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Preface

The work presented in this PhD thesis, entitled “Integrated ecohydrological modeling at the catchment scale”, was conducted at the Department of Environmental Engineering at the Technical University of Denmark (DTU) under the supervision of Associate Professor Peter Bauer-Gottwein (DTU) and Michael Butts (DHI). The PhD research project was conducted in the period March 2009 to June 2012 and was funded by DTU, DHI and the Danish Research Council as part of the Riskpoint project. The study included external fieldwork in Idaho, USA.

This PhD thesis comprises a synopsis and three papers that were submitted to international, ISI-indexed scientific journals:

I. Loinaz, M.C. Davidsen, H.C., Butts, M., Bauer-Gottwein, P., Integrated Flow and Temperature Modeling at the Catchment Scale. *Journal of Hydrology*, under revision.

II. Loinaz, M.C., Gross, D., Unnasch, R., Butts, M., Bauer-Gottwein, P., Ecohydrological impacts of land management and water use in the Silver Creek Basin, Idaho. *Journal of Geophysical Research - Biogeosciences*, submitted.

III. Loinaz, M.C., Hartmann, M.J., Rasmussen, J.J., McKnight, U.S., Butts, M., Bauer-Gottwein, P., Coupling a general ecosystem equilibrium model to a catchment-scale hydrologic model to evaluate ecological status in streams, *Ecological Modelling* , submitted.

The papers are not included in this www-version but can be obtained from the Library at DTU Environment:

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Thank you to my DTU friends for helping me remember that there is more to PhD life than a computer. Enormous thanks to Sara Lerer (and family) for their help in translating the abstract to Danish, as well as for their incredible kindness and friendship through our stay in Denmark.

Thank you to my family for their unfailing love and support. Finally, I am extremely grateful to my amazing partner Shelly, for happily agreeing to come with me to Denmark, for her brilliant editing, and for her constant love in everything.

Maria C. Loinaz
July 2012

Abstract

Water resources managers increasingly face the challenge of balancing water allocation in environments of water scarcity, high food production demand, and rising pollution levels. Scientists face the challenge of providing managers with accurate predictions on the outcome of management alternatives that help to guide the decision process. The need to take a holistic approach and evaluate interrelated factors that impact the availability of water resources, such as climate, landscape processes, and surface water interaction with groundwater at the catchment scale is increasingly recognized. It is through this approach that human interaction with the environment can be properly assessed. The field of ecohydrology is an interdisciplinary science that seeks to understand the links between the physicochemical stressors with biological receptors to support policy for the sustainability of natural resources.

This PhD study focuses in developing integrated ecohydrological models at the catchment scale that quantify the changes in receptors caused changes in environmental stressors as a results of management alternatives. The modeling approach involves coupling spatially distributed and physically based hydrological models to process-based ecological models. The output is a measure of ecological status as a result of a changing environment. The models include the dynamic interactions between the main components of the hydrologic cycle, with a focus on surface water and groundwater interactions, which are key drivers in aquatic ecology. Another key driver in aquatic ecology is stream temperature, which traditionally has been simulated at the local stream scale with point source thermal loads. This study has extended the previous work on stream temperature model development to include diffuse loads at the catchment scale.

The research methodology was applied in two case studies, both located in agricultural catchments. One case, located in Idaho, US, deals with the issues of water scarcity, intensive agricultural practices, high stream temperatures, and fish habitat degradation, which are widespread problems in the Western US. To evaluate management alternatives for an intensively cultivated valley an integrated surface water-groundwater and stream temperature model was developed. The model was coupled to an ecological model that predicts fish growth as a function of temperature and other factors. Among the main findings of this study is that groundwater flow has a strong influence on stream temperature levels and dynamics in areas with high surface water and groundwater exchange. Moreover, the strong relationship between stream

temperature and the volume and source of streamflow (snowmelt, groundwater, urban and agricultural runoff) demonstrate the value of temperature data in an integrated flow model calibration. Land use and water use changes impact both the surface water and groundwater resources and can thus substantially change stream temperature dynamics. Local scale factors such as stream vegetation and geomorphology also play an important role in determining stream temperature. Thus, a combination of restoration strategies must be evaluated to find the optimal thermal conditions. Fish optimal growth and sustainability is dependent on a specific range of temperatures, but is also affected by seasonal variability, which should be taken into account when evaluating restoration alternatives.

The other case, located in an agricultural catchment west of Copenhagen, Denmark, deals with the issue of pesticide toxic effects in a stream ecology. Pesticides are among the most prevalent contaminants of surface waters worldwide. The composition and abundance of aquatic biota, such as benthic macroinvertebrates, are commonly used as indicators of water quality in the streams. The effects of toxicity have different effects on different organisms, which leads to a change in the abundance of certain species and the community structure. To evaluate these effects a general equilibrium ecosystem model was linked to a hydrologic and solute transport model of the catchment. The ecohydrological model transports pesticide loads from agricultural fields to the streams where the concentrations of the pesticides are simulated and linked to the ecosystem model. The ecosystem model includes several macroinvertebrate taxonomic groups and fish and accounts for the mechanisms that affect the stream community structure: energy availability and flow, foodweb interactions, and the toxic responses. Under polluted habitat conditions, physiological changes in an organism can affect not only its metabolic functions and the ability to optimize its energy use, but also its defense mechanisms to avoid predation. This can cause changes in the food availability and the biomass flow, which can lead to changes in the community structure. The model results show than these effects can vary in magnitude and direction under different habitat conditions. However, there is a need to better understand the physical mechanisms that impact an organism in response to stress so that these can be properly parameterized.

Dansk sammenfatning

Forvaltere af vandressourcer står i stigende grad over for den udfordrende opgave at regulere adgangen til vand under omstændigheder præget af knaphed, stor efterspørgsel til fødevareproduktion og tiltagende forurening. Forskere står over for udfordringen at forsyne forvalterne med forudsigelser om de langsigtede konsekvenser af forskellige forvaltningsalternativer, som kan støtte forvalterne i beslutningsprocessen. Der er en stigende anerkendelse af behovet for en holistisk tilgang, der omfatter faktorer, som påvirker tilgængeligheden af vandressourcer, såsom klimaforandringer, landskabsprocesser og udvekslingen mellem overfladevand om grundvand på oplandsskala. En sådan tilgang er nødvendig, for at menneskets samspil med miljøet kan vurderes korrekt. Økohydrologi er en tværfaglig videnskab, der søger at forstå samspillet mellem fysisk-kemiske stressfaktorer og biologiske receptorer med det formål at støtte en bæredygtig forvaltning af naturressourcer.

