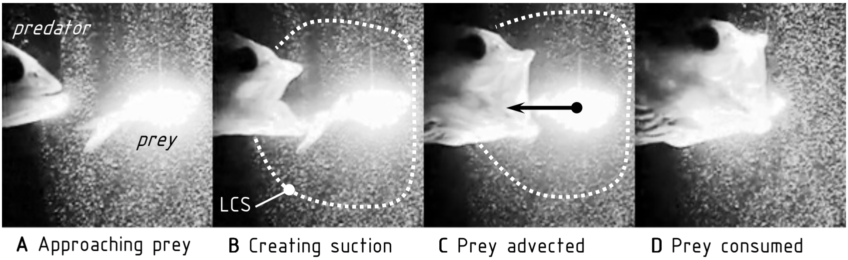


Fig. 4-10 Fish suction feeding with the help of LCS (estimated, not calculated). In this example, the use of the coherent structure makes the separation of the fish, it surroundings and its prey difficult to define discreetly without answering the question: exactly *when* does the prey become part of the predator system? At which of the four frames above **A**, **B**, **C** or **D** does the prey no longer have any chance of escape? Images courtesy of Prof. Peter Wainwright, UC Davis.

Considering the previous statements and following the discovery of the existence of LCS we must come to the realization that even at the small scale of the bottom-up approach, it is not possible to completely abstract the fish from its watery surroundings. Instead, we recognize that our elementary volume now represents a general "water+" system containing both animate (+) and inanimate (water) subsystems. In the case of the alpine river ecosystem it is clear that the inanimate system, the river's turbulent water dominates the system energetics. Following from the Bauer principle, we begin our investigation with the following general statement applicable to the study of an elementary volume of the river ecosystem:

Any system which contains animate subsystems cannot be at equilibrium.

The above formulation says nothing about the type or initial state of the animate or inanimate subsystems, or their functional relations and composition. Put into context, the study of the alpine river and its animate subsystems must include irreversible thermodynamics to be scientifically relevant, because animate systems cannot be at equilibrium. Additionally important is the discovery of ubiquitous LCS utilization by aquatic organisms. This makes it impossible to clearly separate a fish as an animate subsystem from its inanimate surroundings. This statement is strongly supported by recent CFD studies of fish locomotion covering a variety of body morphologies (Borazjani and Sotiropoulos, 2010; Knight, 2010). It is therefore necessary to focus on the patterns of interaction from the lens of irreversible thermodynamics of the water+fish system in our volume element.

4.2.3 Crocco's vorticity theorem

Thermodynamic relaxation processes set up by fluid interactions with a moving body are a source of entropy production, and result on a drag force acting on the body (Becker and Ellermeier, 1977). Thus the presence or absence of a fish (or any other animate subsystem) in a given control volume affects its entropy balance and can clearly be seen in Fig. (4-11).

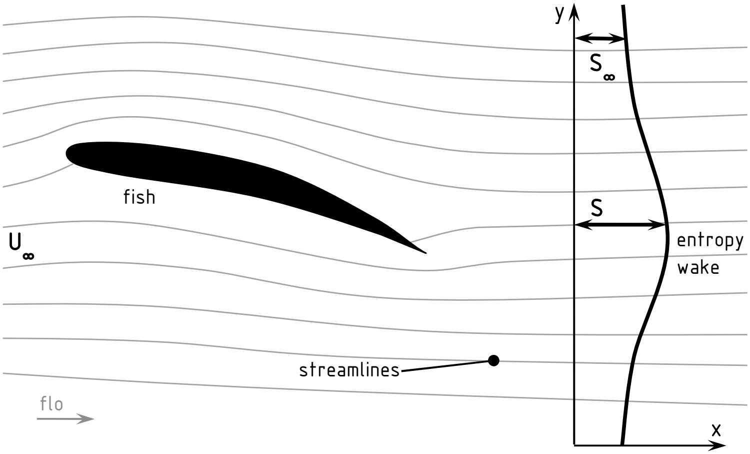


Fig. 4-11 Idealized streamlines around a swimming fish, shown in plan view. Entropy is produced in the fish's wake, due to relaxation processes set up in the local flow field with incoming velocity U_∞. Dissipation in the river continuously produces a quantity of entropy S_∞ in the flow field, whereas the presence of the fish, acting as any bluff body in external flow, produces an additional entropy wake. Under steady flow conditions, the entropy changes only along the streamlines.

In the near vicinity of the fish's body, the fluid pressure, velocity, density, and thus its overall thermodynamic state are changed when compared to the state of the upstream fluid. This occurs due to the disruption in the flow set up by the body, where the effects of the body decrease with increasing distance. The entropy production is highest along those streamlines passing the immediate vicinity of the body. An entropy wake emerges downstream, shown in Fig. (4-11). In this work, Crocco's vorticity theorem is invoked in order to describe fish+river system in thermodynamic terms using vorticity and entropy.

Crocco derived his vorticity equation for a steady, inviscid, uniform flow with no body forces (Becker and Ellermeier, 1977). It is obtained by replacing the pressure gradient in the momentum equation by the conjugate pair Tds under isothermal conditions, where T is the temperature is and s the specific entropy. For a chemically reactive fluid, the specific enthalpy can be derived using the fundamental Gibbs relation:

$$dh = Tds + \frac{dp}{\rho} + \sum \mu dn \tag{4.33}$$

The specific enthalpy considering reactive flow can be broken down into gradients of three quantities: thermal, pressure, and chemical. Thus it is possible to account for the change in dissolved oxygen via respiration, primary production, etc. We focus on the largest producer of entropy in our system, the fluid-body interaction of the fish and river. A full derivation of Crocco's theorem for 3D unsteady, reactive turbulent flows including body and viscous forces, combustion, diffusion, and shockwaves can be found in Emmanuel (2010). Neglecting chemical reactions in the fluid and rearranging terms we have:

$$Tds = dh - \frac{dp}{\rho} \tag{4.34}$$

The expression of the specific enthalpy is replaced using the energy equation, assuming a constant stagnation temperature. The total derivative of entropy is now expressed in terms of the total derivatives of both the velocity and the pressure:

$$Tds = -\left(u\ du + v\ dv + w\ dw + \frac{dp}{\rho}\right) \tag{4.35}$$

This results in the Crocco vorticity theorem for three-dimensional flow (Krause, 2005):

$$T\nabla s + v \times (\nabla \times v) = \frac{\partial v}{\partial t} + \nabla h_0 \tag{4.36}$$

Assuming steady flow at constant temperature, both terms on the right side go to zero. This is because the gradient of the stagnation enthalpy h_0 (the energy remaining after isentropic deceleration at zero elevation) is itself a function of the velocity (Venkanna, 2009):

$$h_0 = C_p T + \frac{v^2}{2} \tag{4.37}$$

where C_P is the specific heat capacity of water at constant pressure. We can now simplify Eq. (4.36) as being only a function of the entropy and vorticity:

$$T\nabla s = \boldsymbol{v} \times (\nabla \times \boldsymbol{v}) \tag{4.38}$$

The equations governing the diffusion of vorticity in the water column are analogous to Eq. (4.26) describing the conduction of heat. Thus vorticity in the fluid body is not produced internally by the viscous fluid, but diffuses inward from a solid-fluid boundary (Julien, 2010).

Crocco's theorem can also be rewritten to explicitly include turbulence using terms for convective and viscous contributions due to changes in the fluctuating component of the vorticity (Emanuel, 2007). Ignoring contributions in the z-direction, we focus only on the effects of the largest eddies in the x-y plane interacting with the fish's body. The drag force F_D per unit length following Fig. (4-12) and perpendicular to the flow is:

$$F_D = \int \rho u(u_\infty - u)dy \tag{4.39}$$

For a slender profile, disturbances in the parallel flow and the entropy production remain small and we simplify by taking $|u_\infty - u| << u_\infty$. Assuming that the fish remains a slender body, we can linearize the theory with respect to disturbances of the parallel flow and Eq. (4.39) can be rewritten as:

$$F_D = \rho u_\infty \int (u_\infty - u)dy \tag{4.40}$$

This provides a simplified linear form of Crocco's vorticity theorem:

$$u_\infty \frac{\partial u}{\partial y} = -T_\infty \frac{\partial s}{\partial y} \tag{4.41}$$

After integrating Eq. (4.41) along the y-axis we now have:

$$u_\infty (u_\infty - u) = T_\infty (s - s_\infty) \tag{4.42}$$

Combination of Eqs. (4.40) and (4.42) leads to:

$$F_D u_\infty = T_\infty \rho_\infty u_\infty \int (s - s_\infty) dy \tag{4.43}$$

We now define $\rho_\infty u_\infty \int (s - s_\infty) dy$ as the rate of entropy $\dot{S}$ leaving a control volume, which is taken large enough to surround the entire body. Equation (4.43) can now be written as:

$$F_D = \frac{T_\infty \dot{S}}{u_\infty} = \frac{T_\infty}{u_\infty} \int\int \sigma \ dxdy \tag{4.44}$$

From this reformulation, $\dot{S}$ is entropy generation rate, and σ is the entropy production rate per unit volume. The integration of Eq. (4.44) extends over the whole volume element and in this case we neglect the vertical component. Equation (4.44) should look very familiar. It turns out that if we assume that a fish's body temperature is equal to the temperature of the surrounding fluid, $T = T_\infty$. We then find that Bejan's Eq. (4.31) for the entropy generation and the entropy generation rate of Eq. (4.44) due to Crocco's vorticity theorem are *exactly equal*. Thus the entropy generation of a poikilothermic fish swimming in our elementary volume can be expressed as:

$$\dot{S}_{gen} = \frac{F_D u_\infty}{T_\infty} = \int\int \sigma \; dxdy \tag{4.45}$$

This is an interesting find, and it provides us with a simple relation between the fish and its surroundings, all whilst measuring this interaction in terms of the rate of change of irreversibility. Unlike the top-down approach, which required a multi-stepped process linking interactions via internal chemical pathways, the bottom-up approach considers only the largest contributor to irreversibility due to drag through the external flow conditions. This simple but powerful approach will form the basis of our unsteady model, as it only requires an estimate of the spatial distribution of the local entropy production rates. Considering practical applications, Eq. (4.44) can be estimated in one of two ways shown in Fig. (4-12).

The first method is to use the center expression including the drag force, velocity, and temperature. This method requires a complex description of perturbation of the local flow field due to the fish, but has the advantage that the interplay between the drag force and local hydraulic conditions even under unsteady conditions is explicitly accounted for.

The second method is the one which we will choose. Instead of taking the flow field in our element and trying to integrate the drag force over the body of the fish, we take the "easy way out." For each flow condition, fish species, and life stage, the corresponding volume integrated value of σ is chosen. That is, we know that since each fish has a unique combination of the flow field, body shape, and mode of swimming, there is also a unique σ. Thus, in lieu of trying to put the fish in the element, and calculate the entropy generation, we simply look for places in the river in which a given σ is possible in the first place. The following section outlines the theoretical basis for this new biophysical concept which we call the locational entropy principle.

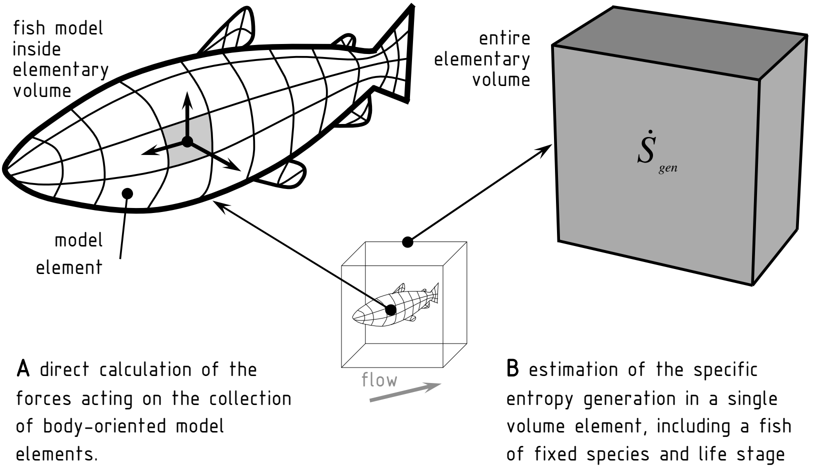


Fig. 4-12 Two approaches can be used when applying the entropy principle for an individual fish+river volume element. Approach **A** requires that flow field-fish interactions are explicitly accounted for, where the estimate of the entropy generation is the result of summing the generation due to the individual body-oriented elements. The second method **B**, used in this work, estimates the total entropy production in the single volume element as a scalar value representative of the fish+river system.

4.3 The Locational Entropy Principle

The previous sections show that alpine fish are finite flow systems. In this last section we summarize the evidence provided and discuss how fish match their physiological evolution and behavior to their surroundings. The **locational entropy principle** is the result. The principle provides the basis of a new approach to modeling fish swimming, perhaps preferable over standard habitat models. Summarizing the information presented in the previous chapter, and in our investigations of the top-down and bottom-up approaches we find that:

1. All animate systems are constrained open, non-equilibrium systems whose persistence comes at the cost of participation with their surroundings (Tuhtan, 2011).
2. Persistence is dependent on the animate system's ability to repel the non-equilibrium state, and requires development and maintenance of species-dependent flow architectures. The svelteness of a given animate system is due to the interplay between internal and external processes. Ontology recapitulates physiology (Caldwell, 2003).
3. The flow architecture of animate systems can only be maintained through the regulation of natural processes via free energy transduction which for any finite system requires the decrease of free energy and the net generation of entropy (Bauer, 1920).
4. Ultimately, both the source of free energy and the sink for entropy is the surroundings, thus all animate systems must be viewed as embedded subsystems of a larger flow system (Jørgensen et al., 1999).

Following these four statements, the following general free energy principle can be made:

In order for an animate system to persist in time, it must be located such that its free energy balance allows for continued departure from equilibrium, considering finite internal and external constraints.

This statement allows us to make use of the theories discussed in the previous section with little detailed knowledge of the complex animate systems we wish to study. Invoking the constructal law we see that globally, the animate system's participation is evaluated in terms of a balance between its ability to improve the access of energy and mass flows to the global system. It acts as both an engine and a brake (Bejan and Marden, 2006a). Thus if its presence increases global flow resistance it must evolve a more svelte design, or risk being replaced with a more efficient alternative. Locally, the animate system is responsible for maintaining its internal structure and maturing to ever lower states of metabolic expenditure. Globally, it must evolve a deep integration with the larger surrounding flow system over time, where it is judged with reference to the other subsystems. The ability of an individual subsystem *to change* makes it easier for the entire system to *continue to change* (Mikulecky, 2000). Freedom to morph is thus both a local and a global property.

The timid nature of the previous statement is purposeful. It is constructed to be valid in the broadest sense, and to provide a guiding principle when dealing with designs involving animate systems. In order to make use of the principle, we impose a single but important restriction on our observational realm: we suppose that the fish which we wish to study is not undergoing any biochemical change. Doing so frees up a great deal, and we can reformulate the above statement as:

Considering finite internal and external constraints, the most viable locations of an animate system in the surroundings are largely functions of their entropy generation.

The following chapters provide further phenomenological evidence for this principle, as well as first model attempts compared to the current state-of-the-art habitat model CASiMiR.

5 River+Fish Energetics

A fish is not a bag of molecules stealthily cruising the river to optimize some primeval objective function lurking deep within its selfish DNA (Dawkins, 2006), nor is it a type of exotic dissipative structure feeding off of energy gradients for survival (Schneider and Sagan, 2006). A fish is concurrently an integral and unique relational entity, a central component of a river+fish flow system. This multicomponent system is irreversible and open. The system can only persist when it possesses constructal openness – it requires access to sources of energy, freedom to evolve and must be allowed to discharge its waste to the surroundings. Broken down into volume elements, each potential river+fish subsystem is a part of the larger irreversible, open river ecosystem. The presence of animate systems is identifiable because from our standpoint, we are capable of distinguishing characteristic functional differences between system types. The mutualism of the fish within its surroundings is what makes a river+fish volume element fundamentally different than just a plain river one.

Once the system, boundaries, and its surroundings are defined the next step is to determine the distribution of energy transformation over space and time, a transductional landscape. It is important to recall that throughout the varied processes, energy is conserved whilst entropy is not. All natural, spontaneous processes occur commensurate with a decrease in their free energy. It is relatively easy to roughly estimate the external energy balance using total quantities at the upstream and downstream end of the alpine river reach based on the hydraulics alone. The major challenge in using the locational entropy approach comes from deriving the necessary accounting procedures used in estimating the entropy generation.

The purpose of this chapter is to shed light on the energetics of a river+fish system so that we may gain a clearer view of the potential sources of uncertainty and error, as well as the general validity of the assumptions behind the locational entropy principle. In order to do so we begin by looking closer at the physics of a single volume element in the alpine river. This chapter equips us with the necessary background as to where the potential pitfalls may lie, and where progress through future studies can be expected to be made. At the end of this chapter, three questions regarding fish energetics are answered based on the analysis afforded by the investigation of the river+fish system.

5.1 Background

The swimming behavior of fish was systematically investigated in a series of empirical studies commencing in the 1950s (Gray, 1953; Bainbridge, 1958, 1960). To understand the physics of fish locomotion, we must begin with the visualization of what takes place when a fish enters an elementary volume, disturbing the surrounding mass of water as it moves within it (Videler, 1993).

The moment the fish fully enters a model element, it changes the energy balance of that element. The fish performs work on the water in making room for itself. In much of the hydrodynamics theory of fish-like swimming, the fish is assumed to be neutrally buoyant and thus the effects of the gravitational potential are assumed to be zero. This is not true, as the fish must lift the surrounding water out of its way and in doing so it does boundary work on its surroundings. A river+fish system thus experiences a *change in enthalpy*, as the internal energy of the element increases due to the fish biomass, and from the expansion work done on the surroundings. Thus the interactions within the element are expressed in the case of an undulating fish, as a change in internal energy. As this energy is converted from the chemical potential to mechanical motion, entropy is produced due to heat transfer and relaxation processes. The work done can be seen as equivalent to moving a volume of water up and over its body. A similar interpretation of fish swimming energetics, not including chemical terms can be found in the paper on animal locomotion by Bejan and Marden (2006a).

Fish locomotion is an extensive and growing field, encompassing the study of evolved fluid-body interactions of some 24,000 different species evolved from the Mesozoic era to the present, covering a span of some 225 million years (Wootton, 1998). Fish such as the trout have varying cross sections and are not perfectly streamlined due to the requirements of their organs. In general, the evolution of animate systems using swimming as their principle method of locomotion exhibits a strong relation with the Reynolds number (Fig. 5-1). Both the body shape and mode of swimming cause variations in the local fluid velocity and pressure fields (Videler, 1993). *A swimming fish is best viewed as an amalgamation of reactive, chemically-sponsored motion.* This stands in stark contrast with the black-on-white pictogram of the slender body presented in the previous chapter. The discrepancies between theory and reality thus begin to emerge. Today's trout are undoubtedly svelte, but their design is constantly evolving in concert with their surroundings.

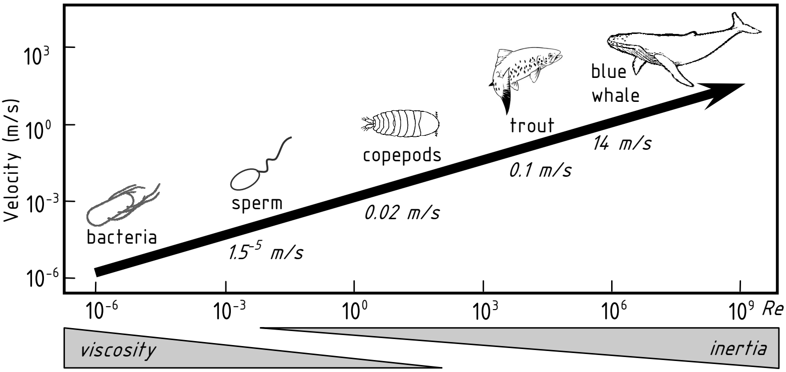


Fig. 5-1 Typical swimming speeds of organisms, increasing in size and as a function of the Reynolds number, Re. Alpine fish such as the trout belong to the medium range of swimmers subject to inertial rather than viscous forces. After Videler (1993).

The locational entropy formulation in the previous chapter relies on the assumption of a steady swimming speed. Studying fish swimming at rest or at a steady speed is typical for two reasons: First, the requirements of the fish at rest represent the theoretical minimum metabolic exertion relative to thrust production. If the thrust is constant over a prolonged time period, differences in the metabolic exertion can be taken with reference to the fish at rest. Second, swimming behavior can be reasonably measured under laboratory settings at a steady swimming speed by keeping the flume flow rate constant (Triantafyllou et al., 1993; Schultz and Webb, 2002).