Nærværende ph.d.-studie har fokuseret på at udvikle integrerede økohydrologiske modeller på oplandsskala, der kan koble miljømæssige stressfaktorer til økologiske receptorer og kvantificere stressforårsagede ændringer i receptorerne under forskellige forvaltningsalternativer. Modelleringskonceptet indebærer kobling af rumligt distribuerede og fysisk baserede hydrologiske modeller til procesbaserede økologiske modeller. Modellerne tager højde for den dynamiske vekselvirkning mellem de vigtigste dele af det hydro-logiske kredsløb med fokus på udveksling mellem overfladevand og grundvand, som er en central parameter i akvatisk økologi. En anden vigtig parameter i akvatisk økologi er vandløbstemperaturen, der traditionelt har været simuleret på lokal vandløbsskala med punktvise termiske belastninger. I dette studie er der fortaget en videreudvikling af tidligere vandløbstemperaturmodeller ved at tilføje en beskrivelse diffuse termiske belastninger på oplandsskala.

Modelleringskonceptet blev anvendt i to casestudier, der begge ligger i landbrugsområder. Den ene case i Idaho, USA, handler om vandmangel, intensive landbrugsmetoder, høje vandløbs-temperaturer og forringelse af levesteder for fisk, hvilke er udbredte problemer i det vestlige USA. For at vurdere forvaltningsalternativer i en intensivt dyrket floddal blev der opsat en integreret overfladevands-, grundvands- og vandløbstemperaturmodel. Modellen blev koblet til en økologisk model, der forudsiger fiskevækst som funktion af temperatur og andre faktorer. Et af de vigtigste resultater af denne undersøgelse er, at grundvandstilstrømningen har en stærk indflydelse på temperaturniveauer og -dynamikker i vandløb i områder med høj udveksling mellem overfladevand og grundvand. Derudover viser den stærke sammenhæng mellem vandløbs-temperatur, volumen og oprindelse af vandføringen i vandløbet (smeltevand, grundvand, by- og landbrugsafstrømning) værdien af temperaturdata i kalibrering af en integreret vandløbsmodel. Ændringer i arealanvendelse og vandforbrug påvirker både overfladevand og grundvand og kan derfor have en væsentlig effekt på vandløbstemperaturens dynamik. Lokale parametre såsom vandløbsvegetation og geomorfologi spiller også en vigtig rolle for vandløbstemperaturen. Det er derfor nødvendigt at vurdere kombinationer af genopretningsstrategier for at finde optimale temperaturforhold. Optimale og bæredygtige vækstbetingelser for fisk er afhængige af et bestemt interval af temperaturer, men er også påvirkede af sæsonmæssige variationer, som bør tages i betragtning ved vurderingen restaureringsalternativer.

Den anden case, som omfatter et landbrugsområde vest for København, handler om pesticiders toksiske effekter på vandløbsøkologi. På global skala er pesticider blandt de mest udbredte forureningselementer i overfladevand. Sammensætningen og mængden af den akvatiske biota, såsom bundlevende smådyr, er bredt anvendt som indikatorer for vandkvalitet i vandløb. Pesticiders toksicitet har forskellige effekter på forskellige organismer, som fører til en ændring i mængden af visse arter og dermed vandløbets samfundsstruktur. For at vurdere disse effekter blev en økosystembalancemodel koblet til en hydrologisk model og stoftransportsmodel for op-landet. Den økohydrologiske model transporterer pesticidbelastninger fra marker til vandløb, hvor pesticidkoncentrationer beregnes og kobles til økosystemmodellen. Økosystemmodellen omfatter flere taksonomiske grupper af makroinvertebrater samt fisk, og simulerer de mekanismer, der påvirker vandløbets samfundsstruktur: energistrømme og energitilgængelighed, interaktioner i fødenettet og toksiske reaktioner. Under forurenede levevilkår kan fysiologiske ændringer i en organisme påvirke ikke kun dets metaboliske funktioner og evnen til at optimere sit energiforbrug, men også dens forsvarsmekanismer mod rovdyr. Dette kan medføre ændringer i fødetilgængelighed og biomassestrømme, som kan føre til ændringer i samfundets struktur. Modelresultaterne viser, at disse effekter kan variere i størrelse og retning under forskellige habitattilstande. Der er imidlertid behov for en bedre forståelse af de fysiske mekanismer, der påvirker en organisme under stress, så de kan beskrives bedre i modellen.

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1 Introduction

Effective water resources management involves balancing water allocation among several users in a watershed and requires knowledge about the societal benefits of such allocation. In recent decades it has been recognized that ecosystems not only provide valuable services, but also will determine sustainability of human society. This has motivated efforts by scientists and economists to quantify ecosystem value (Costanza et al., 1997). The challenges of water distribution and its impact on ecosystem services occur in many settings, but are particularly critical in agricultural areas. Higher food production is necessary to sustain the projected increases in world population, but it is estimated that 50% of the global habitable land has already been developed for agriculture (Tilman et al., 2001). Moreover, 40% of the crop production is generated by the 16% of the agricultural land that is irrigated. In many of these areas, the water used for irrigation exceeds the available capacity and is increasingly in competition with other uses, such as urban development and ecosystem requirements (Tilman et al., 2002).

In addition to the intensive water requirements, the application of fertilizers and pesticides is necessary for highly productive agriculture. This results in significant releases of nutrients and toxic chemicals to receiving waters with high cost to ecosystem services. Tilman et al. (2001) estimated that a billion hectares of natural ecosystems will be converted to agriculture land and that nutrient and pesticides use will more than double from 2000 to 2050. Tilman et al. (2002) argues that the solution to sustainable increases in food production is increased efficiency, and several alternatives already exist to help increase efficiency of nutrient intake by crops, decrease nutrient and pesticide release, prevent erosion, and improve water use efficiency. Thus, water managers have the task of evaluating these alternatives to find optimal and sustainable solutions based on scientific data and insight.

For this purpose, Loucks (2006) proposed a practical methodology that relates hydrology, ecology, and the economics of water resources management for a sustainable environment. It consist of a seven-step planning process in which the first four steps are: identifying performance indicators that represent the objectives; defining hydrologic attributes that impact the performance indicators; developing functional relationships between indicator and hydrologic attribute; and computing performance indicator values as a result of water management policies. The next two steps consist of summarizing and comparing data; the final step involves quantifying the statistical confidence in the decision-making process by means of sensitivity and uncertainty analysis. These steps are anchored in several scientific disciplines, and require collaboration and knowledge from multiple academic backgrounds.

Ecohydrology is the discipline that mostly concerns the development and improvement of strategies for the first four steps of the Loucks' planning process. In order to quantify the value of ecosystem services and the impact caused by anthropogenic resource use, it is important to understand and be able to predict how the various components, i.e. physical factors, chemical and biological processes, and human consumption, interact. Figure 1.1 shows a schematic of the integrated ecohydrologic modeling concept within the framework of decision support for water resources management. An integrated ecohydrologic model evaluates a set of policies where environmental stressors are linked to biological receptors. The integrated model includes a representation of catchment-scale hydrologic processes, including surface water and groundwater exchanges, driven by climate factors, landscape characteristics, and human intervention. These factors determine the aquatic habitat's physical and chemical conditions in terms of the flow, temperature, oxygen, nutrients and other chemicals, which in turn determine the ecological structure. The output of the model is used to evaluate the feasibility of alternatives through an economic model or cost-benefit analysis that includes the value of the ecosystem services. Multi-objective functions are defined in order to find the Pareto front, which contains a set of optimal solutions.

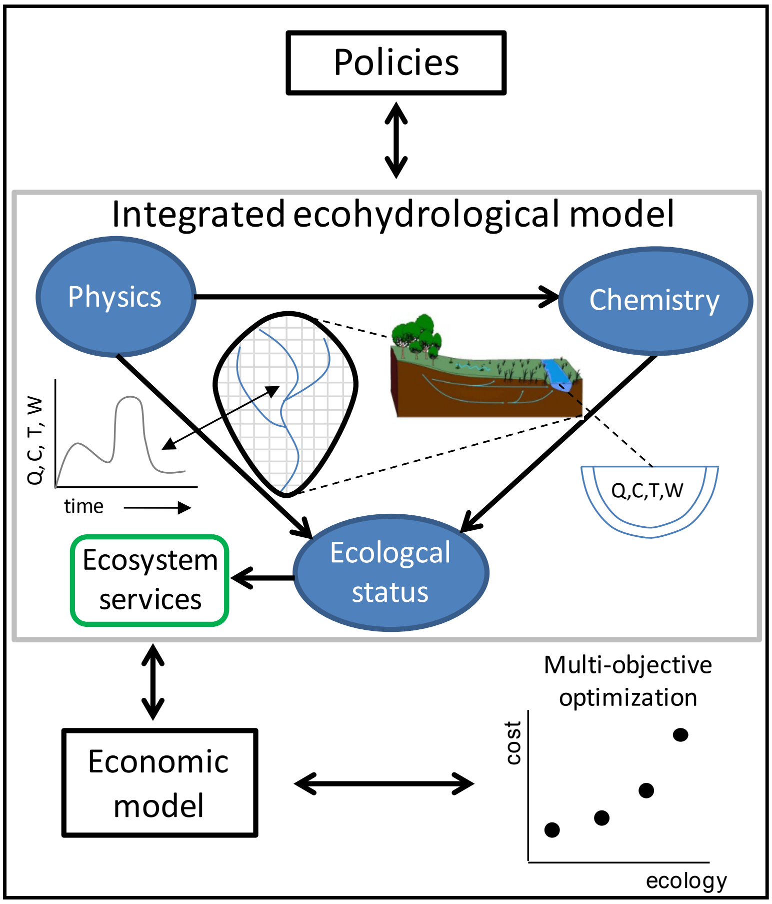

Figure 1.1 Framework for integrated ecohydrology in the context of water resources management. Q = flow, C = concentrations of solutes, T = water temperature, W = weight of fish or other organisms.

In the context of the framework shown above, this PhD research has focused on simulating the response of selected performance indicators to various environmental stressors in agricultural catchments. In one case, the relationships between surface water-groundwater flow, stream temperature, and fish growth is evaluated. In another case, the potential impacts on stream foodwebs as a consequence of the transport of pesticides from agricultural runoff is simulated. This work aims to contribute to the field of ecohydrologic knowledge of catchment-scale surface water-groundwater interactions and how these impact other stressors such as water temperature. The work also investigates practical and process-based approaches to ecological modeling.

The three main objectives of this research were to:

- Develop integrated ecohydrologic models that relate environmental stressors in a catchment to an indicator of ecosystem status.

- Quantify changes in ecosystem status caused by changes in catchment management strategies.
- Evaluate different approaches to ecological modeling that can be practically linked to catchment-scale hydrologic models.

This thesis provides a summary of the three papers submitted for journal publication as part of the PhD study and is structured as follows. Chapter 2 provides a literature review of previous work conducted on the main research topics. Chapter 3 presents the two case studies used to apply the methodologies. Chapter 4 provides an overview of the methodologies applied. Chapter 5 illustrates the main results. Chapters 6 and 7 summarize, respectively, the main conclusions of this research and a list of future research directions based on the work presented in this thesis. Chapter 8 includes the three papers.

2 Literature Review

The first section of this chapter begins with a general overview of the work done in the field of ecohydrology, including different types of ecohydrological modeling tools that have been developed. The second section focuses on work that has highlighted the importance of catchment scale processes and surface and groundwater interactions in stream ecology. The third section provides an overview of some of the existing mechanistic dynamic ecological models and alternative approaches that could offer some advantages over the more complex models.

2.1 Ecohydrology

Although ecologists have always recognized the dependence of organisms and ecosystem community structure on environmental abiotic factors, it has been in the recent decades that ecohydrology has evolved into a separate discipline and exponentially grown in the last decade (Hannah, 2007). However, ecohydrology is a broad field and is defined differently in the scientific community. Hannah et al. (2004) discusses two of the most cited definitions: one from the point of view of ecologists who define ecohydrology as ‘the study of the functional interrelations between hydrology and biota at the catchment scale’ (Zalewski, 2000) and another from the point of view of hydrologists who define hydroecology as ‘the linking of knowledge from hydrological, hydraulic, geomorphological and biological/ecological sciences to predict the response of freshwater biota and ecosystems to variation of abiotic factors over a range of spatial and temporal scales’ (Dunbar and Acreman, 2001). The first definition emphasizes the link between water resource management and ecosystem responses to a changing environment and the second definition focuses on understanding of the fundamental processes that overlap between different disciplines (Hannah et al., 2004). However, it is likely that as the field becomes more interdisciplinary and as predictive tools become more sophisticated, these two definitions will merge.

In general, ecohydrological modeling has consisted of a more complex representation of either hydrology or ecology and more simple representation of the other. Witte et al. (2008) classifies the types of models in ecohydrology as: correlative, semi-mechanistic, and mechanistic citing some examples of Dutch models. Correlative models relate the statistical occurrence of certain species to site factors, neglecting a mechanistic description of the processes and rather treating the ecosystem as a black box. The main advantage is that in theory there is less bias in terms of what causes a response, i.e., if many environmental factors are included, then one or more will statistically have a stronger relationship to the outcome caused by an environmental change based on the observations. The main disadvantage is that these models do not contribute to understanding of the system's response and thus have limited predictive capability. A mechanistic ecohydrological model describes the causal relationships developed from experiments or theory for both hydrology and ecology. Strictly mechanistic ecohydrological models do not exist, which is why many ecohydrological models are semi-mechanistic, having both correlative and mechanistic components (Witte et al., 2008).