The choice to use a steady swimming speed in our model is not only due to the fact that it simplifies the theory and relaxes the model requirements. In their natural environments, fish detect local changes in the flow field using the hair cells of their lateral line system. The lateral line is also used to find prey, detect predators, and to aid in schooling (Liao, 2006). It has been shown that fish prefer to maintain position at zero net velocity because the increased lateral line sensitivity improves prey detection (Feitl et al., 2010). It is currently only possible to model direct estimates of a fish's lateral line response using high-resolution 3D simulations of individual dipoles, oriented along the body of a hypothetical fish (Rapo et al., 2009). Thus the direct estimation of local entropy production and a fish's response to changing flow conditions following "approach A" of the previous chapter is currently infeasible. In the near future, improved models of individual fish and the surrounding flow fields may be available in order to improved estimates of species/life stage parameter sensitivity to near body hydraulic conditions. Thus, future development of the locational entropy approach can be assisted by the inclusion of 3D simulations. Even physical fish models equipped with sensory equipment may soon come into use (Lacey et al., 2011).

5.2 Fish Energetics

Fish exist in a thermodynamically unstable state whose persistence is associated with an increase in the entropy of their environment, releasing energy as heat and substances whose free energy is degraded. In animate systems, this energy is derived from the catabolism of food (Cho et al., 1982). Energy in organic molecules is transduced via a series of chemical reactions in which glucose, fat, and other organic compounds are oxidized. The products of these reactions are carbon dioxide, water, the original reactants, and heat. The energy of the digested food is not just converted into heat, but also harnessed to do useful work; a fish may use it for locomotion, maintenance, fighting illness, and reproduction (Haynie, 2008). Rate equations describing the energy transduction processes in metabolism are strongly dependent on species, lifestage, and water temperature. The new field of metabolic flux analysis (MFA) may yield fruitful mathematical formulations required to model metabolic networks, leading to a further understanding of animate system physiology, growth, and productivity (Dorka et al., 2008). One detailed study on the evacuation rate of trout even found that the meal's initial water content and temperature strongly affects the rate of evacuation (Elliott, 1991). In evaluating metabolic processes, it is useful to recall the fundamental Gibbs equation which provides a breakdown of the energetics in our animate system (in terms of its internal energy) as a response to changes in the surroundings:

$$dU = TdS - PdV + fdl + \sum \mu dn + \ldots \tag{5.1}$$

Recall that we can use the Gibbs free energy to describe the amount of energy available for useful work done, as required by animate systems as the difference between their enthalpy and entropy:

$$G = H - TS \tag{5.2}$$

Note that the body of literature on fish energetics modeling and that of fish locomotion energetics are often segregated, as is commonly reflected in the accounting-style 'first law' conservation of energy approaches used. The works included in Table (5-1) however, are phenomenological studies most often performed in order to either improve fisheries management (e.g. feeding and stocks), or to provide fundamental knowledge of fish energetics and locomotion. Within the conceptual framework of thermodynamics, where the energy quality is considered as well as the quantity, it becomes clear that the coupling between swimming performance, metabolism, and surroundings can be seen to fit together as expressed in the Gibbs relation, providing a new 'second law' perspective. The table provides a series of sources showing the relative importance of the thermal TdS, mechanical fdl, and chemical μdn terms describing the activity of fish.

Table 5-1 Chronological listing of selected phenomenological studies on fish energetics, considering relevant conjugate couples in the fundamental Gibbs equation, Eq. (5.1).

Source	Species	TdS	fdl	µdn	Details
(Bainbridge, 1960)	Dace, Trout, & Goldfish	*	*		Relationship between speed of swimming and frequency of beating tail
(Webb, 1971a)	Trout		*	*	Oxygen consumption at various speeds
			*	*	Oxygen consumption used in swimming
			*	*	Power required and available during swimming
(Stevens and Sutterlin, 1976)	Various	*		*	Oxygen uptake related to temperature
		*		*	Muscle metabolic rate related to the thermal exchange
(Cho et al., 1982)	Rainbow Trout	*		*	Effects of different dissolved oxygen levels in water on performance of rainbow trout
		*		*	Performance of rainbow trout under different light intensities
		*		*	Influence of water temperature on growth of rainbow trout
		*		*	Minimum daily requirement of digestible energy and feed for rainbow trout at three different water temperatures
(Ogilvy and DuBois, 1982)	Bluefish	*	*		Fish swimming angle plotted against swimming speed
		*	*		Drag vs. water speed
		*	*		Thrust versus speed with neutral buoyancy
(Rome, 1990)	Carp	*	*		Effect of temperature on sarcomere length excursion, tail beat frequency and muscle shortening velocity
		*	*	*	Recruitment order of motor groups at 10 and 20 °C
		*	*		Range of V/V_{max} values of red muscles during swimming at different temperature
(Briggs and Post, 1997)	Rainbow Trout	*	*	*	Predictive relationship between respiratory, swimming speed and temperature
(Koskela et al., 1997)	Baltic Salmon	*		*	Temperature effects on feed intake and growth in Salmon
(Smith et al., 2005)	Rainbow Trout	*	*	*	Comparison between turbulent kinetic energy and average velocity in flume experiment
(Bejan and Marden, 2006b)	Various	*	*		Comparison of theoretical predictions with the speeds, stroke frequencies and force outputs of a wide variety of animals
(Syme et al., 2008)	Various		*	*	Cost of swimming and the relation between the whole oxygen consumption and the swim speed
			*		Tail beat frequency and muscle strain at different swim speeds
			*		Net power output
(Clark et al., 2010)	Sockeye Salmon	*	*		Correlation between daily mean visceral temperature and daily mean heart rate
			*	*	Correlation between oxygen consumption rate and heart beat rate

The most comprehensive studies on trout energetics to-date are without a doubt the result of the long-term studies performed by Elliot who proposed the following bioenergetics model for trout (Elliott, 1975; Elliott et al., 1995):

$$dB = C_e - F - U - \left(R_a + R_s + R_d\right) \tag{5.3}$$

where dB is the energy accumulated for growth and reproduction, C_e is the food consumption, F, U are the energy losses due to feces and urine, R_a, R_s are the energy requirements of active and standard metabolism, and R_d is the energy required for digestion.

Elliot's differential model appears to be energetically comprehensive and even performed well in a well-known lifetime study on drift-feeding brown trout in New Zealand (Hayes et al., 2000). However, in order to apply the model in finite time considering hydropeaking, coupling equations for all of the energetic terms would be required on a minute-by-minute basis. Determining the relative contributions to disequilibrium requires coupling the analysis of mechanical, chemical and thermal processes (Table 5-2).

Table 5-2 Required assumptions when considering fish as a thermodynamic system.

	Swimming	**Feeding**	**Reproduction**	**Metabolism**
Activity causing disequilibrium	Acceleration during swimming	Changed swimming behavior, stoichiometric changes due to food input	Changed swimming behavior, stoichiometric change due to egg/sperm production	Chemical processes out of cyclical equilibrium
Impact on the state of equilibrium	Mechanical	Chemical*, Thermal, Mechanical	Chemical, Thermal, Mechanical	Chemical, Thermal

* chemical and thermal processes are coupled via the fundamental Gibbs relation, Eq. (5.1).

5.2.1 Metabolism and growth

The energy of ingested food is divided into a wide array of components in the fish's body. Due to the variety of metabolic pathways, there are many processes in which energy can be dissipated into waste heat. Losses occur in feces, gill excretions, and as heat. The magnitude of the losses depends primarily on the diet and level of feeding. The changes in the free energy in a fish's diet cannot be measured directly, but instead must be estimated by looking at the balance between inputs (food and oxygen) and outputs (feces and metabolic wastes) (Cho et al., 1982).

Breaking down the fish's metabolic processes into a series of energy degrading events, we find that at the end, only some 5-10% remains for growth, storage and reproduction (Fig. 5-2).

Beginning with the intake energy (IE), we find that not all of it can be converted to digestible energy (DE) and is expelled as lost energy in the feces (FE). Metabolizable energy (ME) represents the remaining DE corrected for energy losses by excretion through the gills (ZE) and urine (UE) (similar to Elliot's model). The difference between ME and the energy which is available for growth or reproductive products (RE) is the energy which is lost as heat. Heat loss occurs primarily via two processes: the heat increment of feeding (HiE) and via maintenance heat loss (HEm).

The factors contributing to the HiE are the digestion and absorption processes (HdE), the transformation and conversion of the substrates and their retention in tissue mass (HrE). The temperature plays a major role in the determination of HiE and it has been found that the HiE in fish is greater for diets with high protein content. As an example, it is found that for rainbow trout raised at 15 °C, the HiE is 5-15 % of the total energy consumed (IE) but fell as the ratio of energy to protein decreased. The net energy (NE) is the remaining energy which may be used by the fish for maintenance and growth (US National Research Council Committee on Animals, 1993).

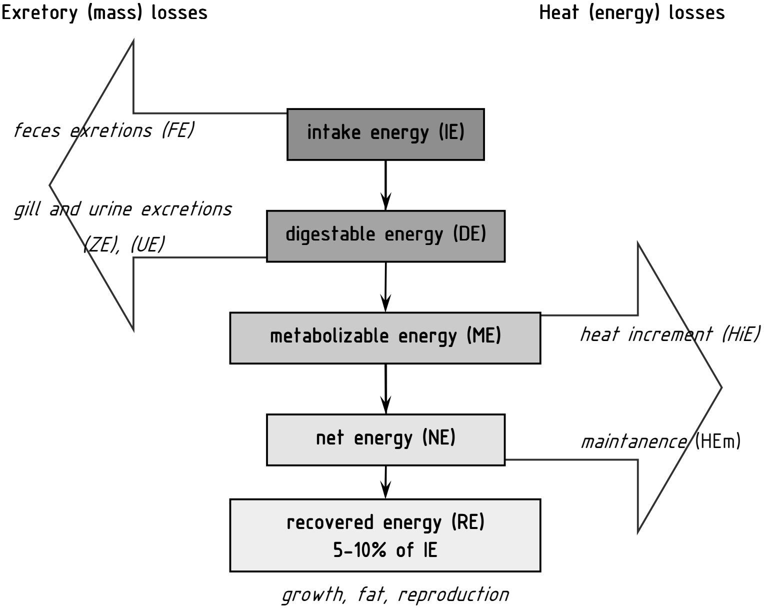


Fig. 5-2 Schematic representation of fish energetics as a linear metabolic chain. The results of energy transducing processes are shown in the grey boxes in the center of the diagram. Mass and energy losses are shown in the italics on the left and right sides, respectively. After US NRCCA (1993).

Bioenergetics models usually consist of a simple differential equation describing growth in terms of intake and output (Rice and Cochran, 1984), although newer models can include terms accounting for the temperature dependence of consumption, metabolism and some dynamic conditions as well (floods, temperature peaks, etc.) (van Poorten and Walters, 2010). Difficulties in using bioenergetics models stem not only from parameter estimation, but from the fact that size-dependent growth rates taken from the field are representative of both consumption *and* metabolism (Walters and Essington, 2009). The resting metabolic cost is taken as a simple function of body mass (in biology often referred to simply as ‘size’):

$$R_b = aM^b \tag{5.4}$$

where R_b is the resting oxygen consumption (mmol h^{-1}) , a is a species and lifestage-specific constant , b is an allometric scaling exponent, and M is the wet body mass (g). In lieu of the wet mass, some studies take fish-specific allometric ratios, such as the height of the caudal fin into account (Palomares and Pauly, 1989). Temperature sensitivity of the metabolic respiration can also be accounted for by correlating the Arrhenius relationship with Eq. (5.3) (Clarke and Johnston, 1999). In addition to temperature effects on the resting metabolic rate, long-term effects of temperature on individual fish growth and development should also be considered (Fig. 5-3). In most fish, there are a relatively small number of metabolic pathways responsible for energy production (Jobling, 1994). Because these pathways are sensitive to temperature effects, it is shown that trout and salmon raised in two different temperature regimes can exhibit a large disparity in size due to the cumulative difference in the relative growth rates of each group (Koskela et al., 1997; Ineno et al., 2005). On average it is found that both trout and salmon raised in warmer waters grew faster and larger.

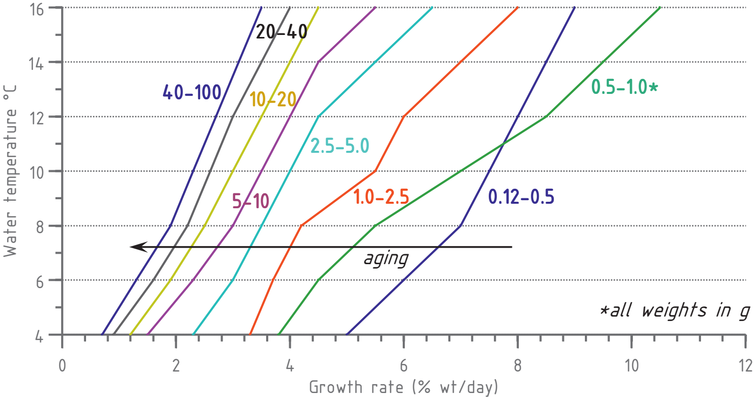


Fig. 5-3 Growth rate of young rainbow trout as a function of water temperature and weight class. Fish grow faster with increasing temperature and slower with age. After Austreng et al. (1987).

We have seen that the use of the Gibbs relation aids in conceptually breaking down the study of fish energetics into thermal, mechanical and chemical components. There exist a wide variety of physiological activities between a fish ingesting high energy quality food (uptake of sources of free energy) and expelling low quality material waste and heat (entropy discharge). Further complicating the study of simple linear metabolism models (Fig. 1-2) are external factors such as the surrounding water temperature, which can affect both short-term metabolic rates and long-term growth. For example, it has been found that interspecies seasonal variation in temperature tolerances exist in stream fish even *after* their acclimation in constant temperature tanks (Kowalski et al., 1978). In this study we acknowledge these variable regulatory processes as a definite source of error, and concentrate only on the short-term effects of hydropeaking on fish. Following the discussion of the last chapter, fish should seek out locations in which their momentary exertion is moderated by access to food and the ability to grow and reproduce. We focus on testable metrics such as respiration which aid in estimating the energy expenditures of fish subject to rapid changes in the local flow field.

5.2.2 Respiration

Although we have previously described the energetics of fish swimming in three simple categories, it should be noted that unlike inanimate chemical reactions where a decrease in temperature may serve to slow the reaction rate, fish locomotion is an integrated process made up of muscular, neural, metabolic and other biomechanical processes (Rome, 1990). Changes in the rate of a fish's oxygen consumption are the net result of these processes, are well correlated to muscle output and embryo growth, and are standard in the study of fish energetics for well over 50 years (Heath and Pritchard, 1965; Zotin et al., 1967).

The field metabolic rate or total respiration of a fish consists of three components: the standard metabolism, activity metabolism, and feeding metabolism (Briggs and Post, 1997). In studying the relation between the local flow velocity and the fish, one important result is that the respiration intensity of trout does not simply increase with increasing flow velocity. This is an important consideration when using standard habitat models which typically use velocity magnitudes. Taguchi and Liao (2011) show that rainbow trout have substantially different oxygen requirements when holding position behind a cylinder, significantly depends on swimming costs due to the induced flow field. They provide evidence over a range of swimming behaviors: entraining, bow riding, and Karman gaiting. Fish Karman gaiting in a vortex street possess an energetic advantage from upstream vortices. They also found that the free stream velocity *in combination* with particular flow field configurations provide the minimum rate of oxygen consumption. This 'energetics hierarchy' is reflected in the fact that entraining uses the least oxygen at 3.5 L/s, but for bow riding the lowest is at 5 L/s. Free stream swimming is shown to have the highest cost (33% higher than the best alternative).

There exist numerous theoretical and empirical studies showing that fish minimize metabolic power used by their muscles at various swimming speeds (Johnston, 1983; Taylor, 1985; Schultz and Webb, 2002; Webb, 2006; Ellerby, 2010), the most applicable to this work being Webb's two-part treatise on 'The Swimming Energetics of Trout' (1971a, 1971b). Webb found through comprehensive analysis that the average active swimming rate of oxygen consumption are 658.5 O_2/kg/h at a critical swimming speed of 58.1 cm/s or 2 body lengths/sec (Fig. 5-4).

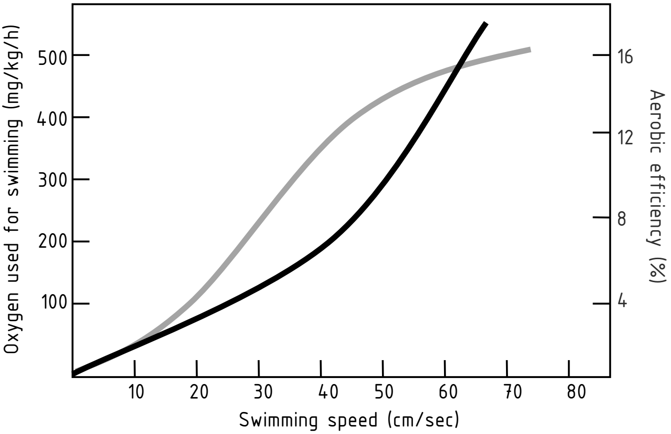


Fig. 5-4 Oxygen consumption (black) and aerobic efficiency (grey) as a function of swimming speed for the control group in Webb's study on the respiration of rainbow trout. After Webb (1971b).

5.2.3 Thermoregulation

Fish are poikilothermic, and for them to maintain a constant temperature there is only one absolute requirement: heat loss must equal heat gain. To maintain a constant temperature, heat transfer from the body to the water must occur at the same rate that is produced internally by its net metabolic activity. Metabolic heat production can easily increase more than 10-fold with activity, and unless heat loss is increased in the same proportion, a fish's body temperature will rapidly rise. Furthermore, the conditions for heat loss vary seasonally with water temperature (Kowalski et al., 1978). For an alpine fish, the physiological heat transfer mechanisms are primarily via *conduction* and forced *convection*. (Although in the last chapter, only conduction is mentioned in the discussion on the practical application of the top-down approach). Heat transfer only becomes possible if a temperature differential exists between the body and the environment (Schmidt-Nielsen, 1997). For fish, 80-90% of the heat from the blood is lost to the surrounding water during passage through the gills. However, this is still a small amount when considering that 70-90% of the total metabolic heat produced is lost through the body wall and fins (Stevens and Sutterlin, 1976). A notable exception in teleost fish is the tuna, which has evolved a vascular counter-current heat exchange process decoupling aerobic heat production from heat loss via the gills (Brill et al., 1994). This remarkable adaptation to active thermogenesis has allowed the bluefin tuna (*Thunnus thynnus*) to adjust its internal body temperature distribution making it effectively independent of the water temperature (Carey and Teal, 1969). Whether trout or tuna, fish are still viewed by many as simply 'cold-blooded.' The fact to keep in mind is that a temperature gradient caused by metabolic heat production however small, does indeed exist.

Heat conduction takes place through the contact of bodies, whether they are solids, liquids, or gases. Heat conduction consists of a direct transfer of the kinetic energy of molecular motion, and following the second law always from regions of higher temperature to those of lower temperature. A uniform conductor in which one end is kept warm and the other cold, the rate of heat transfer can be expressed as:

$$Q = kA\frac{T_2 - T_1}{l} \tag{5.5}$$

Where k is the thermal conductivity of the conductor, A is the area through which heat flows and T is the temperature (at 1 and 2) separated by distance l (Schmidt-Nielsen, 1997).

It is emphasized that for the fish's body temperature to remain constant, the rate of heat loss must be equal to the heat gain. This does not mean that the fish's body temperature always remains constant. Assume a steady state where the heat loss does not quite equal the metabolic heat production and is slightly lower. The body temperature will then inevitably rise. This means that part of the metabolic heat remains in the body instead of being lost, and the increase in body temperature thus represents a net storage of thermal energy.

If the mean body temperature decreases, which happens when heat loss exceeds heat production, we can regard this excess heat loss as heat removed from storage. The quantity of heat stored depends on the change in mean body temperature, the body mass, and the specific heat capacity c_p of the tissues (for most animals approximated as 0.8 J/kg K). Selong et al. (2001) provide key temperature ranges in understanding the sensitivity of a fish:

T_L - Low temperature at which the fish of a given species begin to perish.
T_H - High temperature at which the fish of a given species begin to perish.
T_G - Peak growth temperature at which the fish grow the fastest.
T_F - Threshold feeding temperature at which the fish cease feeding.