Much of the mechanistic models in ecohydrology involve nutrient, soil, and plant processes perhaps because these are better understood than processes that affect individual organisms or a foodweb. One example is the NUCOM model (Van Oene et al., 1999) which models plant species, water, nutrient and carbon cyling, and soil development through decomposition and mineralization. This model simulates complex environmental/ecological processes and simple representations of hydrology and does not, for example, take into account changes in groundwater levels caused by water management (Witte et al., 2008). Carpenter et. al, (1999) linked a phosphorous model of a lake to an economic model and evaluated alternate trophic states of the lake based on different management policies. Band et al. (2012) applied the Regional HydroEcological Simulation System (RHESSys) that simulates water, carbon and nutrient cycling, and vegetation growth in a spatially distributed terrain to a forest ecosystem to assess the interaction of these components and the effect on slope stability and drainage for landslide predictions.

Previous work on the impacts of environmental stressors on aquatic fauna has focused mostly on the distribution patterns and abundances and statistical correlations between these patterns and environmental variables. For example, hydraulic stress based on changes in channel slope has been correlated to the distribution of benthic macroinvertebrates (Statzner, 1981). The Habitat Quality Index (HQI) is a multiple regression model that relates many habitat variables to fish abundance (Binns, 1982). The River Invertebrate Prediction and Classification System (RIVPAC) is another statistical model that predicts the probability of macroinvertebrates species composition using a multivariate analysis based on hydrology, water quality, and geomorpholgy (Armitage, 1989; Carlisle, 2008). Numerous other models that developed statistical correlations between flow and/or temperature and habitat conditions, fish abundance or life cycles (Trépanier et al., 1996; Crozier et al., 2008; Wenger, 2010). Nevertheless, there are other models of aquatic fauna that attempt to predict the behavior of organisms such as the Physical Habitat Simulation (PHABSIM) (Bovee, 1982). This model uses habitat suitability curves in combination with a decision support tool, Instream Flow Incremental Methodology (IFIM) (Nestler et al., 1989). However, it has been criticized for its simple hydraulics that fail to properly describe crucial factors that would affect the organisms behavior that it is trying to predict, such as velocity and depth (Gore and Mead, 2008).

2.2 Role of catchment hydrologic processes on stream ecology

Catchment hydrologic processes cannot be ignored when evaluating stream ecological status or stream restoration strategies. Wissmar and Beschta (1998) argue that the concept of a holistic approach that integrates the biophysical connectivity of the landscape to riparian ecosystems is necessary for the sustainability of these ecosystems. Some of the important features of landscape dynamics include: the distribution of vegetation, which influences nutrient cycling, microclimate, and hydrology, the distribution of sediment and organic matter, which affects the biotic community structure and river hydraulics, and surface water and groundwater exchanges. Moreover, the authors stress the importance of understanding how these processes are altered by human activity when considering restoration alternatives. Molnar et al. (2002) also emphasized the importance of a holistic approach to river management and argue that there is a need for integrated physically-based catchment modeling. Quantifying the interactions between climate, topography, soil, geology, vegetation, river morphology, and ecology requires an assessment at different spatial scales. The authors present a nested modeling approach, which allows for use of different scales, with a focus on sediment dynamics as a connector between hydrology and ecology.

Recent studies have focused on the role of groundwater and surface water and groundwater dynamics in stream ecology. Hayashi and Rosenberry (2002) review some of the physical and chemical characteristics of streams and lakes affected by groundwater fluxes such as the flow volume, temperature, nutrients, pH, and other chemical properties. These are essential factors in determining habitat conditions for aquatic ecology. Smith et al., (2008), focusing on nutrient dynamics, discuss the need for upscaling hyporheic zone processes and the need of better predictions of surface water – groundwater exchanges for catchment scale management.

Recent studies analyzed the role of river flow and groundwater in fish ecology. Olsen and Young (2008) used temperature data to assess whether gaining reaches were likely to represent significant cold-water refuges for brown trout during periods of low flow and high water temperature. They found trout concentrated in a spring area that had a mean water temperature 3°C cooler than the main stream during the summer months. Olsen et al. (2009) studied the effect of groundwater abstractions in Danish streams and the potential impact in fish. The authors combined a lumped parameter hydrological catchment model (NAM) model with a stream habitat model that uses habitat suitability indices based on depth and velocity to estimate the stream habitat conditions for brown trout of different ages. Stewart-Koster et al. (2011) use a statistical model to correlate the highly seasonal flow variations of an Australian river with the fish distribution and abundance. They found significant correlation between the flow magnitude and variation and the species composition throughout the catchment.

2.3 Ecological modeling

As discussed in section 2.1, most of the ecohydrological models are correlative or semi-mechanistic. Because of the limitation of correlative models in terms of lack of description of fundamental processes that cause an ecosystem response and therefore their limited predictive capability, this section presents ecological modeling approaches that use physical and biological principles derived through either empirical or theoretical knowledge to relate organisms to environmental variables.

Several mechanistic foodweb models that describe the biological and chemical pathways of nutrients, other chemicals, and organic matter and the exchange of biomass for different species in a foodweb have been developed. Scavia (1980) developed an ecological model of Lake Ontario that simulates the interactions of phytoplankton, zooplankton and fish, and nutrient cycles. Fitz et al., 1996 developed the Generic Ecological Model (GEM) which simulates the response of macrophyte and algal communities to simulated levels of nutrients, water levels and nutrients. De Angelis et al., (2008) developed a model foodweb dynamics of a wetland including fish, periphyton, and invertebrates applied to the Florida Everglades. Another foodweb model, AQUATOX, is a comprehensive dynamic foodweb model that includes physical and chemical interactions with the organisms in the foodweb, including higher trophic levels (Park et al., 2008). The value of these models is that they are physically-based and they can predict how different environmental factors can impact the populations in an ecosystem.

While, foodweb dynamic models provide useful insight into the system dynamics, they are complex and require large amounts of data. Moreover, dynamic models by definition are in constant changing state; and as such it is difficult to separate the long-term impacts of environmental stress and develop simple measures of ecosystem status. There are alternative ecological modeling approaches that describe causal relationships between stressor and receptor which require less amount of data, provide simpler output, and can be easily linked to other models. One approach is to model an individual organism of interest, such a certain species of fish, and the environmental stressors that have an impact on its sustainability. The ability of this organism to grow, reproduce, and survive serves as an indicator of health of the ecosystem. An example of this type of model is the fish bioenergetics model, which describes the energy balance for different species of fish and relates temperature to fish growth (Kitchell et al., 1977).

Another alternative to complex dynamic models is to use an equilibrium modeling approach. Equilibrium ecological models can simulate complex ecosystems with relatively simple models and are useful in providing insight into ecosystem structure. The ECOPATH model (Polovina, 1984; Christensen and Pauly, 1992) aims at understanding the structures of ecosystems by estimating the biomass balance and energy flows between trophic levels. Hannon (1973) defined the structure of an ecosystem in terms of energy flow interdependence between system components. In the field of bioeconomics modeling strategies have been developed that link ecological models to economic models. Modeling ecology from an economic perspective has the benefit of providing insight into how scarce resources are allocated among users (Rapport and Turner, 1977). Tschirhart (2000) developed the general equilibrium ecosystem model (GEEM) where organisms maximize their energy intake based on the general equilibrium model of economics, in which consumers maximize utility and firms maximize profit. This model has been linked to an economic model and applied to a marine ecosystem to assess the impact of harvesting fish in the ecosystem (Finnoff and Tschirthart, 2003).

3 Case Studies

3.1 Silver Creek, Idaho

Silver Creek is a spring-fed stream ecosystem abundant in wildlife and an important trout habitat located in south-central Idaho (Figure 3.1). The Silver Creek Preserve, managed by The Nature Conservancy, attracts thousands of visitors every year from all around the US and other countries and contributes a substantially to the local economy. Among the ecosystem services provided by Silver Creek are sport fishing, bird watching, hiking, and canoeing. Nevertheless, the sustainability of this ecosystem is at risk due to low flows, accumulation of fine sediment, and high temperatures during the summer months (Gillilan, 2007; Ecosystem Sciences Foundation, 2011).

Figure 3.1 Silver Creek.

The Silver Creek Basin occupies the southeastern portion of a triangular valley known as the Wood River Valley, which is surrounded by high mountainous terrain on all sides (Figure 3.2). An alluvial aquifer system underlies the valley and is the source of water to Silver Creek. The aquifer system links two surface water basins, the Big Wood River Basin and the Little Wood River Basin. Silver Creek is a tributary of the Little Wood River, however the Big Wood River and its diversion canals recharge the aquifer that feeds the Silver Creek Basin. In the south-central portion of the valley thick, extensive layers of fine-grained material serve as barriers to groundwater flow. Springs form in the central area of the valley where the confining units constrain the movement of groundwater. Some of these springs flow to the west into the Big Wood River and some form the tributaries that flow southeast to Silver Creek.

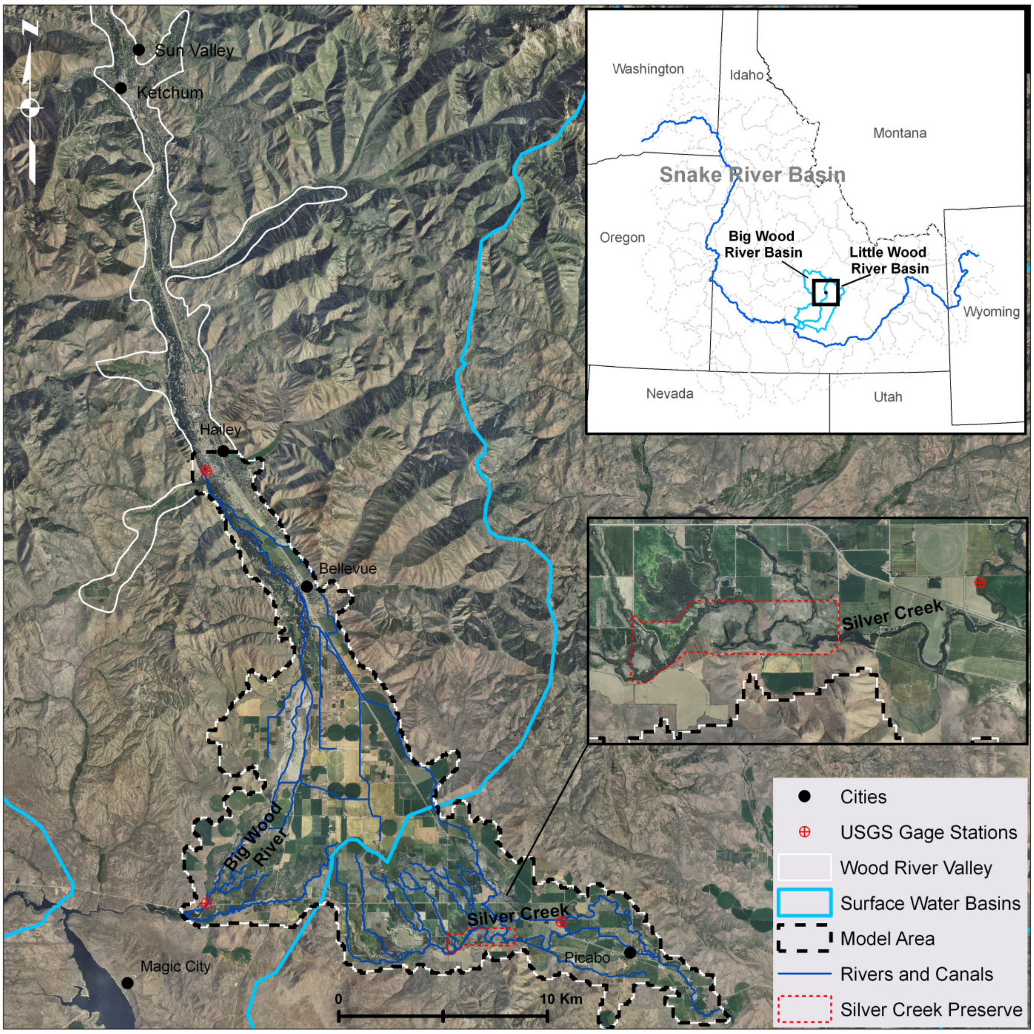

Figure 3.2 Location of the Wood River Valley and Silver Creek.

The climate of the Lower Wood River Valley is semi-arid with low precipitation and high evapotranspiration (Brockway and Kahlown, 1994). The valley is intensely cultivated (approximately 64% of the area) and approximately 80% of the crop area is irrigated via both surface water diversions and groundwater abstractions (Brockway and Kahlown, 1994). The crop demand is over twice as much as the available water from rainfall. As a result, studies have shown declines in streamflows and the water table from the 1950s to the present (Skinner et al., 2007). Lowering groundwater elevations decreases the spring flows that feed the Silver Creek Basin. The lower flows and higher stream temperatures during the summer months pose a threat to the health of the aquatic habitat. Periods of drought have caused higher-than-normal temperatures and low dissolved oxygen that have resulted in fish kills (Wetzstein et al., 2000).

In this case study we evaluate the impacts of changes in flow and temperature on fish populations. We built a catchment-scale integrated surface water-groundwater model dynamically linked to a stream temperature model. The output of the temperature model is input to a fish model. The model can simulate the diffuse sources of heat into the Silver Creek Basin streams, which include atmospheric heat, groundwater flow, agricultural return flows, and mountain snowmelt (paper **I**). We investigate the causes of stream habitat deterioration by applying the model to a set of catchment water use and land use alternatives, stream scale restoration scenarios, and a climate change scenario (paper **II**).