Related to metabolism and growth, there is a correlation between the T_L and the feed, lipid, and protein efficiencies within 'suitable' ranges allowing for the direct study and determination of temperature dependent effects on an individual fish. Temperature changes are expected to account for sublethal differences in the growth rate, feed consumption, and the feed efficiency. The effect of temperature on the mortality of a given species is only relevant to a critical threshold range at or below T_L, and above T_H. All temperatures in between may not be optimal, but are not lethal (Fig. 5-5).

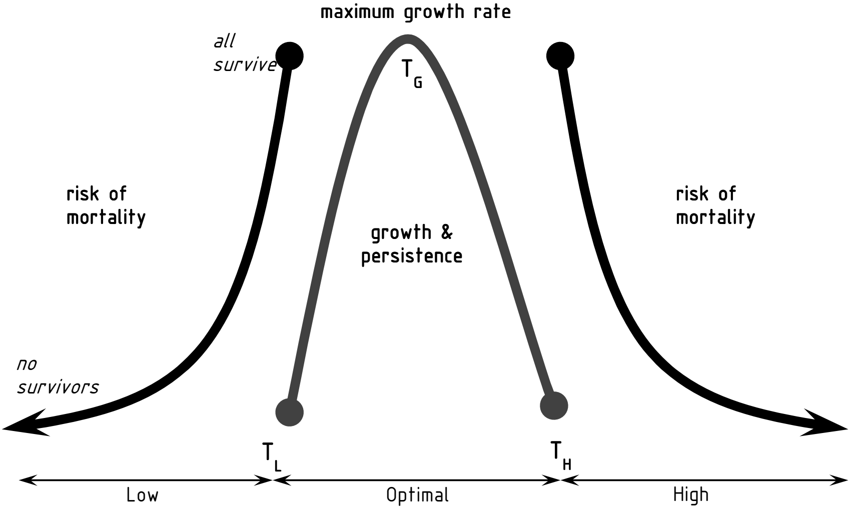


Fig. 5-5 Temperature dependence of growth and mortality for an ideal alpine fish. Low and high regions indicate an increased risk of temperature-dependent mortality. Whereas within the optimal range, no temperature-dependent effects of mortality are expected to occur. Within this range considerable change in the growth rate as a function of the surrounding temperature is expected to occur, where each individual has a *de facto* species specific maximum growth rate. The optimal zone is that which is close to the optimal steady-state growth rate of a given species and lifestage.

The previous sections have focused on the internal energetics of the fish, yet we know that the river+fish system, the majority of the energy is in the flowing water. The second half of this chapter is dedicated to investigating the effects of the flow field on the alpine fish.

5.3 Hydraulics

Scale, turbulence, drag, vorticity and periodicity are at a minimum the five main properties needed to study the flow patterns found in, and used by the river+fish system. The purpose of this section is to paint a picture of the hydraulic conditions experienced by the alpine fish. It is hoped that in the end it will be shown that *patterns* not point values are the parameters we seek. Lacey et al. (2011) have recently published a work on fish locomotion, and recommend using a framework which includes the combination of four turbulence factors to better identify relations between fish swimming and hydraulics; *Intensity, Periodicity, Orientation, and Scale* (IPOS). This section is written in the same spirit, focusing on describing a constellation of parameters and their importance on fish locomotion.

5.3.1 Scale

Coherent flow structures smaller than LCS (Eq. 4.32) possessing vorticity are considered 'eddies', and regions of flow occurring as fronts of high and low speed fluid are considered 'wedges'. The largest length scale of interest L, is characterized by the Reynolds number Re:

$$\mathrm{Re} = \frac{\bar{u}_i L}{\nu} \tag{5.5}$$

Where ν is the kinematic viscosity, $\bar{u}_i$ is the characteristic mean velocity, and L is the characteristic length scale determined by the channel geometry. In this work, the bounding maximum length scale is taken to be the water depth (Fig. 5-6). The Reynolds number is the measure of inertial to viscous forces and governs both the transition to turbulence and the range of available eddy sizes in the river.

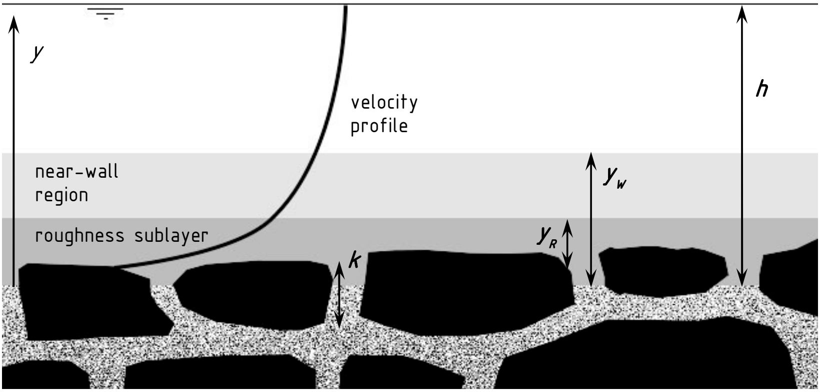


Fig. 5-6 Terms used in estimating the vertical turbulent length scale. The roughness height k is taken to be 1.5 times the height of the dominant substrate, assuming that the bed layer is spatially homogeneous in terms of its grain size distribution. After Bezzola (2002).

The length scale of interest for the study of individual fish is the correlation length or integral length scale L_u. Often called the eddy length scale, it is a measure of the smallest spatial extent, or wedge over which a region of fluid can be considered to have a uniform velocity. When the scale of turbulent eddies is small compared to the fish length scale, L_f they lack the momentum required to affect the fish (Tritico, 2009). A wedge with constant average convection velocity $\bar{u}$ has the momentum $\rho L_u^3 \bar{u}$. A swimming fish encountering this wedge has a momentum proportional to $\rho L_f^3 u_f$. Considering the ratio of the wedge momentum to the fish momentum provides an interesting relation:

$$\frac{\textbf{\textit{wedge momentum}}}{\textbf{\textit{fish momentum}}} = \left(\frac{L_u}{L_f}\right)^3 \frac{\bar{u}}{u_f} \tag{5.6}$$

Eq. (5.6) clearly shows that it is the *size* of the wedge relative to the fish, not its velocity which plays the largest role. This finding stands in stark contrast to the assumption used in conventional habitat models which use estimates of the local velocity magnitude as one of the main components in estimating fish habitat suitability. A wedge one quarter the size of the fish traveling at the same velocity will only have 1/64th of the fish's momentum and is not likely to affect the swimming performance of the fish. Tritico and Cotel (2010) demonstrated that when the largest eddies in a turbulent flow reach approximately $\frac{3}{4}$ of the fish length, creek chub had difficulty maintaining posture in the flow and their critical swimming speed are reduced by 20%. Lupandin (2005) also showed that there is a strong positive correlation between the body and turbulent length scales in the vertical plane, where longer bodies have higher turbulence thresholds (Fig. 5-7). The effects of turbulence above a threshold scale destabilize the fish, where larger fish are able to withstand a wider range of eddy sizes.

The smallest length scale in a turbulent flow is limited by the fluid viscosity and is defined as the Kolmogorov microscale η:

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \tag{5.7}$$

Where ν is the kinematic viscosity and ε is the specific energy dissipation rate. For a given river reach, the flow regime will result in a spectrum of characteristic length scales ℓ, related to the turbulence (Roy et al., 2004):

$$\eta \le \ell \le L \tag{5.8}$$

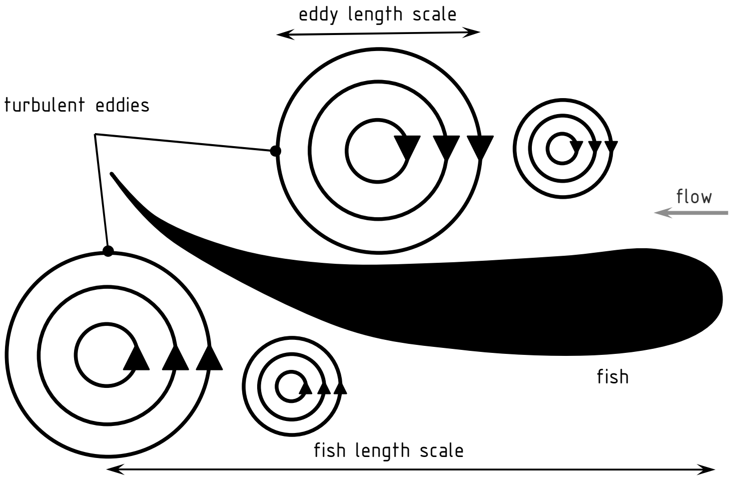


Fig. 5-7 Schematic showing the eddy orientation on fish swimming behavior. Fish are also affected by large wedges, not shown. Here a trout is shown using the Kármán gait due to the presence of periodic flow structures. After Lacey et al. (2011).

Alpine rivers subject to hydropeaking are uncertain environments where turbulence and coherent flow structures manifest across a range of scales from millimeters to meters. Further complicating the study of river hydraulics in the natural environment is that fact that turbulent eddies are in constant interaction with larger structures, where the wake of individual bodies enhance non-periodicity within the shear layer (Lacey et al., 2011).

5.3.2 Thrust and drag

Leonardo da Vinci is the first person on record to have carried out experiments of static friction, and the empirical law found for describing friction was published in 1699 by Guillaume Amontons (Butt et al., 2003). Generally stated, the frictional force is proportional to the load, and does not depend on the contact area. Generally, the relation between the frictional force F_F the load F_L is proportional to the product of the load and the coefficient of friction μ_F

$$F_F = \mu_F F_L \tag{5.9}$$

The reason why the resulting friction force is not proportional to the area at first seems puzzling, and was first adequately explained by Bowden and Tabor (2001) in their work on the microscopic analysis of surfaces. They found that the actual microscopic contact areas resemble atomic ‘alpine mountain peaks’ where polished or worn surfaces cause the rough peaks to be reduced to contact regions, resembling rolling hills. In the case of our alpine fish, the resulting friction losses are due to *skin friction* at the exterior interface with the water, a type of shear. In this case it is necessary to consider that the total friction loss is then estimated as the sum of the friction losses integrated over the body's wetted area.

The force of interest in the study of fish locomotion is the drag force. An equivalent is the work produced by the drag force along the body length, x. Thus the total boundary work is actually created by the drag along its body. The drag coefficient (C_D) is useful for comparing the hydrodynamic forces acting among different swimming animals. Careful attention must be paid to which coefficient is used, either the total surface area ("wetted area") or the maximum cross-sectional area ("frontal area") since both are commonly used in the literature. Engineers tend to use the frontal area for drag coefficients where the viscous drag is important, and the wetted area where pressure drag is more important (Alexander, 1990). In steady swimming, thrust equals drag, and data on thrust production are requisite to study swimming biometrics and energetic transport costs (Vogel, 1996). The dimensionless drag coefficient (Oertel et al., 2008) is defined as:

$$C_D = \frac{2F_D}{\rho v^2 A} \tag{5.10}$$

Where ρ is the fluid density, v the velocity, A is the reference area, and F_D is the drag force. The drag coefficient is useful to compare the effects of drag on objects of different configurations or morphologies. Furthermore, the dependence of C_D on the Reynolds number can deliver important information regarding the relative ratio of pressure (inertial or form) drag versus viscous (friction) drag. For fully turbulent flows, the behavior of C_D becomes complex and may be strongly influenced by turbulence. It has been found that most swimming animals have intermediate Re (10^2-10^5), where neither viscous nor inertial forces dominate the flow (Blake, 1986).

Fish are self-propelled systems whose body shape closely resembles that of an airfoil, where fluid forces in the axial direction are coupled to the motion of their center of mass (Borazjani and Sotiropoulos, 2010):

$$\frac{m}{\upsilon L^3}\frac{dU^*}{dt} = \frac{F_A}{\rho U_0^2 L^2} \tag{5.11}$$

m is the fish body mass, U^* is the normalized body speed, F_A the axial force, and U_0 is the self-propelled swimming speed in which the body is 'tethered' (Borazjani and Sotiropoulos, 2009). For a fish swimming steadily along the x direction, the axial component of the instantaneous hydrodynamic force along the x direction can be computed by integrating the pressure $pndA$, and viscous forces τn acting over the body surface:

$$F_A(t) = \int_A \left(-pn_3 dA + \tau_{3j} n_j\right) dA \tag{5.12}$$

where n_j is the j^{th} component of the unit normal vector over the area dA and τ_{ij} is the viscous stress tensor. Determining whether the axial force contributes a net drag or net thrust effect is accomplished via force decomposition, as an immersed self-propelled body produces both thrust and drag simultaneously. A full description of the method can be found in Borazjani (2008). The power at time t can be calculated as:

$$P(t) = \int -pv_i n_i dA + \int v_i \tau_{ij} n_j dA \tag{5.13}$$

where v_i is the velocity of a single immersed surface element dA. At mechanical equilibrium, the net drag and thrust forces are in balance such that it is either moving with constant velocity, or remains stationary. As soon as the forces are not in balance, the fish will either accelerate or decelerate, and the body velocity will no longer be constant. Thus the basic stability criteria for fish locomotion can be stated in terms of the relative balance between thrust and drag forces:

$$\begin{array}{ll} F_T = F_D & \text{Fish is stable, } v = const \text{ or } v = 0 \\ F_T \neq F_D & \text{Force imbalance, } dv/dt \neq 0 \end{array} \tag{5.14}$$

The concept of mechanical stability can useful when we observe that the instantaneous force or power estimates, though important may not be as critical as assumed when our observation of the undulatory locomotion of the fish is extended over a complete cycle.

Further complicating deterministic models of fish locomotion is the fact that fish use at least two known methods: drag and lift (Vogel, 1996). Drag-based thrust is used by fish to maintain position and perform quick movements using its paddle-like fins. Lift-based thrust however, is the propulsion method of choice for large-scale locomotion, and is most commonly associated with studies of fish-like swimming (Fig. 5-8).

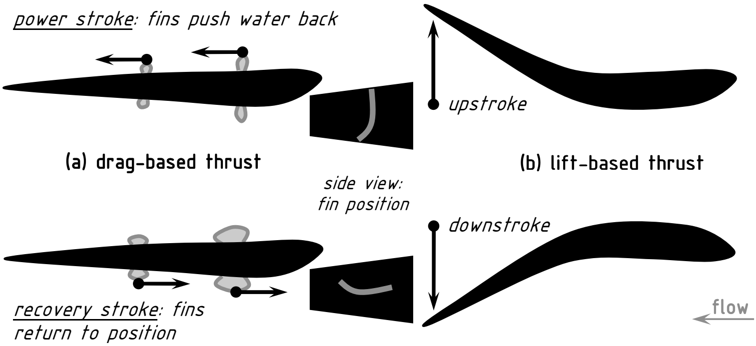


Fig. 5-8 Simplified image of the paddling, drag-based thrust mechanism of the pectoral and pelvic fins, and the oscillatory, lift-based thrust of a carangiform swimmer such as the trout. After Vogel (1996).

A wonderful example of the importance of thrust and drag in fish-like swimming is exemplified in a study on porpoise propulsion by Fejer and Backus (1960): It is known that porpoises are often seen 'jumping' away from the bow waves of large ships. After studying the problem it was found that the porpoises are not trying to escape at all. They are instead seen at first to coast along side, while making small adjustments in their position relative to the ship (Fig. 5-9). After finding spots with just the right imbalance of force and drag, they would hold a rigid posture and allow themselves to be 'shot' right out of the wave!

5.3.3 Vorticity

Most studies of muscle power production by fish have focused on steady or burst swimming. In alpine rivers, it is important to include both the heterogeneity and unsteady of the flow field, especially if we are to investigate hydropeaking. Obstructions in the water column create complex flow patterns with a huge variety of characteristics (Cook and Coughlin, 2010). Liao (2007) has shown that trout are particularly attracted to specific vortex characteristics, presumed due to their energetic savings. His study of the neuromuscular control of trout swimming in a vortex street showed that muscle activation is used for stability and control, but the vortices determined the trout's head motions. Furthermore, it is found that often *no* axial muscle activity is measured when in the gait, providing evidence that fish may be using vortex shedding from obstacles to get a 'free ride' (Fig. 5-10). When exposed to vortices induced by a cylinder wake, trout moved with the transverse flow component, allowing them to generate sufficient thrust to maintain their position relative to the cylinder (Liao, Beal, Lauder, and Triantafyllou, 2003a, 2003b).

A dead fish can even be propelled upstream when its flexible body resonates with oncoming vortices formed in the wake of a bluff cylinder. The body of the fish is thus able to extract sufficient energy from the oncoming vortices and develop sufficient thrust to overcome its own drag. The mechanical energy is extracted from the flow at the same time that thrust is produced. This is experimental proof that under proper conditions, a body can follow at a distance or even catch up to another upstream body without expending any energy of its own (Beal et al., 2006). This resonance plays an important role when considering the lift-based thrust mechanism used by fish. It is for this reason that we need to include periodicity into our constellation of parameters used to describe optimal flow patterns used by the river+fish system.

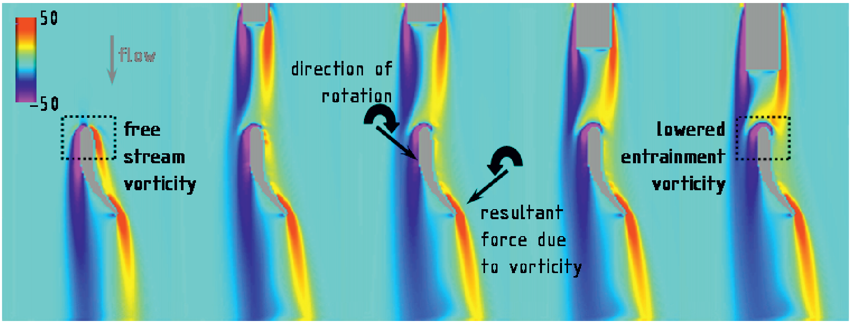


Fig. 5-9 Vorticity (Hz) estimates around a trout silhouette (Liao, 2004) at full tail stroke modeled using *flowsquare* 2.01 in a stationary, 2D flow field at 2 m/s. From left to right the length of the upstream bluff body increases, resulting in an asymmetric vorticity field at the front of the trout's body and a more uniform vorticity field around the left side of the body. The rightmost configuration results in the strongest couple against which the fish 'pushes,' propelling it forwards.

5.3.4 Periodicity

In general, the structure of a wake induced by submerged obstructions depends primarily on Re and St (of the fish's tail-beat frequency) and only *secondarily* on the body shape or swimming mode (Tytell et al., 2010). It is found that a critical Strouhal number St^* exists for fish at which constant speed inline swimming is possible for a given Reynolds number. Furthermore, it is found that St^* is a decreasing function of the Reynolds number for both carangiform and anguilliform swimmers. Thus neglecting small differences between individual fish, for each Re there exists a *unique* species and life stage dependent St^* at which steady inline swimming becomes possible.

This is important because it suggests that for each local Re fish are forced to select a restricted range of frequencies at which to undulate their bodies. There is only one 'optimal' St at which the production of thrust is large enough to cancel the drag they generate (Borazjani, 2008). This is confirmed by empirical observation of Pacific salmon (Lauder and Tytell, 2005), and on general reviews of fish propulsion kinetics (Triantafyllou and Triantafyllou, 1995; Triantafyllou et al., 2000). The extraction of energy from unsteady flows as a result of a stationary foil is called the **Katzmayr effect** (Lewin and Haj-Hariri, 2003). This work is extensively followed up on in studies of mechanical energy transduction processes from the mean flow field into the oscillatory motions of a body both generating and feeding off of vortex shedding processes (Sarkar and Venkatraman, 2006; Patel and Kroo, 2008).

5.3.5 Turbulence

Turbulence in alpine river systems is important because of the effects of energy and material exchange due to mixing. Three-dimensional fluctuations initially bring fluid parcels close to each other and then rapidly separate them. This action leads to an effective exchange of heat, mass and momentum. In this work, the timescales of 10 min+ investigated are too large to explicitly consider diffusive properties in the time scales over which they occur and thus mixing is considered to be instantaneous and complete. This does not however mean that aquatic organisms do not take advantage of this. The respiratory requirements of incubating eggs, drift feeding macrozoobenthos, aquatic plants and fish all require the diffusive turbulence-aided fluxes of dissolved oxygen and nutrients within constrained limits in order to persist.

Turbulent flow structures are often described using a multitude of metrics, including the turbulence intensity, turbulent kinetic energy, relative turbulence intensity, Reynolds shear stress, vorticity, eddy length scale, eddy diameter, circulation, turbulent energy dissipation rate, axis of eddy orientation, direction of dominant fluctuation, and just plain energy. Such a huge range of ways of describing ‘turbulence’ makes the direct comparison of field and laboratory studies difficult to extrapolate into engineering best practice. However, analysis of the fundamental equation of fluid flow – the Reynolds-averaged-Navier-Stokes equation (RANS) can provide information about the role of turbulence in our hydraulic system.