3.2 Hove Å Catchment, Denmark

The Hove catchment is an agricultural catchment in the island of Zealand, Denmark (Figure 3.3) and was the study area selected for the Riskpoint project. Several studies were conducted as part of this project, including an evaluation of the physical and chemical stressors to the stream ecology (Rasmussen et al., 2012).

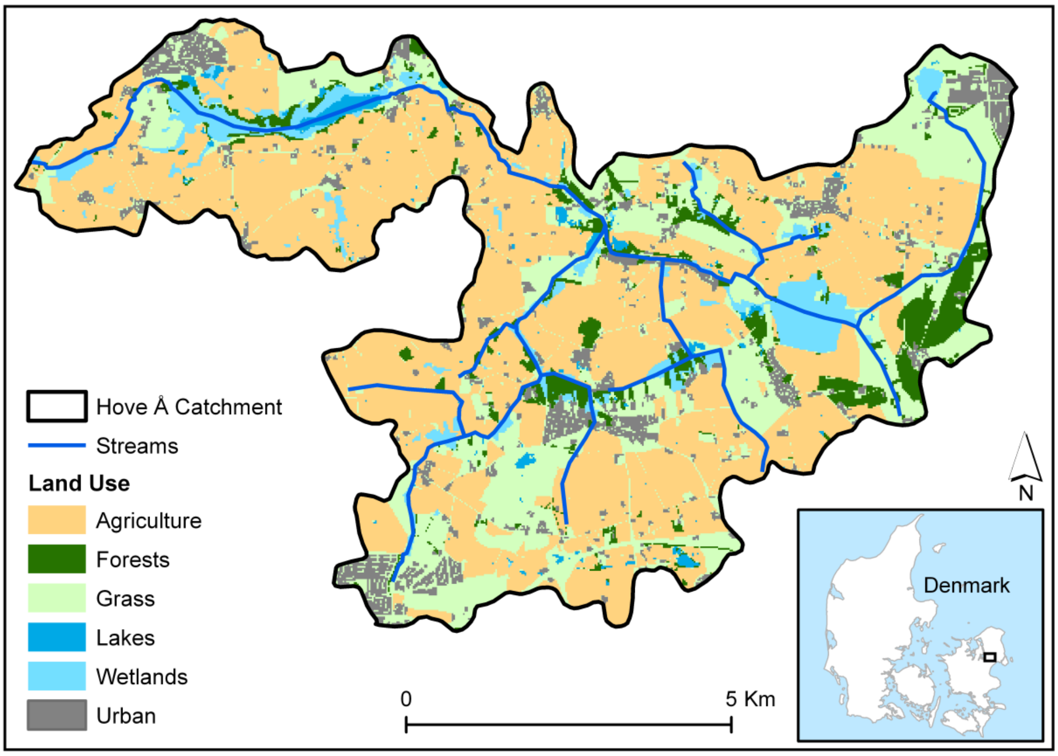

Figure 3.3 Hove catchment, Denmark.

The Hove stream flows from the south of the catchment to the northwest and ends at the Roskilde Fjord. The stream network in the catchment connects important wetland and lake habitats, such as Lake Gundsømagle, which is a bird sanctuary and nature reserve (Figure 3.4). Agriculture is the dominant land use in the area. Much of the area is drained for agriculture use and many of the streams have been channelized. The streams in the catchment are narrow and shallow and have mostly homogeneous physical conditions, with high percentage of silt and low percentage of coarse materials (Rasmussen et al., 2012) (Figure 3.4).

Figure 3.4 Lake Gundsømagle, located at the downstream portion of the Hove stream, and collection of storm water samples in the Hove catchment streams.

In this case we evaluated the impact of pesticides on the Hove catchment stream ecosystem. Studies in Denmark have found high occurrence and concentrations of numerous pesticides in streams (Kronvang et al., 2003, Rasmussen et al., 2012). It is believed that one of the main pathways of transport of pesticides is through the subsurface drainage water during rain events (Kronvang et al., 2003, Rasmussen et al., 2012). Pesticide concentrations in streams have been correlated to changes in stream macroinvertebrate community abundance and composition (Liess and Schulz, 1999; Friberg et al., 2003). We applied a surface water – groundwater model to simulate the transport of pesticides from agricultural fields into the streams and input the pesticide concentrations into an ecological model of a macroinvertebrate and fish foodweb. The focus of this study was to test the application of an equilibrium ecological modeling approach to simulate the impacts of toxicity in a foodweb (paper **III**).

4 Methods

4.1 Integrated modeling at the catchment scale

An overview of the modeling tools and how they were applied to both cases is given below. The first section contains an overview of the integrated surface water – groundwater model equations and a brief discussion of the model setup for both case studies. The second section provides an overview of the temperature model, which was only applied to the Silver Creek, Idaho case study. The third section discusses the two types of ecological modeling approaches used; one was applied to the Idaho case and the other to the Danish case.

4.1.1 MIKE SHE – MIKE 11

The coupled MIKE SHE – MIKE 11 model was used for both cases because it is a suitable tool for surface groundwater interactions and conjunctive water use studies in agricultural catchments (Refsgaard and Storm, 1995; Graham and Butts, 2006). MIKE SHE is a physically-based and spatially distributed model that calculates the main processes of the hydrologic cycle in a catchment using finite difference numerical solutions (DHI, 2011a). These processes include snowmelt, interception, overland flow, infiltration into soils, evapotranspiration from vegetation and subsurface flow in the unsaturated and saturated zones. For both case studies the processes above were included in the model using spatially distributed and time varying input data.

MIKE 11 is a one-dimensional surface water model that solves the St. Venant equations (4.1a and 4.1b). Equation 4.1a, known as the continuity equation, describes the conservation of mass and equation 4.1b describes the conservation of momentum in a control volume. The model output is water levels and discharge in alternating computational nodes along the streams (DHI, 2011b).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (4.1a)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} - gA(S_o - S_f) = 0 \quad (4.1b)$$

where, Q = flow (m^3/s), x = longitudinal distance (m), A = cross-sectional area (m^2), t = time (s), q = lateral inflow (m^3/s), g = acceleration due to gravity (m/s^2), h = water level (m), S_o = channel bed slope (-), S_f = friction slope (-).

The 3-dimensional saturated groundwater flow equation used by MIKE SHE and based on Darcy's Law can be written as equation (4.2).

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - Q = S\frac{\partial h}{\partial t} \quad (4.2)$$

where, K_x, K_y, and K_z = hydraulic conductivities in the x, y, and z directions, respectively (m/s), h = hydraulic head (m), Q = source/sink flow (m^3/s), S = storage coefficient (specific storage for confined conditions and specific yield for unconfined conditions).

The exchange flow between the groundwater flow in MIKE SHE and the surface water flow in MIKE 11 is calculated by equation (4.3) (DHI, 2011a).

$$Q = C\Delta h \quad (4.3)$$

where, C = conductance (m^2/s) and Δh = water level difference (m). The conductance term in the exchange flow calculation is controlled by a stream bed leakage coefficient, aquifer conductivity, or both. Figure 4.1 shows a schematic of the surface water groundwater exchange between the surface water model and the groundwater model.

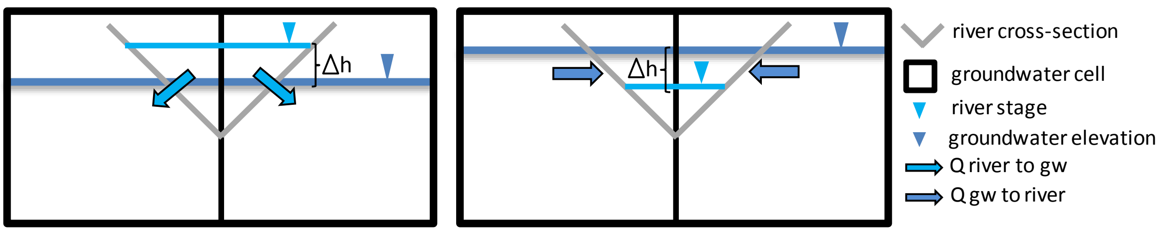

Figure 4.1 Surface water and groundwater exchanges in MIKE SHE.

4.1.2 Wood River Valley flow model

The availability of spatial and time series data for Idaho allowed us to include a considerable amount of detail in the Wood River Valley model. Thus, substantial effort went into building and calibrating the model. Fieldwork was also conducted in collaboration with The Nature Conservancy to measure groundwater levels, stream flows, and temperatures and to obtain information about the water distribution system (Figure 4.2). Pressure transducers were installed at several locations throughout the valley and the data was recorded for one year to capture the spatial and temporal variability of groundwater flows. Streamflows were measured at many locations throughout the Silver Creek Basin to identify the locations of gains and losses in Silver Creek and tributaries and to quantify the distribution of flows throughout the basin.

Figure 4.2 Fieldwork.

The main target of the Wood River Valley hydrologic model calibration was to optimize the accuracy of the Silver Creek flows. Since the flows are spring-fed, the groundwater model has to be fairly accurate and since the Big Wood River and canal system lose a significant portion of water to the aquifer, the surface water distribution also has to be fairly accurate. The main challenges in calibrating the model were the limited geologic data for building the groundwater model and the limited data on water distribution and abstractions. Following the approach of previous groundwater studies of the area, the geologic model was conceptualized into three layers: an unconfined aquifer, a confining unit, and a confined aquifer. However, in reality the geology of the valley is much more heterogeneous. An effort was made to capture some of this heterogeneity during the calibration of the hydraulic conductivities. For example, the upper unconfined aquifer layer was divided into zones based on transmissivity data from previous studies and semi-automatic calibration was performed varying the conductivities of the various zones. Other calibration efforts and model checks included varying the leakage coefficient in the streams and irrigation canals, ensuring consistency in the topography between MIKE SHE and MIKE 11, optimizing the simulation of water distribution system, (e.g., representation of the canal storage and seepage, applied irrigation volumes, groundwater abstractions) with the available data.

4.1.3 Hove catchment flow model

The Hove catchment model was extracted from an existing model of the entire island of Zealand, Denmark (Kürstein et al., 2009). The model boundaries were determined by running particle tracking simulations to find the groundwater flow divide. The groundwater head elevations from the larger model were used as boundary conditions. The cell size was reduced to a 100-meter grid and some of the stream data was updated with new information from field studies. The model includes spatially distributed climate data, 13 geologic layers, 15 soil types, 10 streams, and 54 groundwater abstraction wells. The streamflow calibration statistics are quite accurate for the two flow stations available in the catchment (paper **III**).

4.2 Stream temperature modeling with diffuse catchment loads

Modeling water temperature is similar to modeling a solute concentration because heat and mass are analogous (4.4).

$$C = \frac{m}{V} \iff T = \frac{H}{\rho C_p V} \quad (4.4)$$

where, c = concentration (g/m^3), m = mass (g), V = volume (m^3), T = temperature (°C), H = heat (J), ρC_p = heat capacity ($J/m^3 \cdot K$) (ρ = density of water (kg/m^3); C_p = specific heat water ($J/\ kg \cdot K$)). Thus, MIKE 11 can transport heat by adapting the one-dimensional advection-dispersion for solute transport to the heat transport equation (4.5).

$$\frac{\partial T}{\partial t} = \frac{1}{A}\frac{\partial (QT)}{\partial x} + \frac{\partial}{\partial x}\left(D\frac{\partial T}{\partial x}\right) + \frac{H_{ATM}+H_{SED}}{d\rho C_p} \quad (4.5)$$

where T = average water temperature in a channel cross-section (°C); A = cross-sectional area (m^2); D = longitudinal dispersion coefficient (m^2/s); H_{ATM} = the net rate of heat exchange between water and atmosphere and H_{SED} = the net rate of heat exchange water and sediment bed ($J/s \cdot m^2$); d = water depth (m); t = time (s); x = longitudinal distance of the channel (m). The last term of equation (4.5) is the heat source and sink term, which is calculated by an process solver called ECO Lab. The atmospheric heat balance includes: solar, atmospheric, evaporation, convection, and backwater radiation (Figure 4.4). In addition, heat exchange from groundwater and runoff sources is added. Paper **I** provides a detailed description of the equations used to calculate the heat exchange and explains how MIKE 11 and ECO Lab dynamically interact.

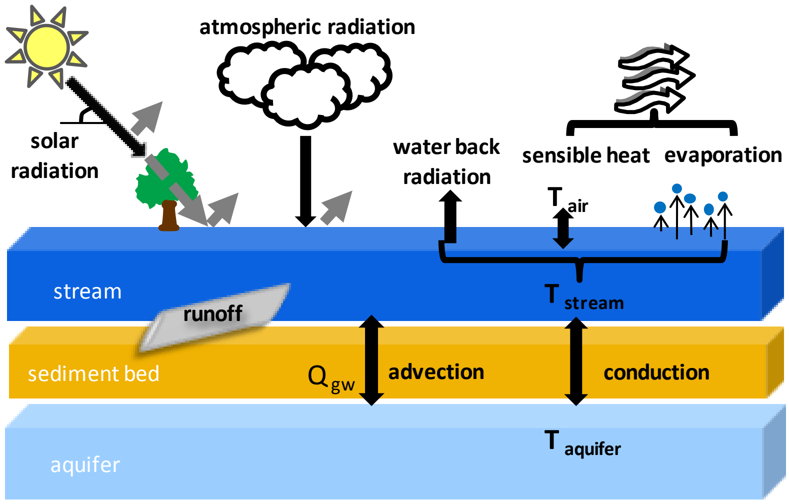

Figure 4.4 Heat balance processes and the source/sink terms in the heat transport equation.