Particular to turbulent flow is its random macroscopic nature, which prohibits exact numerical solutions in real engineering applications unless every particle can be resolved. Even if this were possible, microscopic imperfections in the flow field numbering in multiples of Avogadro’s number would make perfect representation impossible. We can make use of the random nature of the flow fluctuations, which can be in part accounted for and included in numerical models by decomposing the flow into a steady *mean value* $\overline{u}$ and its *time-dependent fluctuations*, u' leading to an expression of the local velocity as:

$$u_i = \overline{u_i} + u_i' \tag{5.15}$$

The mean flow component does stretching work on the large eddies, providing energy to maintain the turbulent flow. An energy cascade develops in which kinetic energy is progressively diminished from the largest eddy scales to the smallest, finally dissipating into heat. The scaling behavior in turbulent flow can be observed in terms of the wavenumber of the fluctuations $(2\pi\ f/U)$ where f is the frequency. Thus an entire *energy spectrum* of turbulence exists within a single volume element, not just one single magnitude (Fig. 5-11).

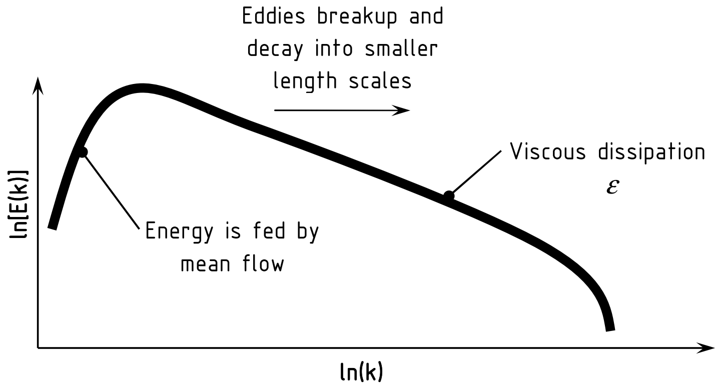


Fig. 5-10 Graphical relationship between log energy spectrum, E(k) and turbulent kinetic energy, k.

The gravitational body force, pressure and friction drag, isotropic hydrostatic pressure, viscous stresses (taken as negligible outside the viscous sublayer), and the Reynolds stresses caused by turbulence all interact inside a single river+fish volume element. The Reynolds stress tensor is symmetric and includes six terms; three along the diagonal (normal stresses) and three nondiagonal shear stresses:

$$\begin{bmatrix} \rho\overline{u'u'} & \rho\overline{u'v'} & \rho\overline{u'w'} \\ & \rho\overline{v'v'} & \rho\overline{v'w'} \\ & & \rho\overline{w'w'} \end{bmatrix} \tag{5.16}$$

The Reynolds shear stresses in Eq. (5.10) represent the turbulent flux of momentum within a fluid element related to the force via Newton's second law. In turbulent flows, the normal stresses are always non-zero because they contain the square of the velocity fluctuations (Fig. 5-12). The non-diagonal shear stresses associate correlations between velocity components, and because they are not statistically independent their time-averaged product ($\overline{u'v'}$) also does not go to zero (Versteeg and Malalasekera, 1995). In turbulent flow, the non-diagonal Reynolds shear stresses are much larger than the viscous stresses and are used to estimate the turbulent flow resistance using the eddy viscosity, μ_T:

$$-\rho\left(\overline{u'w'}\right)=\mu_T\,\frac{\partial\overline{u}}{\partial z} \tag{5.17}$$

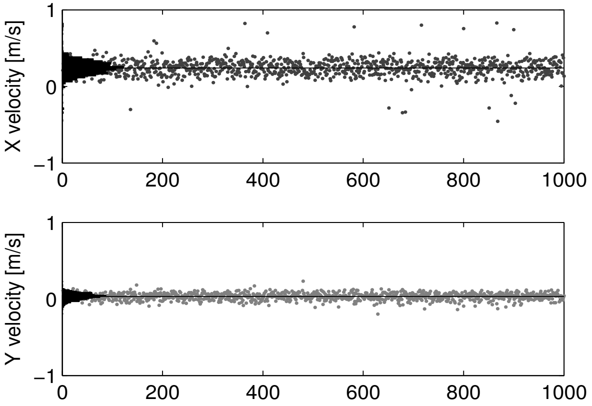


Fig. 5-11 Measured turbulence at 12 cm above the bed in a small creek with a flow depth of 20 cm. The top graph shows the principle downstream x-velocity component measured at 1 Hz using an acoustic Doppler velocimeter, bottom the y or transverse velocity. Both locations show a clear mean velocity as well as different ranges of symmetric fluctuations about the mean. The histograms of each data set are shown vertically on the left of each graphic.

The turbulence intensity $\overline{u'_i u'_i}$ is a vector quantity whose components are derived from the three normal turbulence intensities. They are often normalized by the shear velocity, or local longitudinal velocity, and referred to as *relative turbulent intensities*. As discussed previously, within acceptable range, fish do not have problems maintaining stability within a range of turbulence (Ogilvy and DuBois, 1982), however more recent studies on rainbow trout by Smith et al. (2005, 2006) show that turbulence intensity may be a good proxy variable describing overall habitat complexity, and also suggest that turbulence intensity thresholds may trigger a particular behavioral response.

The instantaneous kinetic energy of a volume element $KE(t)$ taken at time t and containing a turbulent flow is the sum of the mean kinetic energy $MKE = 1/2\rho\left(U^2 + V^2 + W^2\right)$ and the turbulent kinetic energy $TKE = 1/2\rho\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$:

$$KE(t) = MKE + TKE \tag{5.18}$$

The full equation for the turbulent kinetic energy (Versteeg and Malalasekera, 1995) broken down into its component parts leaves the following seven terms:

$$\frac{\partial(\rho k)}{\partial t} + div(\rho k\boldsymbol{u}) = div\left(-\overline{p'u'} + 2\mu\overline{u'e'_{ij}} - \rho\frac{1}{2}u'_i\cdot\overline{u'_i\,u'_j}\right) - 2\mu\overline{e'_{ij}\,e'_{ij}} - \rho\overline{u'_i\,u'_j}\cdot E_{ij} \tag{5.19}$$

(1) (2) (3) (4) (5) (6) (7)

1 – Rate of change of k
2 – Convective transport of k
3 – Transport of k by pressure
4 – Transport of k by viscous stresses
5 – Transport of k by Reynolds stress (due to fluctuations)
6 – Rate of energy dissipation
7 – Turbulence production

The specific rate of energy dissipation, ε (term 6 of Eq. (5.19)) can alternately be written as:

$$\varepsilon = \frac{v^3}{l} \tag{5.20}$$

where v is the velocity and l is the characteristic eddy length. Since the dissipation rate varies over the location of the volume element, we wish to determine the *average dissipation* within the volume element and must therefore resort to determining the local dissipation estimate in terms of average quantities inside each individual model element.

The $k-\varepsilon$ model allows for the use of the element's estimated TKE to calculate the turbulent length scale as:

$$\varepsilon = \frac{C_\mu TKE^{\frac{3}{2}}}{l} \tag{5.21}$$

Where C_μ =0.09, and TKE can be determined based on observed fluctuations from the mean velocity. However, in using the results of a 2D hydraulic model, we only obtain the mean depth-averaged velocities at our model nodes, and must thus then come up with estimates of both TKE and l if we wish to use Eq. (5.15) to estimate ε. In this work, we first estimated the numerator of Eq. (5.15) as the product of the empirical constant k_T (discussed in the following section) and the depth averaged velocity at each model node, U. This reformulation is a combination of Eqs. (5.14) and (5.15):

$$\varepsilon \approx \frac{k_T U^3}{l} \tag{5.22}$$

It is important to note that even in flows where large changes in the mean velocities and pressures can be found in one or two dimensions, turbulent fluctuations *always* have a three-dimensional character. Further complicating the issue is the fact that even the simplest turbulent flows – those over a fixed flat plate of uniform roughness *contain a range of eddies.*

As a reference, Table 5-3 provides an overview of the turbulent eddy scales found in a 50 mm pipe with a Re of 10^5.

Table 5-3 Eddy size and frequency for water flowing through a 50 mm diameter pipe at a velocity of 1.8 m/s and Re = 10^5. After Ahmadi (2011).

Eddies	Size [mm]	Frequency [Hz]
Largest eddies	25	3.5
Energy containing eddies	0.6	140
Dissipative eddies	0.125	450
Kolmogorov eddies	0.025	1300

Turbulent flow regimes are described using a characteristic velocity and characteristic length of the larger eddies which are usually of the same order of magnitude as the mean length scales in a volume element of velocity U and depth L. For systems with large eddy Re, the inertial effects of the mean flow are much greater than the viscous effects, driving the system.

In the sections on thermodynamics, it is shown that the temperature scales the rate of entropy production with respect to heat transfer. However in hydrodynamics, the rate of turbulent dissipation is assumed to be *independent of temperature* since we are dealing with high Re systems. For low Re systems however, the temperature dependence of dissipation processes should be taken into account as the temperature affects the fluid viscosity as well. The local entropy production in a volume element of the river is estimated due to viscous stress in the fluid element body as the ratio of the product of the hydraulic viscous dissipation rate and the fluid density to the water temperature:

$$\sigma_H = \frac{\rho}{T}\varepsilon \tag{5.23}$$

The numerator provides an estimate of the heat transfer due to viscous dissipation in the fluid. Additionally, even under steady flow conditions where $\rho\varepsilon = const$ in given model element, diurnal temperature changes in the river will cause a shift in the local distributions of σ_H (Fig. 5-13). The inclusion of both the hydraulic *and* thermal properties of the water body surrounding a fish can be therefore estimated relatively accurately, as long as the time scales of analysis chosen during intervals of thermal and mechanical equilibrium of the surrounding system.

Due to the simplifications inherent in using a 2D model, temperature gradients in the vertical direction are not included. This is a recognized source of error, as vertical temperature gradients are expected to play a large role in the near shore regions where water may have locally higher temperatures.

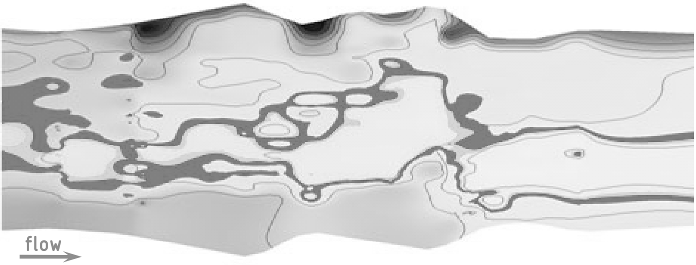


Fig. 5-12 Spatial distribution of estimated σ_H under steady flow conditions, but after a change in temperature from 5 to 10 °C. Note the spatial shift of the range of epsilon values. Correspondingly, it can be expected that the fish will react to this change and relocate themselves in the river where the entropy production rate is once again lowered.

In a river with a water temperature of 10 °C, the kinematic viscosity is $1.307\text{x}10^{-6}$ (m^2/s), requiring that the smallest eddies have a characteristic velocity and/or depth in the submilimeter range. Currently such accurate measurements are not possible for widespread investigation in river systems, and in this work estimates of the mean value of the velocity are taken directly from the results of the depth-averaged 2D hydraulic model. Determination of the statistical properties of the fluctuations is considerably more difficult without direct measurement of the turbulent fluctuations themselves. In the proceeding section, ranges of values for both the velocity and depth fluctuations are presented based on field surveys.

5.3.6 Energy dissipation estimates

A turbulence intensity of 1% or less can be considered as low and those larger than 10% high (FLUENT, 2011). The coefficient k_T introduced in Eq. (5.16) is devised in order to aid in accounting for the portion of the kinetic energy dissipated into heat as a function of both the mean and turbulent kinetic energies. It is needed to:

1) Account for variation in the use of depth-averaged velocities from the 2D model.

2) Remove the contribution of the turbulent energy involved in the transport and production terms representing the mechanical energy *not dissipated* into heat.

This simple metric is derived to investigate the different levels of turbulence in the investigation reaches, and is taken as the ratio of turbulent to mean kinetic energy:

$$k_T = \frac{TKE}{MKE} = \rho g \frac{(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})}{(U^2 + V^2 + W^2)} \tag{5.24}$$

This quantity differs from more common metrics using the turbulence intensity, which compare the root mean square of the fluctuations against the magnitude of the mean velocity. It can be thought of as the turbulence relative to a background mean flow field. When using the metric in Eq. (5.24), it is important to take into consideration the relative magnitudes of the TKE as they are experienced by the fish, as normalizing turbulence metrics tends to obscure the magnitude of the turbulence as experienced by the fish. For example, a normalized turbulence intensity measured in two separate experimental setups may be the same even if the measured turbulence is of different orders of magnitude.

The results of the reference study are shown in Table 5-4. where the average k_T ranges from 0.10-0.23. Surprisingly, the highest value is found in the shallow, slow flowing creek. Samples in this reach were taken in front of, behind, and along side a small boulder, where the highest k_T of the three is found to be in the wake at 0.93. On average, highest values are however found where they are most expected: in the turbulent and fast-flowing fish pass, where one location alone had a k_T of 23! The main finding is that there is no well-defined function relating the TKE directly to MKE in flow systems of ecological importance. In cases where no velocity measurements can be taken, reference values can offer valuable guidelines for estimating point wise values of the TKE when U is available from numerical models. In general, if no other information is available, a safe assumption would be to use the following empirical relation, when the average velocity and length scale are known:

$$\varepsilon \approx \frac{0.12\ U^3}{l} \tag{5.25}$$

Table 5-4 Summary of field data used in estimating the relation between k_T and U. The investigation reach with the highest average kinetic energy is the Kocher Fish Pass, and the lowest is the Bärensee Creek. Intermediate reaches with natural morphologies include data from the Puni and the Kocher.

Reach Name	**No. Sampling Locations**	**No. Obs.**	**Obs. Length (sec)**	k_T **mean**	k_T **min**	k_T **max**	U **(m/s)**
Bärensee Creek	3	3,000	1,000	0.23	0.23	0.93	0.19
Kocher Fish Pass	13	780	60	0.12	0.02	23.42	0.80
Kocher River	16	960	60	0.14	0.05	6.43	0.11
Puni 1	10	1,440	90-180	0.13	0.02	13.24	0.44
Puni 2	12	1,440	90-180	0.10	0.02	0.31	0.22
Puni 3	10	1,440	90-180	0.19	0.05	2.77	0.24
Total	**64**	**9,060**					

5.4 Answering three questions in fish energetics

5.4.1 Why are fish poikilotherms?

The answer of course, lies in thermodynamics. The specific heat of water is the measureable quantity characterizing the amount of heat required to change a substance's temperature, given in J/K. As previously shown, the alpine fish are submerged in water, experiencing constant thermal contact with their surroundings via their exterior appendages, gills and skin. Knowing that this is the only method of heat and entropy transfer out of the fish, the question: "why are fish poikilothermic?" is a valid question which should be asked.

As alluded to in the beginning of this chapter, water has the highest specific heat capacity of any common earth substance at 4.186 J/gK, whereas air at 25 °C and 1.103 bar has a specific heat capacity of only 1.006 J/gK. Considering an equal mass of each, water can store 4 times more thermal energy than air, subject to the same conditions. As mentioned previously, systems submerged in water lose or gain thermal energy primarily via conduction and forced convection. Fish thus experience changes in the temperature of the river much more severely than their terrestrial counterparts due to the higher specific heat capacity of the surroundings, all else being equal.

It is shown that fish must maintain a body temperature gradient so that entropy can be exported into the surrounding water. The maximum power output of an irreversible heat engine occurs when the energy conversion efficiency is (Curzon and Ahlborn, 1975; Bejan, 1996b):

$$\eta = 1 - \left(\frac{T_L}{T_H} \right)^{1/2} \tag{5.26}$$

Where T_L and T_H are the high and low temperature reservoirs. Recall that the heat flux (at constant mole numbers) over any process is defined as the difference in internal energy between the final and initial states minus the work done during the process (Callen, 1960). In performing mechanochemical work, the fish's body most often has a higher temperature than its surroundings. The maximum efficiency of an equivalent animate "power plant" would appear to occur when the ratio of T_L to T_H is minimized. Though perhaps not immediately obvious when looking at the above equation, for the animate system the optimum case actually occurs when $T_H \approx T_L$. This is because fish muscle is made up of microscopic mechanochemical engines, *not* heat engines.

According to Eq. (5.26), if a fish acted as a heat engine, it would have a maximum theoretical efficiency of zero. However, we must remember that animate systems possess flow structures whose processes are evolving whilst maintaining the balance between the useful work done and the waste heat produced, following the engine+brake concept of the previous chapters. The thermal energy generated during spontaneous chemical reactions always result in a lowering of the free energy (usually Gibbs), where the heat exported to the surroundings should be only the waste heat, or entropy given off by the fish's body. Because some of the thermal energy is used *internally* to drive endothermic reactions, it can be expected that a large gradient between T_L and T_H would be energetically unfavorable. This is due to the fact that animate systems have finite energy storage. Modern research on the evolutionary development of thermoregulation (Clarke and Pörtner, 2010) also follows this point of view. When less energy is given off as waste heat, more of the available energy which is stored within the body can be used to do useful work. This is the reason *why* fish are poikilothermic. For poikilotherms it makes sense to maintain their temperatures as closely to those of the surroundings as possible in order to balance the work done during free energy transduction with the entropy generated and discharged as waste heat to the surrounding water.

To wit, homeotherms (T_H is fixed, T_L varies) are also beholden to the same rules. However, since the specific heat capacity of air is much lower than that of water, terrestrial organisms have evolved other strategies: evaporative cooling (sweating) and adaptive heterothermy, the ability to retreat to locations where T_L can be moderated by burrowing, posturing, and otherwise modifying their body core temperature to shed excess heat (Schmidt-Nielsen, 1997; Vaughan et al., 2010). The evolution and behavior of terrestrial homeotherms such as mammals due to heat transfer is clearly to be seen. Thermodynamics wins every time.

5.4.2 Why are fish open systems?

Consider for a moment the fish as a closed system and the alpine water as the surroundings. The fish may exchange some small amount of heat with the surrounding water and its interactions are considered irreversible. The accounting of the total change in entropy is then given by an equivalent reversible heat transfer $\delta q/T$, and the entropy produced due to irreversibilities $d\sigma$:

$$dS = \frac{\delta q}{T} + d\sigma \tag{5.27}$$

The fish is now approximated as being an irreversible, quasi-closed thermodynamic system (no feeding or excretion, respiratory expenditure included only in the work and heat terms) and we can thus apply the first law as $\delta q = dU - \delta w$. Recalling that the entropy production for an irreversible process must lead to a net positive entropy production we also have the additional inequality constraint $d\sigma > 0$. We are then left with the familiar expression of the work done by the fish on the surroundings in terms of the change in internal energy and the net positive total change of entropy as:

$$-dw < TdS - dU \tag{5.28}$$

Equation (5.28) points out that in order to produce work on the surrounding water, the fish must reduce its usable energy through regulated free energy transduction, at the cost of producing entropy. Recall also that all spontaneous or natural processes can *only* occur when the net change in Gibbs free energy $\Delta G = \Delta H - T\Delta S$ is negative. If the fish could not feed, breathe, or is unable to expel its entropy-laden waste, following the second law it would eventually dissipate away all its stores of free energy (carbohydrates, fats and proteins) and no longer able to resist equilibrium, and following the Bauer principle, it would perish. Persistence comes at the cost of participation (Tuhtan, 2011). It should thus be clear that thermodynamics has shown that a fish *cannot* be viewed as a closed system.

5.4.3 Why do fish use undulatory locomotion?

It is clear that fish utilize oscillatory propulsion. Let us therefore portray the motion of an individual fish as a type of simple oscillator. An oscillator is a term used to describe any system which exhibits a periodic steady behavior with time (Tribus, 1961). Here a special type of mechanical oscillation exists: the oscillation of the fish's body is a direct result of interactions between the kinetic energy of the fish and the energy of the surrounding water. The state of this fish+water mechanical system is described at mechanical equilibrium when the fish has either zero or a constant velocity relative to the surrounding water. We are not investigating the case when the fish has a net acceleration. The kinetic energy of an ideal fish can be represented as the integral of its average kinetic energy over the time period t_0:

$$\frac{1}{2}m\dot{\bar{x}}^2 = \frac{1}{t_0}\int_0^{t_0}\left(\frac{1}{2}m\dot{\bar{x}}^2\right)dt \tag{5.29}$$

Reformulating the kinetic energy of the fish as a simple harmonic oscillator gives:

$$\frac{1}{2}m\dot{\bar{x}}^2 = \frac{1}{t_0}\int_0^{t_0}\frac{1}{2}m(\dot{x}_0\cos\omega t - \omega x_0\sin\omega t)^2\,dt \tag{5.30}$$

Evaluating the integral and collecting terms results in:

$$\frac{1}{2}m\dot{\bar{x}}^2 = \underbrace{\frac{1}{2}m\left(\frac{1}{2}\dot{x}_0{}^2 + \frac{1}{2}\omega^2 x_0{}^2\right)}_{A} + \underbrace{\frac{m}{8\omega t}\left[\left(\dot{x}_0{}^2 - \omega^2 x_0{}^2\right)\sin 2\omega t + 2\omega x_0\dot{x}_0(\cos 2\omega t - 1)\right]}_{B} \tag{5.31}$$

This simplified formulation of fish swimming energetics exhibits two very interesting points:

- If the kinetic energy is evaluated over a cycle, then $2\omega t = 2\pi$ and $t = \pi/\omega$, causing the entire second term, B to go to zero.
- As $t \rightarrow \infty$, B also goes to zero.

Thus in the ideal reversible case, over one complete cycle or over a long time period consisting of an integer number of cycles, the fish's average kinetic energy is equal to the initial average kinetic and potential energies in term A. Cyclical, oscillatory motion therefore provides *stability* to the energy expenditures required for propulsion. Aside from the fact that the mathematical expression is greatly simplified, it is important because the general expression of a fish as an oscillator could be used for the study of more complicated fish motion, e.g. when the fish is not in mechanical equilibrium. This may be accomplished by including dissipative damping into the equation system (e.g. by using a type of modified Langevin equation), considering effects of turbulent fluctuations from the mean over a cycle.

5.5 The Importance of Pattern

The purpose of this chapter is to introduce the parameters and mechanisms which affect the animate-inanimate interactions between an alpine fish and its surroundings. The first section provided an outline of the energetic processes occurring within the fish, focusing on the concept of energy flow as metabolism. Material exchanges with its environment provide both the source of free energy and a sink for its nonusable waste. Energy exchanges are primarily due to thermoregulation and excretion, where key temperature ranges necessary for survival and optimal growth are briefly discussed.

The second section introduced the five minimum parameters which should be considered when studying the short-term interactions of a fish within the local flow field. Here it is shown that a variety of interactions play significant roles in estimating fish behavior, and that it is effectively the interplay between a constellation of variables and the fish which are most likely to determine its response, suggesting that a single variable such as velocity magnitude is wholly inadequate in describing fluid-body interactions.

Finally, the chapter is wrapped up by answering three simple questions regarding fish energetics from a physical perspective. The first two questions are essentially energetic questions: Why are fish poikilothermic? ⇒ How do fish exchange heat? Why are fish open systems? ⇒ What are the requirements of an animate system persisting at nonequilibrium? The third question is a question of the *pattern of interaction* with its surroundings. In order for a fish to remain stable and persist in a turbulent flow field, it has evolved propulsory mechanisms allowing it to interact in the river as a part of its overall flow system. The main message of this chapter is that energetics is not only about first law accounting schemes, or about the necessity to consider the dissipative nature of spontaneous chemical reactions required to sustain animate systems. Rather we focus on the necessity to view our volume element as a constructally open river+fish system. The 'best case' scenarios match a fish into a pattern of flow in the river, an energetic piece of a dynamic watery puzzle.

In order to incorporate the theoretical portions of this work (chapters 3-5), it has been necessary to introduce basic concepts of thermodynamics and their roles in the alpine river (chapter 3), to describe the energy transduction processes both from the top-down and from the bottom-up (chapter 4), and finally to present an aggregated modeling approach which takes into consideration both the macroscale evolution of the river as a flow system dominated by the energy of the flowing water, as well as the energetic contributions of its animate components (this chapter). This chapter rounds out the theoretical portion of this work. The remaining chapter provides a side-by-side comparison of the locational entropy principle with the state-of-the art habitat model CASiMiR and provides a case study on its use under hydropeaking conditions on the river Inn.

6 Locational Entropy Model (LEM)

In this chapter, the river+fish concept is implemented as a numerical model. The first section of this chapter describes the modeling steps required to determine estimates for the local entropy generation rates. A numerical model based on the LEM concept is then compared with the CASiMiR fuzzy logic model in a river reach are fish positions are measured. The third section provides a comparison of 30 individual alpine reaches run in both the LEM and CASiMiR under a wide range of steady flow conditions. Finally, a case study under unsteady flow conditions at the river Inn at Martina is presented, where it is shown how the LEM modeling framework may be used to simulate effects on fish due to hydropeaking.

6.1 LEM Modeling Procedure and Parameters

Considering the assumptions and limitations of using a 2D model, the local entropy production due to kinetic energy dissipation in a 2D flow field $\sigma(x, y, \xi, t)$ is shown to be given by the product of the ratio of two intensive properties, density ρ and temperature T, with the extensive property of the kinetic energy dissipation rate ε:

$$\sigma = \frac{\rho}{T}\varepsilon \tag{6.1}$$

The temperature is given in Kelvin (°C+273.15). Because σ estimates are functions of the fluid density and local temperature, model outputs will change along with circadian fluctuations in the river water temperature, a feature common to almost all individual-based bioenergetics models, but not currently included in either PHABSIM or CASiMiR. Over the modeling interval, the water temperature can be calculated, taken from measured values, or set as a constant (Fig. 6-1). In this work both measurements from gauging stations and constant values are applied. The density of water is calculated as a function of the temperature using spline interpolation; though for most practical applications it too can be assumed constant.

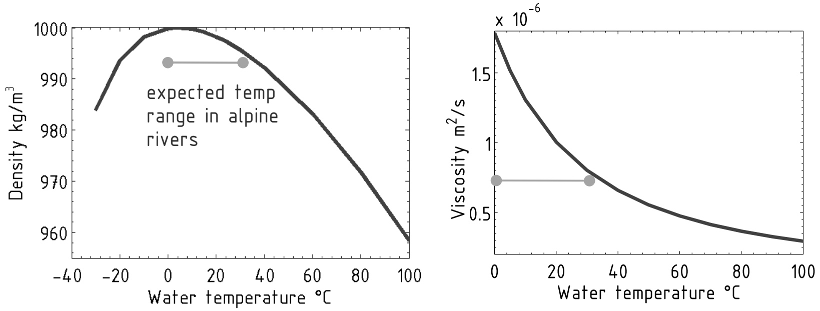


Fig. 6-1 Temperature dependence of the density and kinematic viscosity of water. For high Reynolds number swimmers such as fish, the viscosity plays a small role. However for low Re systems, the temperature influence on viscosity requires consideration over the expected range (0-30 °C) found in alpine rivers.

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

$$\varepsilon = U_*^3 9.8\xi^{0.5} \exp(-3\xi) \tag{6.2}$$

Where the relative depth is given as $\xi = y/h$, 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 and the relative depth. In this work the relative depth is fixed at $\xi = 0.6$ as it is taken as representative of the depth at which the average velocity calculated by the model is delivered. This *does not* mean 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 required. Ideally, the model should make use of 3D velocity field data including turbulence estimates. Furthermore, the formulation used in this chapter requires assuming isotropic turbulence and local dynamic equilibrium conditions such that the rate of turbulence production is equal to its dissipation, $k = \varepsilon$. It must also be noted that Eq. (6.1) is *only applicable* when the relative depths of interest range from $\xi = 0.2 - 0.8$. Thus, the model as currently defined must be reworked to include estimates at the bed where dissipation in the viscous sublayer is important, i.e. for aquatic macrophytes, fish eggs, bottom-feeding fish, or macrozoobenthos.

After determining the limitations of using a 2D depth-average approach and the required assumptions, it is necessary to return to Eq. (6.1) and fill in the only missing parameter: the shear velocity. For a given volume element, the shear velocity can be estimated as a function of the local water depth and gradient of S_0:

$$U_* \cong \sqrt{ghS_0} \tag{6.3}$$

Note that for steady, uniform flow this is often taken to be equal to the gradient of the river bed and/or free surface. For highly unsteady flow in rivers with complex morphology, such as hydropeaking events in alpine rivers, this can be substantially different than the bed slope and S_0 requires direct calculation in each volume element.

By definition, the friction or shear velocity is:

$$u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{\upsilon \frac{du}{dh}} \tag{6.4}$$

However, in this work 2D models are used, where it is not possible to estimate the vertical velocity gradient du/dh in each model element. Thus, Eq. (6.3) is applied in order to calculate local estimates of S_0, where it is necessary to first determine the magnitude of the energy grade line surface, the EGL at each model node i (Fig. 6-2) using the following equation:

$$EGL_i = z_i + h_i + \frac{U_i^2}{2g} \tag{6.5}$$

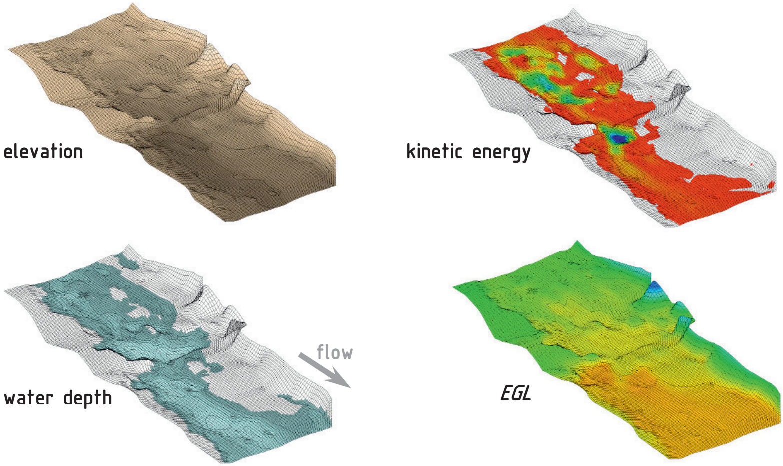


Fig. 6-2 Reference reach Olivone showing 3D mappings of elevation, depth, kinetic energy, and *EGL*. During calculations, unsubmerged portions of the *EGL* mapping are removed.

This is done in two steps, the first of which is to calculate the gradient:

$$\nabla EGL = \frac{\partial EGL}{\partial x}\hat{i} + \frac{\partial EGL}{\partial y}\hat{j} \tag{6.6}$$

Since the gradient of a scalar field (EGL mapping) results in a vector field (Fig. 6-3) pointing in the direction of largest increase, the negative of the gradient points in the direction of largest decrease, and is found by multiplying the gradient vector components by -1.

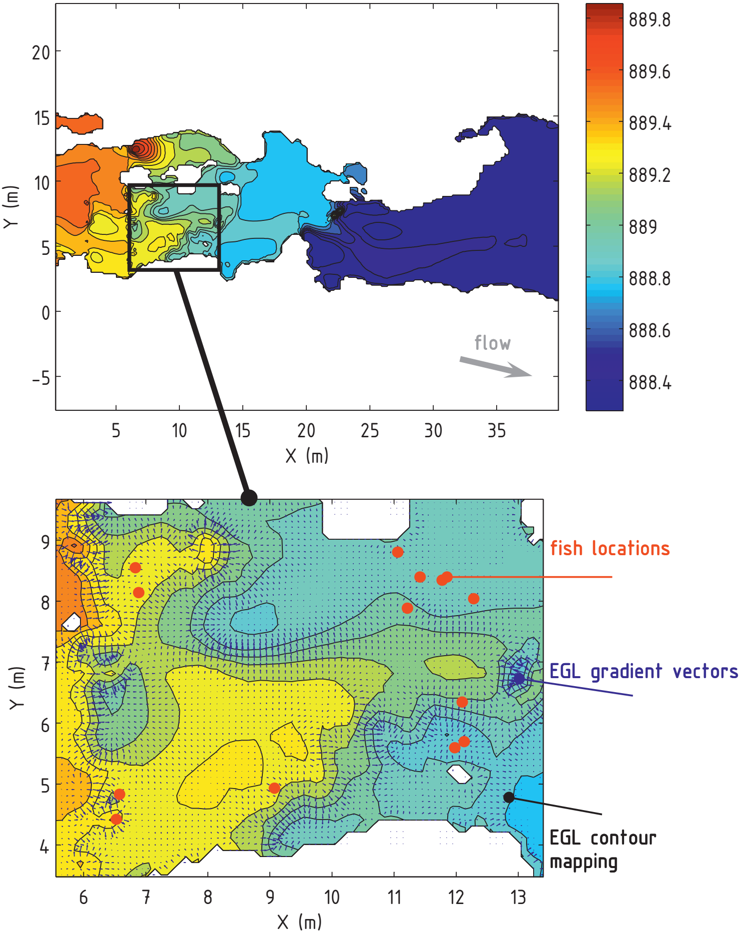


Fig. 6-3 Example of the EGL gradient method used in estimating the shear velocity. The approach allows for the explicit consideration of a local flow pattern, the key parameter in the LEM concept. Shown above is the mapping of the EGL after Eq. (6.5), and below is a cut-out illustrating the gradient (arrows) after Eq. (6.6). Fish locations are red dots corresponding to low or medial EGL gradients.

The second step involves consideration of the magnitude of the gradient S_0. In the simple 1D case, the negative gradient of the EGL is monotonically decreasing with respect to the change in potential energy, travelling downstream and is assumed to be approximately equal to the bed slope under steady uniform flow conditions. In reality, we know that the EGL is not 1D, but is in actuality the result of a fully 3D energy landscape. It may include components due to the variations in the relative contributions of potential and kinetic energies in all directions. In this study the strong unsteady of the flow regime due to hydropeaking often creates water surface profiles which do not have the same slope as the bed; uniform conditions do not apply. For this reason, the second step is required to calculate the magnitude of the negative gradient for the 2D case in order to provide estimates of the local distribution of U_*:

$$S_0(x, y, t) = \sqrt{\left(-\frac{\partial EGL}{\partial x}\hat{i}\right)^2 + \left(-\frac{\partial EGL}{\partial y}\hat{j}\right)^2} \tag{6.7}$$

After calculating local estimates of S_0, Eq. (6.3) is used to determine the value of u_* at each model node for each time step. As mentioned previously, local dissipation estimates should be calculated directly using the results of a 3D model. However, in the case in which such data is not available, Eqs. (6.2), (6.3), and (6.7) can be used to estimate the local dissipation.

It should be noted that one of the main assumptions implicit in Eq. (6.3) is that the water surface is linearly changing between nodes. Field observations of hydropeaking events using high resolution (10 Hz) ultrasound measurements show the presence of wave action. Thus in many cases, the assumption of steady linear relations is not correct, and that during hydropeaking, substantial errors in the model can result. This is illustrated in Fig. (6-4).

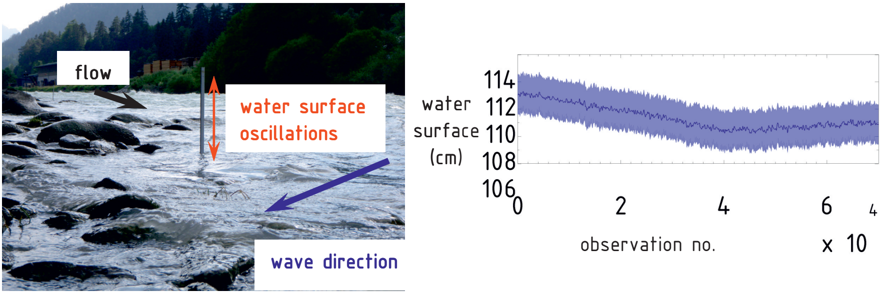


Fig. 6-4 Water surface fluctuations observed during hydropeaking at the river Inn at Martina (CH). The photo on the left shows the small-scale *micropeaking* wave action. The graph on the right shows a hydropeaking event where fluctuations can clearly be seen. Both the mean value over 1 second (dark blue) and the fluctuations (light blue) about the mean can be seen. The data was taken using an ultrasound measuring device which records the water surface fluctuations at 10 Hz.

The LEM numerical model presented in this section should be seen as an *extension* of the LEM conceptual model. Using 2D hydraulic model results have several deficiencies, namely the lack of a vertical velocity profile and turbulence estimates. It is also important to consider that within the framework of the LEM model, it is the local flow *pattern* that is important, and requires consideration of both small and large scales. The LEM approach ideally requires not only element-wise point value estimates of σ, but also descriptive parameters which may include Lagrangian coherent structures (LCS), water temperature gradients, lighting, access to food, etc. Considering that PHABSIM and CASiMiR relate point value estimates of hydraulic variables to biotic preferences, a direct 1:1 comparison with LEM poses a difficult challenge. In order to compare LEM with CASiMiR, the pattern criterion is significantly relaxed in order to facilitate evaluation where focus is on the comparison of spatial distributions of σ and the habitat suitability index.

6.2 Model Comparison Including Fish Data

A reference reach (Table 6-1) on the river Olivone (CH) is chosen due to the presence of available fish observation data for adult brown trout at the steady flow rate of 900 L/s. The model is also frequently used in teaching courses on the application of the CASiMiR program as thus serves as a good choice when comparing other habitat models to CASiMiR.

Table 6-1 Summary information on the investigation reach Olivone.

Reach Name	No. Nodes	No.Elements	Width (m)	Length (m)	Slope (m/m)	Total Area (m^2)	Resolution (m^2/node)
Olivone	10,803	10,620	20	41	3.E-02	648	0.060

6.2.1 Fuzzy logic based CASiMiR habitat suitability model

Fuzzy-set theory was first developed by (Zadeh, 1965) and characterizes complex systems through imprecise, fuzzy state transitions. Contrary to Boolean logic, fuzzy-logic allows a system to obtain intermediary states, e.g. a state can be described as being both partially A and B simultaneously. In ecological modeling these intermediary states are very important as transitions in ecology are not crisp but gradual (Salski, 1992; Cadenasso et al., 2003). Classical aquatic habitat modeling techniques include crisp boundaries between two parameter ranges. For example, if the limit of the variable *low velocity* is set to 0.3 m/s, then a value of 0.29 m/s is considered *low*, while 0.31 m/s becomes *medium*. This crisp assumption does not fit into the ecological boundary theory as defined by Strayer et al. (2003) where the boundaries should be defined through their gradients. Fuzzy-logic has proven to be an excellent modeling technique for ecological gradients as the overlapping fuzzy-set theory reflects these gradual transitions between pre-defined classes (Van Broekhoven et al., 2006; Mouton, 2008). Another drawback in classical or statistical modeling approaches is the inability to incorporate ecosystem behavior information in the form of expert knowledge (Austin, 2002). Other advantages of fuzzy-logic modeling are that they allow for the implementation of qualitative data in numerical processing (Ahmadi Nedushan et al., 2008), they are able to consider multivariate effects without assuming independence of input variables, they have the ability to consider numerous combinations of habitat variables, and the models are directly interpretable (not a black box). These attributes allow for a sound basis for collaboration between scientists and political decision-makers (Casillas, 2003).

The habitat model CASiMiR (Computer Aided Simulation Model for Instream Flow Requirements) was developed in the early 1990s at the Institute of Hydraulic Engineering at the University of Stuttgart (Fig. 6-5). Its principal purpose is the investigation of fish and invertebrate habitats as they change with river discharge.

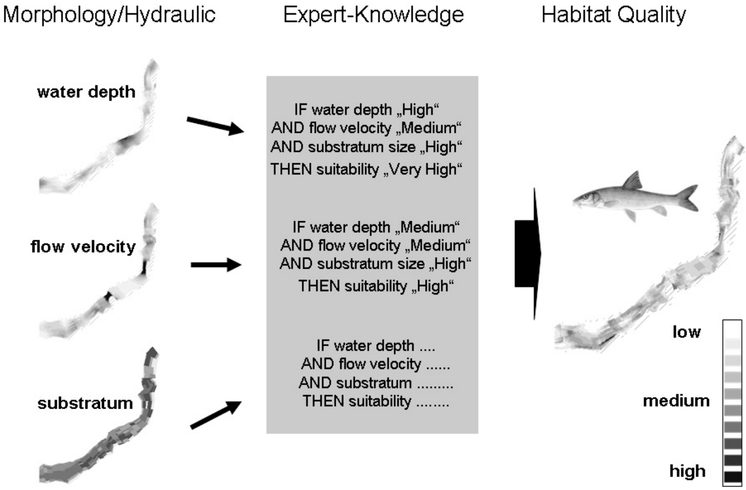


Fig. 6-5 Graphical presentation of the CASiMiR modeling concept. After Schneider (2001).

Contrary to other fish habitat models, CASiMiR applies a knowledge-based multivariate fuzzy-logical approach to link physical parameters with biological habitat requirements (Schneider, 2001). Knowledge-based rules are applied connecting physical habitat parameters to fish habitat requirements through the use of conventional linguistic terminology such as “high”, “medium” or “low”. Case-specific input parameters often occur when modeling biological systems and can be easily integrated directly into the fuzzy logic method. The standard CASiMiR model output is the habitat suitability prediction ranging from 0 (unsuitable) to 1 (suitable). Results vary depending on the flow rate and corresponding changes to the other input parameters.

In order to illustrate both the range of possible outcomes a series of diagrams are prepared. Fig. (6-6) shows the substrate, water depth, velocity, and HSI matrices used. For each species and lifestage, all possible combinations of the three input variables (substrate, depth, velocity) are shown in the matrix. The results of the CASiMiR model for both the European grayling and the brown trout are shown in Fig. (6-7). The juvenile grayling has a more or less fixed constellation of water depth and velocity combinations, where the impact of substrate scales the overall HSI. The adult grayling in contrast have a wide acceptance of all variable combinations where the best conditions exist only in a very narrow combination of velocity (50 cm/s) and depth (2+ m). Results for the juvenile brown trout are split into three groups; the best conditions existing at around 10 cm of depth and 15 cm/s velocity, medial values are found regardless of substrate for both constant depth of 10 cm and constant velocity of 15 cm/s. Adult brown trout is the only example where strong effects from substrate conditions are clearly found. Across substrate types 6-8 optimal conditions occur, at a constant velocity of 1 m/s for any depth greater than 15 cm.

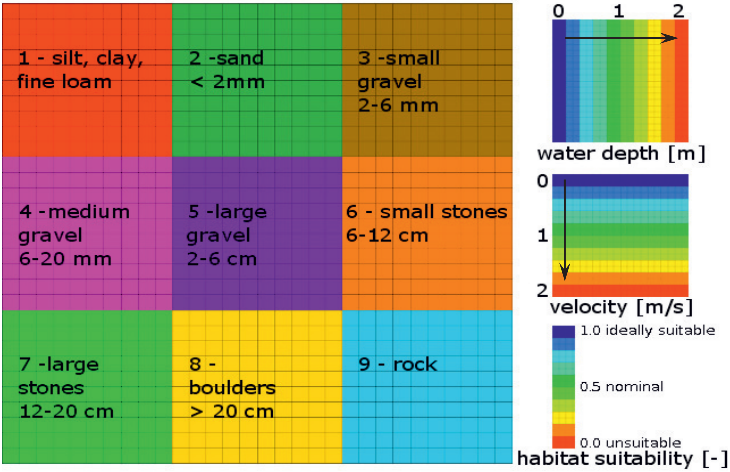


Fig. 6-6 Matrix used to graphically depict the outcome of the CASiMiR fuzzy logic model. The large square represents a grid of all possible substrate types. To the left are shown the matrices of increasing water depth (from left to right), and velocity magnitude (from top to bottom). Each substrate square thus includes all possible combinations of water depth and velocity.

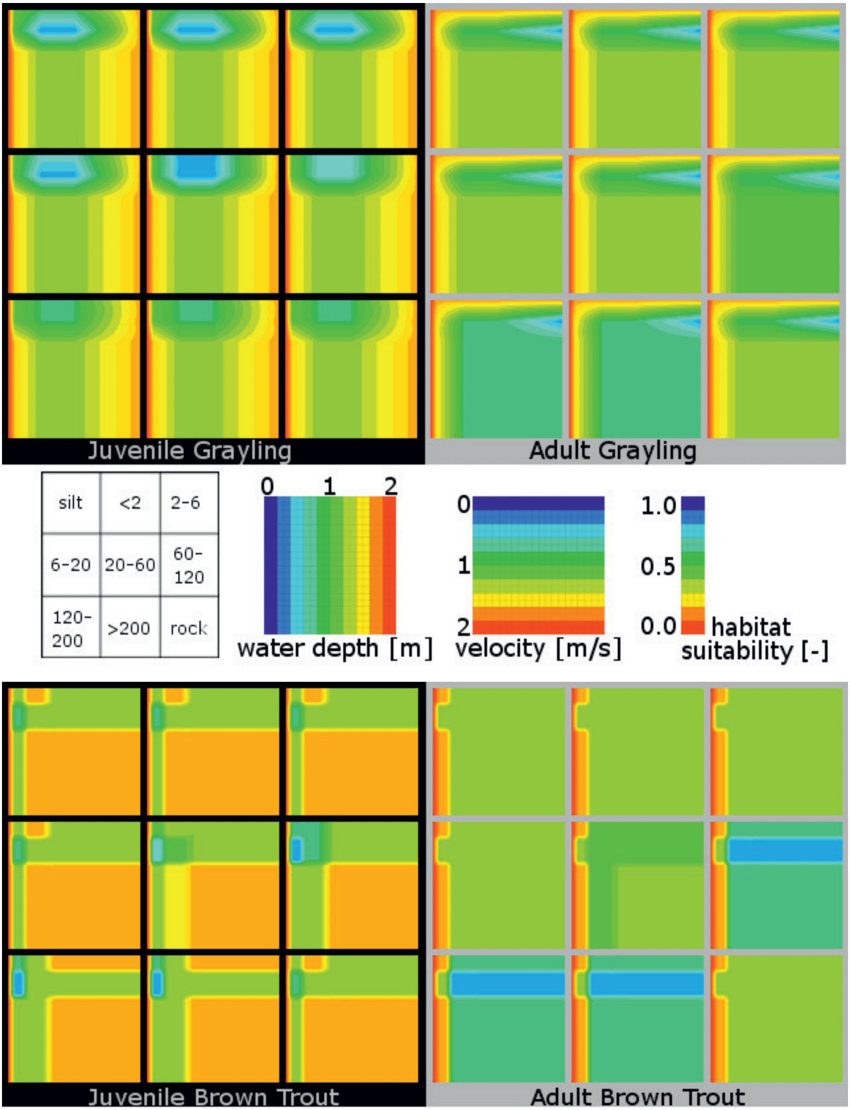


Fig. 6-7 Suitability matrices showing all possible HSI combinations from the CASiMiR model for the European grayling (above) and brown trout (below). Both adult and juvenile life stages are shown. In the center of the figure from left to right: the substrate size of each block (mm), horizontally increasing water depth from 0-2 (m), and vertically increasing velocity 0-2 (m/s).

6.2.2 2D hydraulic model

In this work the hydraulic model of choice was Sedimentation and River Hydraulics 2D (SRH-2D), a two dimensional finite volume model developed by the US Bureau of Reclamation (USBR). The model solves the two dimensional 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 temporal varying water surface elevation, bed elevation, water depth, bed shear stress and Froude number. SRH-2D is suitable for applications in which two dimensional and highly unsteady effects such as those occurring in the varial zone during hydropeaking conditions are important (Tolossa et al., 2009).

6.2.3 CASiMiR and LEM model results

Both the CASiMiR and LEM models are run using identical model outputs from SRH, under steady flow conditions. The results are shown in Figs. (6-8), (6-9), (6-10), and (6-11). In the second depiction of the fuzzy logic approach shown in Fig. (6-9), it can be seen that the model results are found to be a reasonable predictor of fish location for 21 of 44 observations.

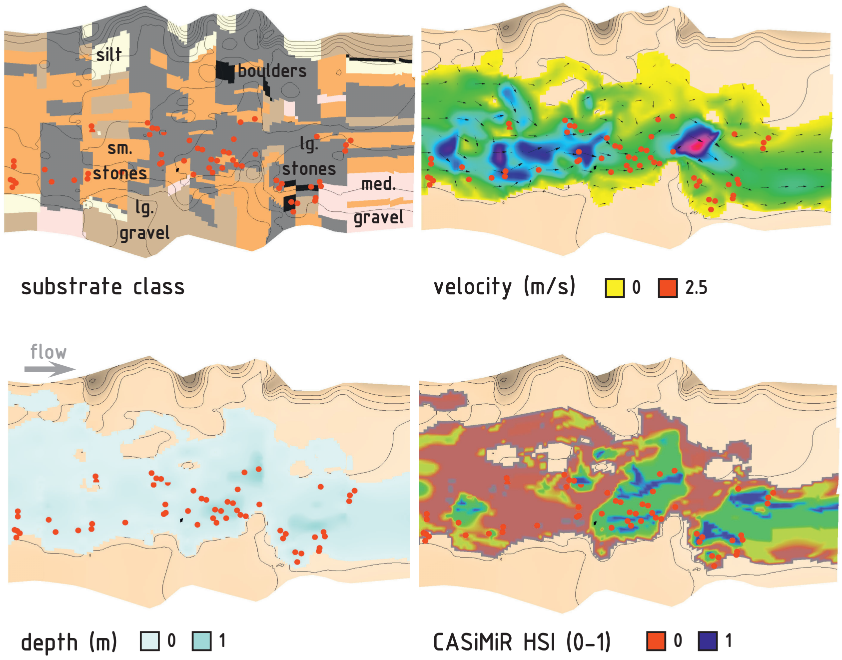


Fig. 6-8 Mappings of the substrate, velocity magnitude, water depth, and the results of the CASiMiR model (adult brown trout) compared with fish observation data on the river Olivoneat 900 l/s. Fish are found primarily in areas with small or large stones and medial velocities. A strong correlation with the water depth is not apparent. Considering the spatial accuracy of the observed locations is ± 1 meter, the CASiMiR predictions are reasonable.

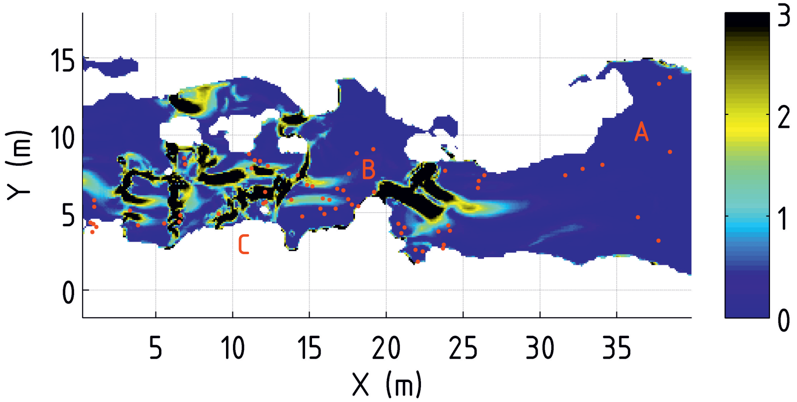


Fig. 6-9 LEM-σ (kg m^2/s^3) mapping with known fish locations. Qualitatively, there are three ranges of dissipation corresponding to fish locations; A has low dissipation, B medial and C high dissipation.

Direct comparison of the CASiMiR and LEM model results as previously mentioned is challenging because the LEM concept is not explicitly meant to be incorporated into a numerical model and because of the inaccuracies in using a 2D hydraulic model. Comparing Figs. (6-9) and (6-10) one major difference in using LEM-σ results vs. CASiMiR's HSI is found: the σ values match a series of flow patterns corresponding to the different possible types of fish locomotion (entraining, gaiting, etc.) whereas the HSI outputs offer a single index. Qualitative assessment of Fig. (6-10) indicates that there are three regions (A, B, C) which are correlated to the presence of fish corresponding to different rates of dissipation.

Further expanding on the LEM concept requires the inclusion of flow pattern. In this study, it is not possible to gather information on the local flow pattern in each model element beyond the water depth and x and y velocity components. However, by dispersing massless tracer particles in the flow field, we can get a look at the large-scale flow pattern of the river reach. Fig. (6-11) clearly shows the presence of LCS recirculation zones, as well as a main flow path through the river. Following the LEM concept, we should expect to find correlations between the fish location and the reach-scale flow pattern not only considering swimming stability, but because a fish's position in the river also enhances its probability of feeding. We see that the majority of the fish are found in the main flow path, and the remaining fish are almost exclusively located in the LCS 'side rooms' which have the highest recirculation density (number of pathlines per area).

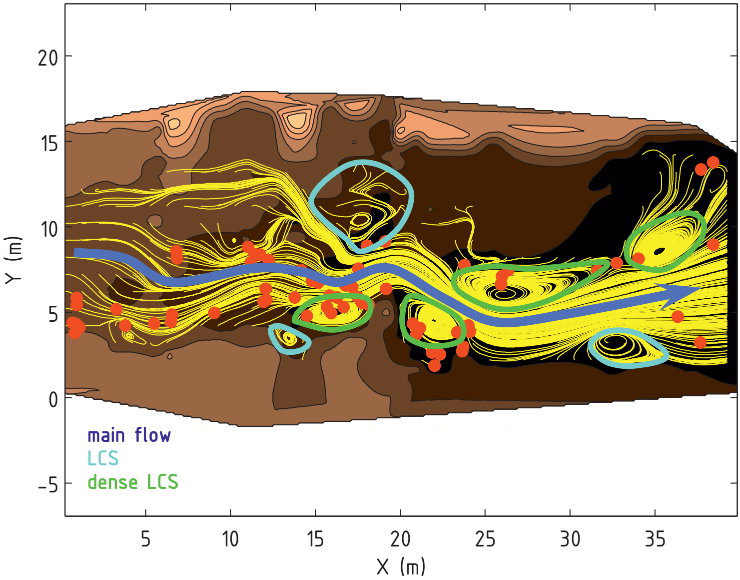


Fig. 6-10 Pathlines of the investigation reach showing 6 circulatory (LCS) regions, as well as the main flow through the river. Fish locations are shown as red dots. It can also be seen that the fish in the upstream and downstream most portions of the reach are located in regions of stable streamlines. The fish in the center portions are almost exclusively located inside the densest LCS regions.

In the next section, a scale survey of 30 alpine reaches is conducted using only the LEM-σ and CASiMiR in order to compare the simplified LEM model to the existing expert-logic model. The thesis tested is that perhaps CASiMiR is modeling *one* of the types of fish locomotion and that if is the case, a single value of σ should be found common to those regions with high HSI index values regardless of the investigation reach chosen.

6.3 Steady Analysis of 30 Investigation Reaches

The previous sections introduced a simplified model focusing on estimates of the local hydrodynamic dissipation rate, and showed how it may be used in conjunction with hydraulic model outputs similar to that of CASiMiR. However, it became clear that one of the main difficulties in projecting the LEM conceptual model onto a numerical framework is that the conceptual model allows for a high degree of flexibility in interpreting the results, whereas the numerical model does not. At the end of the last section the thesis is introduced that CASiMiR and LEM should have some similarity. The purpose of this section is to test this thesis. Here the goal is to gain a ‘big picture’ perspective of how the two models differ under the widest possible range of alpine watercourses which may be impacted by hydropeaking activity.

The first part of this section introduces the 31 models which are used and describes their ensemble characteristics. Next, the similar reaches are introduced and reasons for similarity are investigated. Finally, dissimilar results are discussed with a focus on the way both models interpret hydraulics and their effects on fish.

6.3.1 Characteristics of the investigation reaches

In order to observe possible trends when comparing the LEM-σ and CASiMiR approaches, the characteristics of individual reaches are collected and are presented graphically in Figs. (6-12), (6-13), (6-14), (6-15), (6-16) and (6-17). An overview of the sizes of the models is shown in Fig. (6-18). Additionally, a listing of reach scale characteristics is found in Table (6-4) for reference.

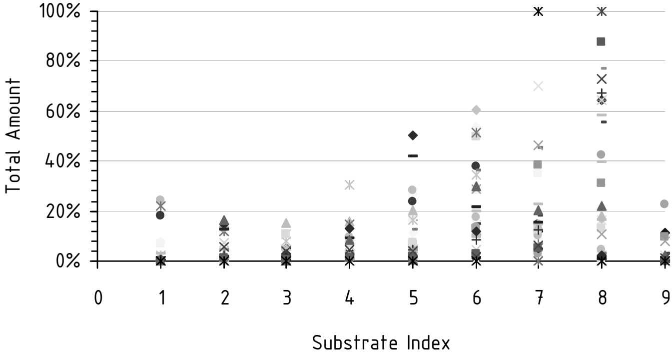


Fig. 6-11 Plot of the total amount (%) of bed coverage for each of the 10 (0-9) substrate classes. Because all investigation regions are alpine, there is a tendency towards coarser substrate.

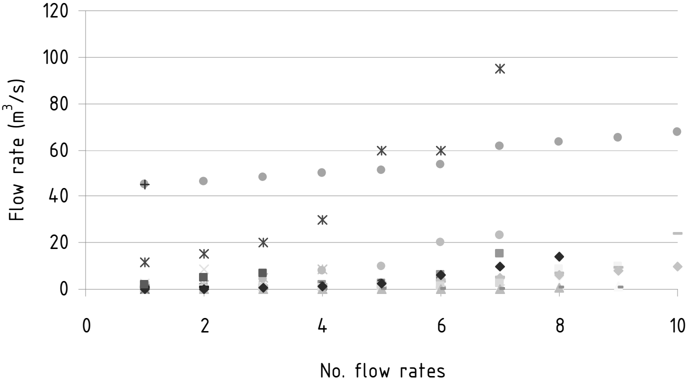


Fig. 6-12 Number count and value of flow rates for each of the 30 investigation reaches. Only reach 25 had more than 10 individual flow rates, and thus some values for this reach are truncated.

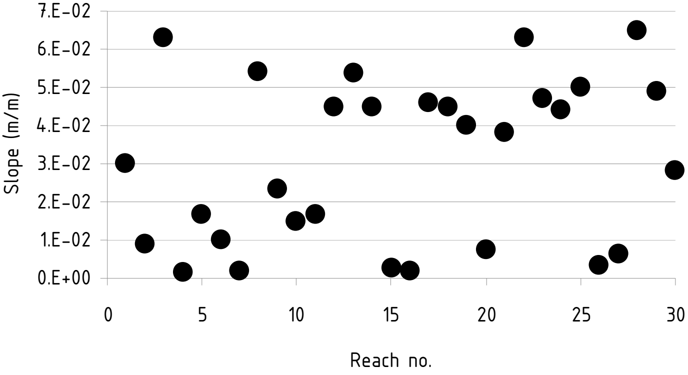


Fig. 6-13 Plot of the bed slope (m/m) vs. investigation reach number.

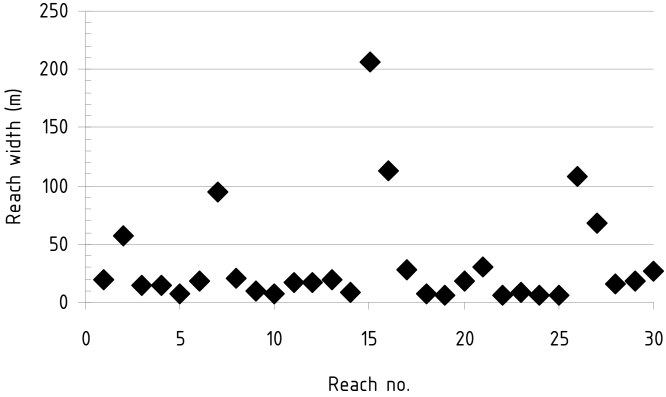


Fig. 6-14 Plot of the reach width (m) vs. the investigation reach number.

Following the concept of OCN as presented in chapter 3 and after investigating possible variable combinations, it is found that relations between the channel slope, area and width variables are the strongest. This is certainly not a surprise, but it is interesting to observe that the width vs. slope relationship exhibited a great deal more variety than slope vs. area. This may indirectly show the extent of anthropogenic influence on the rivers investigated, since many of the studies from which the reaches are taken are from investigations where the 'natural' width is modified in terms of hydraulic conveyance instead of left to its own development processes.

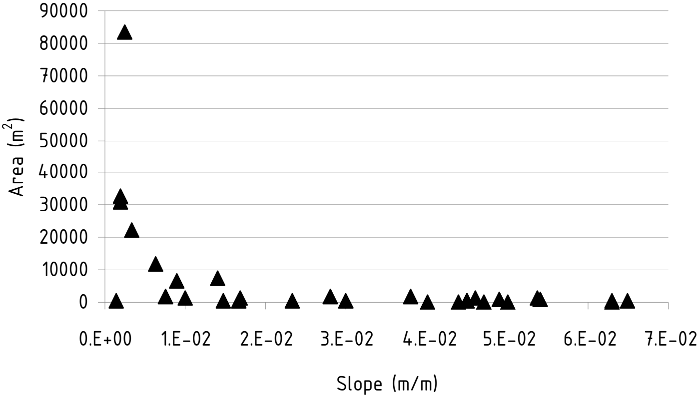


Fig. 6-15 Plot of the investigation reach mesh area (m^2) vs. the average bed slope (m/m). The area of the investigation reaches decreases exponentially with increasing bed slope.

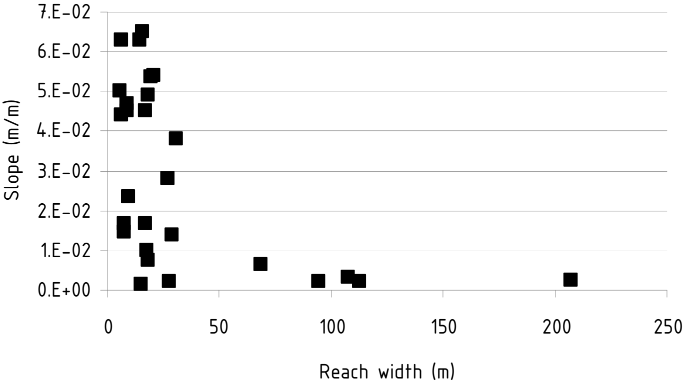


Fig. 6-16 Plot of the inverse relationship between the investigation reach width and the bed slope.

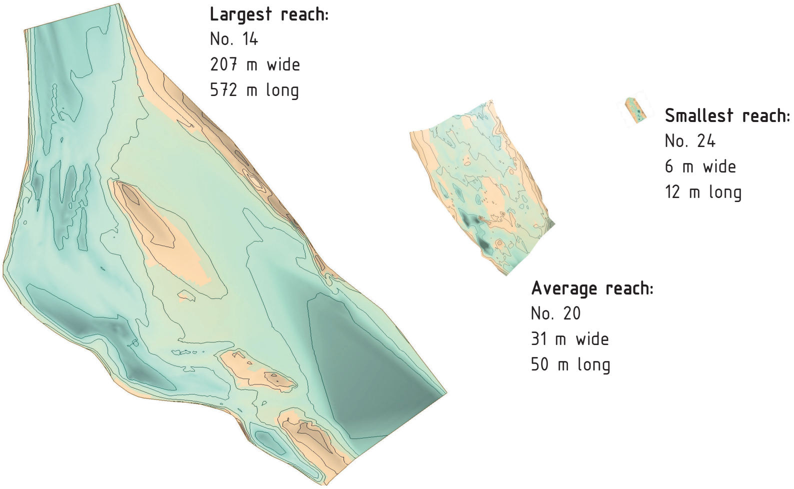


Fig. 6-17 Graphical illustration of the wide range of sizes encompassing the 30 reaches. Not to scale.

Table 6-2 Summary statistics on each of the 31 investigation reaches used in the model comparison. The models (largest / smallest) had widths of 207 / 6 m, lengths of 572 / 12 m, and total areas of 83,477 / 66 m^2.

Reach No.	No. Nodes	No.Elements	Width (m)	Length (m)	Slope (m/m)	Total Area (m^2)	Resolution (m^2/node)
Olivone	10,803	10,620	20	41	3.E-02	648	0.060
1	23,057	23,024	57	139	9.E-03	6586	0.286
2	25,745	25,472	15	78	6.E-02	366	0.014
3	7,299	8,473	15	27	1.E-03	389	0.053
4	24,165	23,616	8	67	2.E-02	476	0.020
5	9,579	9,325	18	84	1.E-02	1503	0.157
6	120,473	232,105	94	402	2.E-03	30845	0.256
7	15,249	14,960	21	56	5.4E-02	1051	0.069
8	13,313	13,424	9	30	2.3E-02	262	0.020
9	24,165	23,616	7	67	1.5E-02	476	0.020
10	70,149	69,504	17	97	2.E-02	1195	0.017
11	25,844	25,470	17	43	5.E-02	586	0.023
12	53,966	53,400	20	65	5.E-02	1206	0.022
13	14,602	14,256	9	57	5.E-02	389	0.027
14	7,996	7,934	207	572	2.E-03	83477	10.440
15	18,961	22,687	113	361	2.E-03	32586	1.719
16	36,421	36,000	28	47	5.E-02	1182	0.032
17	4,671	4,480	7	42	5.E-02	273	0.058
18	14,649	14,336	6	32	4.E-02	192	0.013
19	5,357	5,181	18	48	8.E-03	1541	0.288
20	10,800	10,561	31	50	4.E-02	1565	0.145
21	7,646	7,421	7	23	6.E-02	127	0.017
22	3,167	3,068	9	23	5.E-02	192	0.061
23	1,355	1,272	6	26	4.E-02	153	0.113
24	2,159	4,121	6	12	5.E-02	66	0.031
25	45,395	21,668	107	224	3.E-03	22166	0.488
26	34,021	12,132	69	174	6.E-03	11845	0.348
27	25,529	25,408	16	35	7.E-02	420	0.016
28	48,110	49,035	18	57	5.E-02	868	0.018
29	79,905	79,424	27	74	2.8E-02	1720	0.022
30	7,910	7,440	29	275	1.4E-02	7265	0.060

6.3.2 Model comparison

After collecting the necessary data the LEM-CASiMiR comparison can only be made once a procedure is decided upon which allows the two models to be compared to one another in the same way across all 30 reaches. As mentioned previously it is not possible to fully describe local flow pattern characteristics using a 2D model, nor is it possible to compare CASiMiR to the LEM concept when reach-scale pathlines and LCS regions are applied. We have opted only to test the theory that the two models should deliver a similar result based on fixed values of σ (Fig. 6-19). In order to test this hypothesis the following steps must be carried out:

1. **Run both CASiMiR and LEM-σ for each reach and flow rate.**

2. **Locate model coordinates in which CASiMiR has a high habitat prognosis (HSI>0.8), and retrieve the LEM-σ values from the *identical spatial locations*.**

3. **Create histograms for N flow rates (TS1, TS2, … , TSN) for the number of HSI>0.8 locations vs. the values of the retrieved LEM-σ from step 2.**

4. **Compare the histogram determination results for all 30 investigation reaches to see if across all flow rates a constant σ corresponds to a high HSI mapping.**

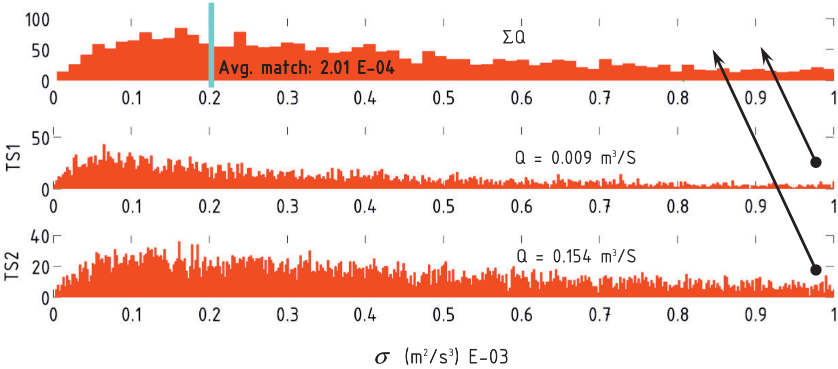


Fig. 6-18 Example of the juvenile brown trout histograms used to search for a constant σ for reach no. 21. The *bottom two* histograms represent the full spectrum of σ across the entire mapping found for the two flow rates modeled (0.009 and 0.154 m^3/s). The *top* histogram summarizes both flow rates, where *only* the σ matching HSI>0.8 coordinates are filtered out. The final choice of σ is taken as the average of the highest two performing bins. For this reach σ =2.01E-04.

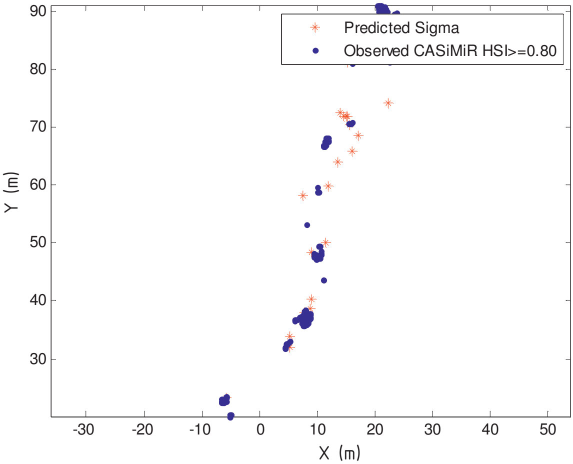


Fig. 6-19 Results from reach No. 2, Q=0.5 m^3/s comparing the HSI>0.8 to a constant σ=2.75E-04 for the adult brown trout.

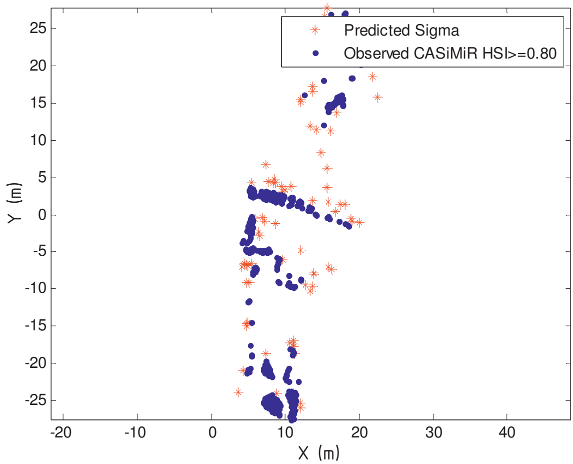


Fig. 6-20 Results from reach No. 7, Q=2.25 m^3/s comparing the HSI>0.8 to a constant σ=4.40E-04 for the adult brown trout.

As seen in Figs (6-20) and (6-21), it is certainly possible to achieve spatial distributions of both a constant value of σ with areas of HSI>0.8. This indicates the possibility that CASiMiR may be acting as a proxy model for estimates of fixed dissipation rates in the river. In order to test this theory further, we need to look at the results of not only a few selected reaches but the ensemble results of all 30.

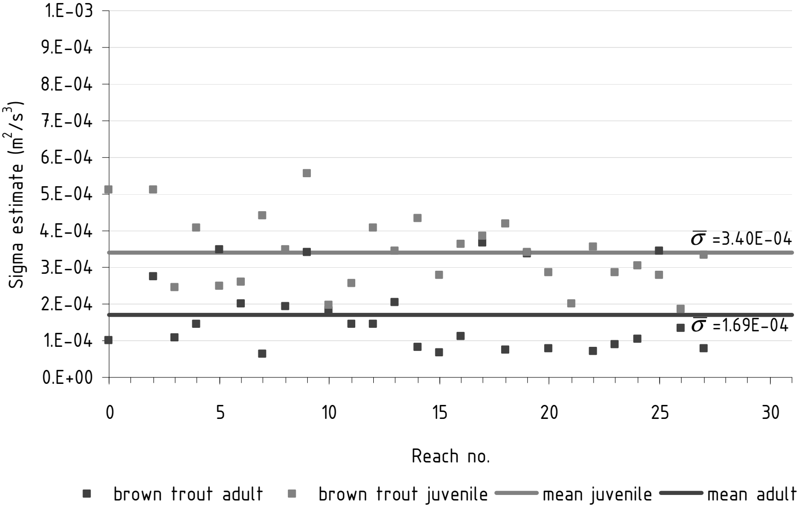


Fig. 6-21 Results of the 30 reach comparison between constant σ and HSI>0.8. The results show that over the possible spectrum of σ found in all reaches a correlation exists between the LEM and CASiMiR model results with high habitat suitability. A noticeable difference between adult and juvenile mean values can also be seen.

The results shown in Fig. (6-22) are surprising. Not only does it indeed appear that there is a direct relationship between local estimates of σ, 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 LEM concept since it is found that aging creates a *decrease* in the specific rate of entropy production regardless of the type of animate system, mammals, birds, fish, or 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 numerical models. The results of the 30 reach comparison study thus suggest that CASiMiR may be actually be acting as a proxy model for a fixed dissipation rate, and that this rate (based on the discussion in chapter 5) 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 $\overline{\sigma}$ for different modes of behavior for each species and lifestage, and model them in an improved 3D LEM approach.

Thus far we have not achieved our goal of looking at the LEM model under unsteady conditions. Concluding this dissertation is the modeling of unsteady flows under hydropeaking conditions, comparing the results both with and without dynamic water temperature effects (Table 6-3).

Table 6-3 Comparison of the LEM and CASiMiR modeling approaches.

LEM	CASiMiR
Based on assessment of environmental patterns of a river+fish flow system	Based on assessment of local point values of hydraulic variables correlated to biotic preferences
Assumes that there are no deterministic relations between a fish and the river, only propensities	Assumes the fuzzy rules and sets defined by fisheries experts are adequate for relations
Volume element as a river+fish system	Volume element as river water only
Analysis of the ecosystem as open, irreversible and unsteady	Analysis of hydraulics as open and steady, rules don't include irreversibility
Physical model based on first principles	Expert-knowledge model based
Total number of relevant parameters decrease with increasing model complexity	Total number of relevant parameters increase with increasing model complexity
Conceptual model	Numerical model

6.4 Unsteady Case Study: River Inn at Martina

Here, the LEM model is used exclusively under unsteady flow conditions to showcase what results may be taken under hydropeaking conditions. The investigation reach is on the river Inn at the Swiss-Austrian border 3.25 km downstream of the hydropower plant outlet at Martina. The stretch chosen for analysis is generally representative (Table 6-4) of the Inn in the Alpine region, with wide, flat cross sections and a rough, rocky bed (Fig. 6-23). Gauging data for the discharge hydrographs are provided by the Swiss Federal Office for the Environment's (BAFU) (station no. 2067) for the years 2000-2010 for both the water elevation and flow rate in 10 minute intervals (Fig. 6-24). The data is broken down into monthly datasets, visually inspected, and individual days of interest are then selected for further modeling using SRH-2D.

Table 6-4 Summary information on the Martina Inn (CH) investigation reach.

Investigation Reach	Reach Length (m)	Bed Width (m)	Bed Slope (m/m)	Substrate Composition
Martina	188	56	0.006	90% stones 12-20 cm 5% small stones 6-12 cm 5% rocks > 20cm

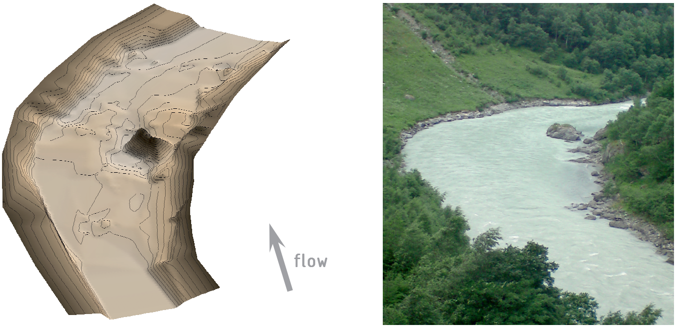


Fig. 6-22 The investigation reach at Martina. *Left*: the model mesh. *Right*: recent image of the reach.

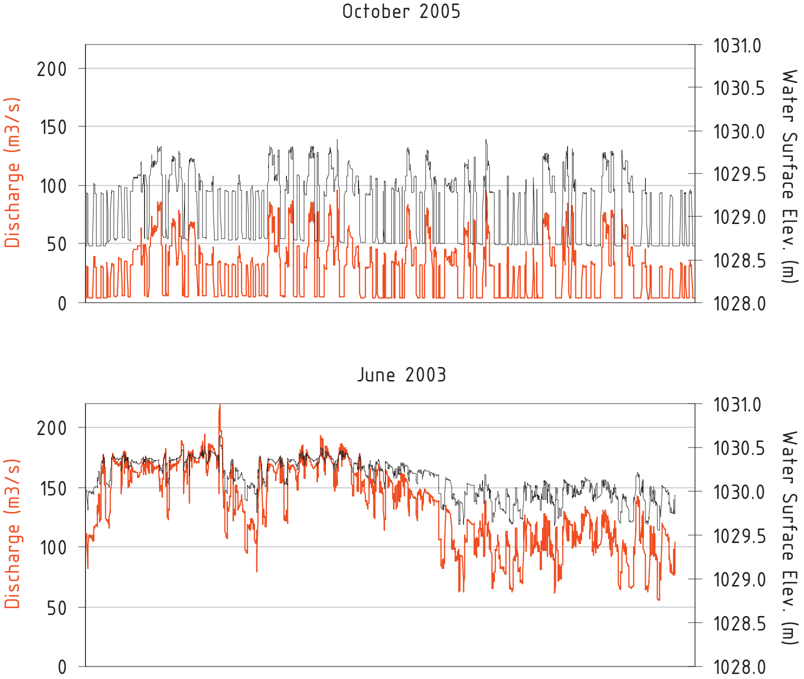
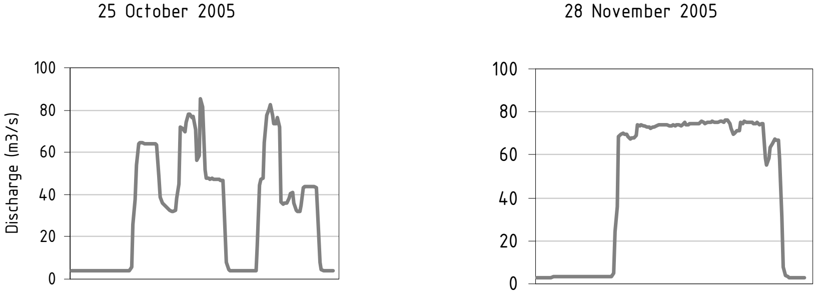


Fig. 6-23 Comparison of two months at Martina, October 2005 and June 2003. During the drier, colder months, the minimum flow of 3.6 m^3/s serves as the basis of all daily fluctuations. During the spring, the base flow is significantly higher and fluctuates depending on the upstream conditions.

One of the difficulties in modeling the effects of hydropeaking is determining which events are ‘typical.’ As shown in the top chart in Fig. (6-24) choosing to observe only a cold month such as October it is easy to come to the conclusion that typical days exist and are ubiquitous. After looking at a spring or early summer hydrograph, as shown in the bottom chart of Fig. (6-24), it becomes clear that the notion of a typical event is not so easy to define. It should further be noted that the observation of seasonal changes are important due to the fish's life cycle, where events of the same frequency in magnitude can have different effects on eggs, juveniles, young-of-year, and adults.

Another interesting observation is that there is a difference in hydrograph *type*. Typically on the weekends, or during periods when the plant is operated primarily for local network load regulation, a highly variable hydrograph could be found. During the weekdays, a more stereotypical flat hydrograph exhibiting early morning and late night up and down surge events occurred (Fig. 6-25).


25 October 2005

28 November 2005

Fig. 6-24 Comparison of two types of daily peaking hydrographs: *Left*: variable. *Right*: flat.

From the available BAFU data, a total of 6 variable and 6 flat hydrographs are chosen for further analysis and modeling. Comparison of the up and down ramping effects on the water surface elevation is shown in Fig. (6-25). It can clearly be seen that the variable type of hydrograph contains more extreme fluctuations than the flat type, and that for both types, down ramping has a larger percentage of higher ramping rates, especially in the range 0.10-0.15 m /10 min (Fig. 6-26). Due to the paucity of events exhibited by the flat hydrographs, the 25.10.2005 hydrograph is chosen to be run in the LEM-σ model for further investigation.

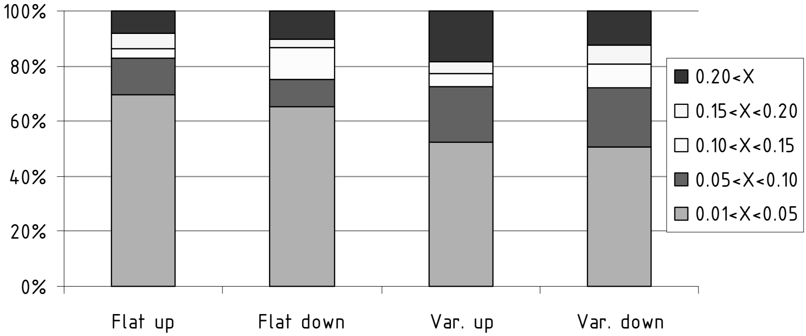


Fig. 6-25 Assessment of the frequency of the rate of water surface change (m/10 min) occurring for both normal 'flat' hydropeaking hydrographs and 'variable' hydrographs occurring on weekends or during periods of load regulation on the basis of 12 selected hydrographs.

6.4.1 Running the unsteady LEM model

The computational meshes are 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 is run as a 24 hour unsteady simulation, are 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), already shown in Fig. (6-25). Downstream boundary conditions are input as rating curves based on measured field data. Manning's roughness values n are assumed constant over the hydrograph and ranged from 0.013-0.83 depending on surface conditions. Estimates of the water temperature are not available for the BAFU gauging station at Martina and are instead taken from the nearby station at Rom-Müstair (station no. 2617). An overview of the modeling procedure is shown in Fig. (6-27).

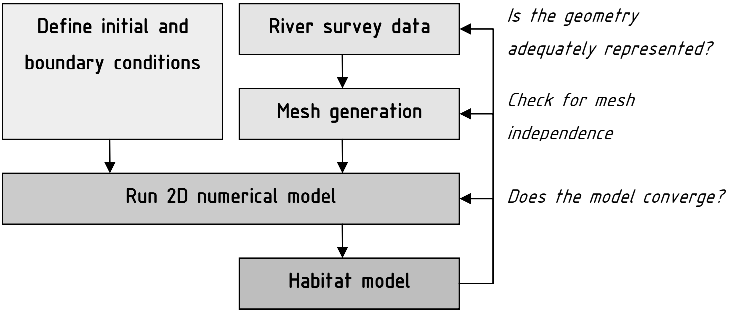


Fig. 6-26 Steps followed when running the SRH-2D numerical hydraulic model. After: Zielke (1999).

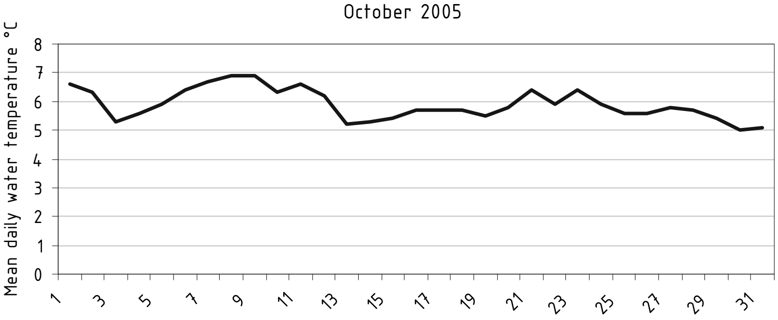


Fig. 6-27 Average daily water temperatures in October 2005 taken from neighboring BAFU gauging station (Rom-Müstair 2617). Ideally, running the LEM-σ model should include in-situ temperature measurements.

6.4.2 Analysis of unsteady results

After running both CASiMiR and the LEM-σ under unsteady flow conditions, the results of both models are investigated. As seen in Fig. (6-29), CASiMiR has overall a strong *negative correlation* with the hydropeaking activity, however it has a significant problem in that because it is designed for the study of steady flows, it exhibits the greatest amount of suitable habitat directly in the middle of some of the largest hydropeaking events! The spatial distributions of the HSI are also shown in Fig. (6-31) at 7:00 AM during a stable high flow period, and in Fig. (6-32) at 2:15 PM during the largest decrease in the flow rate. Comparing these results with that of the LEM-σ model, a striking trend is observed (Fig. 6-30). In the case of the locational entropy model, the number of suitable locations based on the assessment carried out in the previous section *actually increases* during hydropeaking events! The spatial distributions of both models are compared in Figs. (6-31) and (6-32).

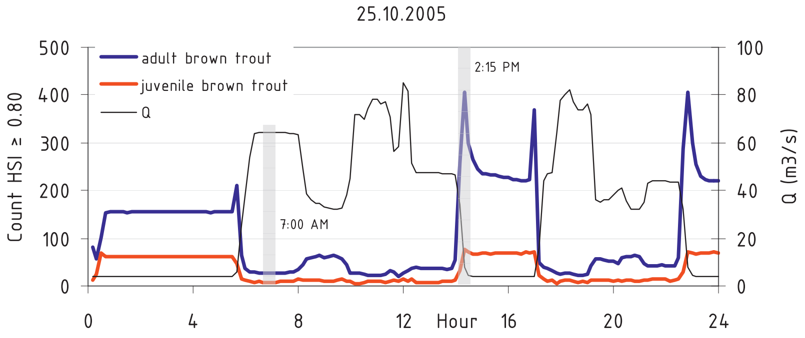


Fig. 6-28 Number count of model nodes having a HSI 0.8 for both the adult brown trout (blue) and juvenile (red) in the investigation reach Martina. Results show a strong negative correlation with hydropeaking events.

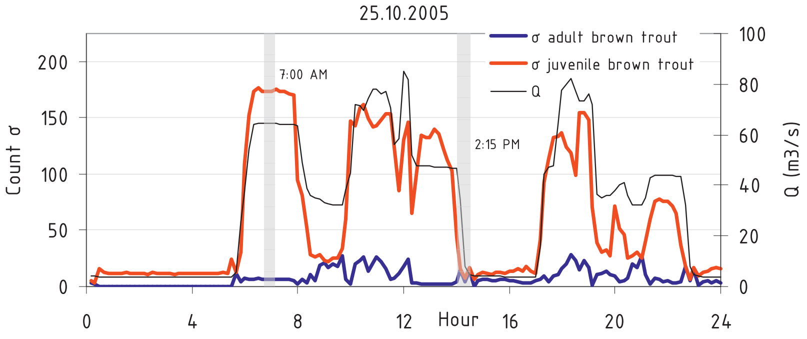


Fig. 6-29 Number count of model nodes having a σ_{adult} = 3.4E-04 and $\sigma_{juvenile}$ =1.69E-04 for both the adult brown trout (blue) and juvenile (red) in the investigation reach Martina. Results show a strong positive correlation with hydropeaking events.

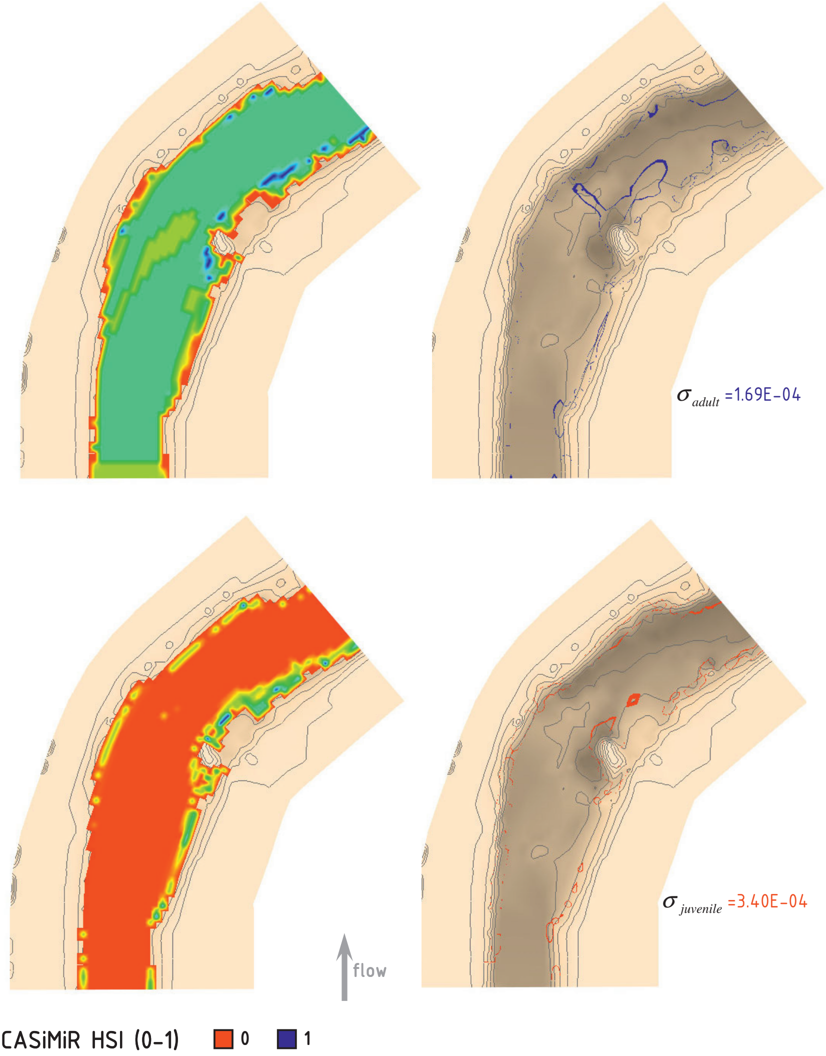


Fig. 6-30 Comparison of model results at 7:00 AM with a *stable steady* discharge of 64.3 m^3/s. *Left*: CASiMiR HSI mappings, dark blue areas are those with the highest suitability. *Right*: LEM-σ results based on the average values for the adult brown trout (top) and juvenile (bottom).

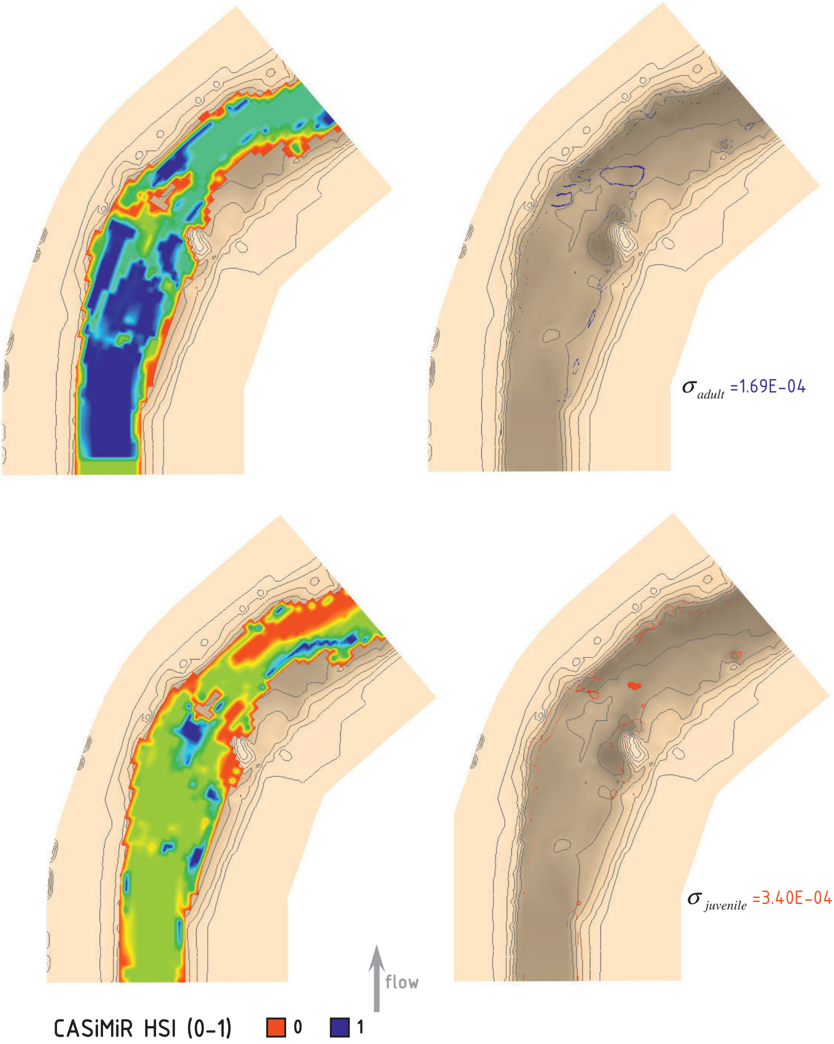


Fig. 6-31 Comparison of model results at 2:15 PM during the *largest decrease* in discharge from 47 to 4 m^3/s over the time period of 1:45-2:30. *Left*: CASiMiR HSI mappings, dark blue areas are those with the highest suitability. *Right*: LEM-σ results based on the average values for the adult brown trout (top) and juvenile (bottom).

Thus at first glance, it would appear that the LEM model is predicting that the overall habitat is improving during hydropeaking conditions. This is of course not the case. What is being observed is that the relative numbers of locations which are found to have dissipation rates in which fish are able to hold position increases during these events. Although an exact number count of these locations and a detailed analysis of the flow field is not possible due to the inaccuracy inherent to the 2D model, the LEM model clearly shows that in either case, there is a great deal less suitable locations than predicted by CASiMiR. Expanding the LEM approach to 3D and including pattern properties such as local turbulence estimates, and reach-scale LCS would no doubt provide further information as to how the LEM can be used to assess the number of suitable locations for fish during hydropeaking events.

This chapter introduced a way to roughly estimate the local entropy generation in an alpine river based on the results of a 2D hydrodynamic model. First results are compared to the state-of-the art fuzzy logic expert knowledge based CASiMiR model including fish location data on the Olivone river. It is found that although the two modeling approaches are significantly different (point values vs. patterns), correlations between high HSI and between 3 different dissipation rates could be found. Furthermore, including LCS regions it is found that the fish are in either the main channel or in high-density LCS.

After comparing CASiMiR and LEM, the thesis is presented if that the models should have some similarity, even despite their fundamental different approaches. To test this thesis, a wide range of 30 alpine river reaches are run with both models, and for each model and flow rate, points with HSI 0.8 are correlated to a fixed estimate of σ for the brown trout, for both adult and juvenile life stages. The results showed that indeed two single values did exist, prompting the theory that CASiMiR is a proxy dissipation calculator.

Finally, a highly unsteady 24-hour hydrograph is run on the river Inn at Martina, considering both CASiMiR and LEM-σ. The results showed that under unsteady conditions, there are significant differences between the results, and that the stationary concept behind the CASiMiR modeling framework predicted the greatest values of suitability during up and downramping rates, whereas the LEM-σ is correlated to the flow rate directly.

7 Conclusions

This work has covered a broad field in an attempt to develop a more concise conceptual understanding of a very specific problem. There is no doubt that there is much left to discover and even more to discuss, but it is the author's hope that some headway is made.

The second chapter told the story of the hydropeaking problem in the European Alps and presented a wide variety of mitigation measures, from local to regional. In doing so, it became apparent that our existing aquatic modeling tools, habitat models, are not adequate for the job ahead. Statistical approaches which are based on field observations (preference curves) may be suited for stable ecosystems where interest lies in teasing out relevant parameters, but they fall far short of providing explanatory variables needed to assess fish response under rapidly changing flow conditions. More recently, the expert knowledge approach has gained ground, primarily because it allows for model application in reaches where either no data exists, or in cases in which future prognosis depends on modeling scenarios which cannot be directly measured. However when experts are faced with new scenarios the habitat modeler is left with an empty set; as the conjugate to conjecture, incomplete knowledge cannot deliver complete results. The purpose of the 'second law' approach introduced in this work is to provide a deeper and more fundamental conceptual basis for aquatic ecosystem modeling.

7.1 Evaluating the Research Objectives

The goal of this work is to provide a new theoretical background for aquatic modeling in alpine rivers which can be used in even the most extreme hydropeaking conditions. The objectives of this dissertation are:

1. **Incorporate thermodynamic principles into an aquatic habitat model which can be effectively applied for highly unsteady flow regimes.**

2. **Evaluate the model in terms of performance, ease of application and theory.**

How well are these objectives reached? Regarding the first objective, there can be little doubt that a great deal of 'new' theoretical information is introduced to the aquatic habitat modeling community, most noticeably through the consideration of energy quality (free energy) and irreversibility (entropy). However, the effectiveness of this approach leaves something to be desired. Instead of reaching a set of fundamental equations which we can happily insert into a numerical model as is the original purpose, a general phenomenological principle resulted:

Persistence comes at the cost of participation.

In the final chapters, it became clear that the persistence of a fish (its ability to survive) subject to hydropeaking depends wholly on its architecture and the interactions with its surroundings. Although this statement may come as blatantly obvious, it is the first such account which is framed thoroughly using phenomenological and theoretical study. Accompanying any future modeling work on the hydropeaking problem thus requires an enhanced fundamental understanding of the fish's biomechanical response within its physiological constraints to hydrodynamic forcing caused by changes in the local flow field. Out of this, the river+fish concept can be further developed.

Addressing issues of performance is not directly possible due to the lack of observation data. Instead, the model is compared over a series of 32 alpine river reaches with the manifestation of expert knowledge via the CASiMiR model. Here it is found that there is with no doubt a strong correlation between fixed, species and life stage specific values of the areas with high habitat suitability and a fixed range of dissipative rates. Under unsteady conditions, it is however found that while the CASiMiR results provided suitable habitat mappings during steady flow regimes, the model often delivered spurious results during the most volatile periods. The LEM model by comparison provided unsteady estimates of locations based on the hydraulic gradient, and is thus conceptually tuned to changing local flow scenarios from the beginning. However the LEM model requires additional pattern parameters outside of the dissipative estimate to be of practical use. This brings us now to addressing the question of applicability.

The LEM model is not at all easy to apply. In order to calculate one single 24 hour period, even when only the dissipative estimate is used, months of careful preparation and programming are required. Furthermore, the use of a 2D model to estimate dissipation rates is problematic, especially when concerning the large surface instabilities observed on the investigation reach at Martina. Although a series of parameters is discussed, there remain many open questions regarding the proper derivation of conjugate relations: How is metabolism related to turbulence? What constellation of parameters results in a particular mode of swimming? How can the effects of temperature on a fish's specific metabolic rate be tied to changes in the local flow pattern? Even with the most state of the art 3D models, it is likely that such questions are to remain in the purview of the conceptual framework.

Although critique of the top-down approach is directly included in the main text of this dissertation, there are some theoretical difficulties present in the bottom-up approach as well. The first difficulty is the focus on only the determination of the local rate of entropy generation. Although this approach works well in inanimate, mechanochemical systems such as chemical reactors and heat exchangers, a healthy amount of doubt should be taken in its direct application to animate systems. Thus the notion of 'ecological entropy' must be either only applied as in the small scale 'fish in a box' approach used in this work, or a larger holistic notion of energy transducing processes must be accounted for.

A second point of weakness is the use of Prigogine's splitting of the entropy into internal and interactive components. This issue in irreversible thermodynamics is skirted by lumping the river+fish system into a single volume element, where the fluxes,plus internal generation is accounted for. In the case that we actually try and model a fish's entropy, we see that we indeed cannot. The breakdown of the entropy generation into two components is a somewhat misleading notion. However, it may be possible to study the interactions in a manner similar to the break down of pressure and form drag on the fish's body during swimming.

7.2 Difficulties on Theory

In writing this work, it has come to the attention of the author that there exist some points in the development of the theory as presented to which attention should be drawn. In order to keep this section concise, the author has decided to list the assumptions and difficulties in a simple tabular form

Assumption or difficulty requiring further consideration	**Section**
The physical uniqueness of an individual animate system can be mostly neglected.	*Introduction*
Alpine river conditions.	*2.2.1*
Bed sediment is not mobile.	*2.4, 3.2.2*
Quasi-equilibrium of the fish system.	*3.1*
Linear heat transfer.	*3.2.1*
There exists a species and life stage specific value of the chemical potential.	*4.1.2*
In the time intervals of study, the animate systems are in a state of homeostasis.	*4.3*
A fish's metabolic network can be seen as a type of higly variable chemically regulated process.	*5.2.1*
A fish has a fixed number of swimming modes particular to that species.	*5.2.2*
Fish locomotion is in fact not only driven by the flow field and body interaction, but is a pattern of interaction between muscular, neural, metabolic and biomechanical processes.	*5.2.2*
Fish has a steady swimming speeding over the time interval of analysis.	*5.3*

7.3 Outlook

As is mentioned in the introduction, the main goal of this work is to provide a deeper conceptual basis to the field of aquatic ecosystems modeling. As pointed out in the previous section, there are difficulties in both the applicability and theoretical underpinnings of parts of the work, there can be no doubt that the inclusion of second law irreversibility cannot impede progress in the field of aquatic ecosystems modeling.

Following Gibbs and reframed by Jaynes, it is important to recall that our imperfect knowledge of thermodynamic systems requires us to make a leap from deductive reasoning to an observer-biased inference of the natural systems surrounding us, of which we are an integral part. Instead of demanding that the laws of physics deliver us clear and exacting solutions (which cannot be answered without complete knowledge of the microstates), we should instead ask ourselves "What is our *best* guess, given the available information?" Asking this question alone requires an implicit understanding that the 'best' depends on the knowledge of the person asking the question. Thus the main goal of this work is to add to the field of aquatic ecology the optimistic notion that we *can* do better, if second law irreversibility is included in our conceptual theories of how animate systems function.

To answer the question of how the model can be improved, the author will only state that future work should focus on principles taken from constructal theory: persistence, design evolution, and information exchange are surely to play central roles. If this work is to be extended, it is necessary to revisit the weaker points previously mentioned, while remaining hopeful that new theoretical and phenomenological works will provide the necessary information to lead us forward.

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