The temperature model was calculated at all the computational nodes of the streams in the Silver Creek Basin and was simultaneously run with the flow model. The average distance between the nodes is ~180 m. Thus, the flow inputs from MIKE SHE and MIKE 11, which are forcings in the temperature model, are updated at every temperature model time step (½ hour) and at every node location. Other forcings in the model are hourly climate data, obtained from a weather station near Silver Creek (paper **I**).

A sensitivity analysis and calibration of the atmospheric heat balance parameters were conducted using a stream-scale model of only Silver Creek. The available flow and temperature data from the tributaries was used as boundary conditions. The groundwater and drainage components were later added to the model and coupled to the catchment scale hydrologic model. The methodology used to simulate the heat exchange with the groundwater fluxes (paper **I**) assumes that the stream bed is in thermal equilibrium (or steady-state condition). Moreover, due to the lack of data, it was assumed that groundwater temperature is spatially uniform. A time series was generated to simulate the groundwater seasonal temperature variation in a year based on shallow groundwater temperature measurements and was used for all the simulation years. Drainage return flows were assumed to be in equilibrium with the atmospheric temperature. The equilibrium water temperature is that at which the sum of all heat fluxes is zero.

4.3 Ecological modeling

When building an ecological model there is a tradeoff between the amount of detail that can be represented and the level of simplicity needed that allows it to be easily integrated to other models and its output easily understood (Carpenter et al., 1999). Thus, when choosing the model it is important to understand the purpose of the model and determine whether is sufficient for the objectives. In order for the model to have a predictive capability it should represent the fundamental mechanisms of the simulated species behavior and how these respond to changes in stressors.

We evaluated two types of approaches that we believe meet these requirements: the fish bioenergetics model, which simulates the metabolic processes of individual fish as a function of its size and temperature, and a general equilibrium ecosystem model, which simulates the equilibrium conditions of a foodweb based on individuals maximizing energy.

4.3.1 Fish bioenergetics

The fish bioenergetics model describes the energy balance for different species of fish and can relate temperature results to fish growth (Kitchell et al., 1977). The energy budget for an organism is given by equation (4.6). This equation is solved for growth by calculating the other terms as a function of numerous variables. All of the energy components are temperature and size dependent.

$$\text{Consumption} = \text{Respiration} + \text{Waste} + \text{Growth} \quad (4.6)$$

The relationships between temperature and these components are represented by empirical response curves (Figure 4.5) developed from data mostly from laboratory studies in which the components are measured under different weights, temperature, and food portions (Elliot, 1976). More recent studies are improving the empirical response curves using field data (Hayes et al., 2000).

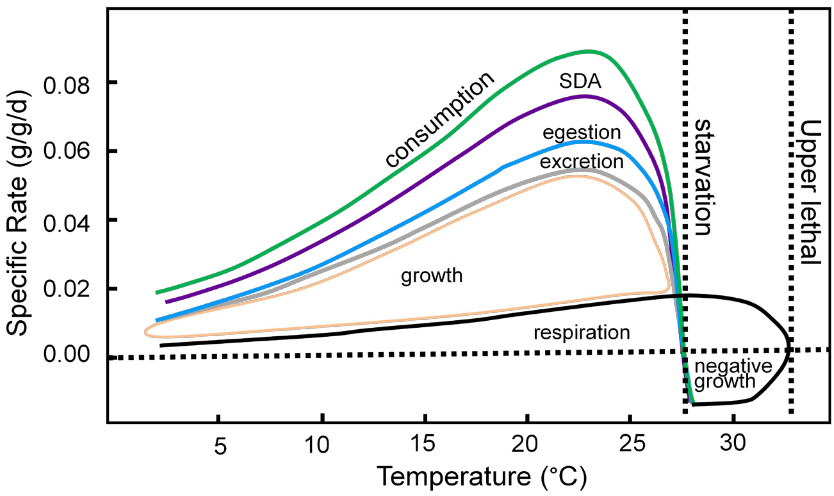

Figure 4.5 Example of a relationship between stream temperature and fish energy budget components (adapted from Hanson et al., 1997). The specific rate of an energy component is in grams of prey per grams of predator per day. To covert from energy rate to specific rate the energy densities of the predator and prey in Joules/gram are used.

Some of the advantages of this model are:

- There is extensive data available for many salmonid species.
- It is easy to use by itself or code into other programs.
- It is flexible enough to add more complexity, such as other species, nutrients and contaminants and other environmental variables (Hanson et al., 1997; Megrey et al., 2007) and it can also be incorporated into foodweb models (Park et al., 2008).
- Its output provides a measure of sustainability because fish growth is an indicator of reproductive capability (Meyer et al., 2003).

Furthermore, this model is suitable for comparing, for example, the response of two or more fish species to changes in habitat conditions based on their energy budget requirements, temperature thresholds, and acclimation capabilities.

The main inputs to the bioenergetics model are a number of parameters that fit the curves for each metabolic process for the species of fish simulated and a time series of average daily water temperature. The parameters representative of rainbow trout from previous studies were used (paper **II**). Rainbow trout is a highly valued species and studies have found that its numbers have declined in Silver Creek in the last decades (IDFG, 2007). The daily average was calculated from the hourly output of the temperature model for a 3-year simulation period and was input into the fish bioenergetics model. The model was run for all the temperature computational nodes in all the streams of the Silver Creek Basin. In order to compare the output of different model scenarios, an ecological indicator was defined by dividing the area under the growth curve for each scenario by the area under the growth curve under the simulated natural conditions. Thus, one of the main outputs of the ecohydrological model is a map of the Silver Creek Basin streams with values representative of their ecological status.

4.3.2 General equilibrium ecosystem model (GEEM)

The general equilibrium ecosystem model (GEEM) was applied to a typical Danish stream ecosystem to simulate the effect of a toxic response in a foodweb. This is the topic of paper **III**, which contains the model equations and details of the approach used.

Our application of the GEEM is based on the model formulated by Tschirhart (2000). The GEEM is a model of the net energy of an organism that is embedded into a foodweb. The net energy equation has four terms: 1. energy intake from prey, 2. energy supply to predators, 3. variable respiration, and 4. resting metabolism. The terms 1, 2, and 3 are dependent on the food consumption and term 4 is independent of food consumption. The energy intake term is the food intake minus the energy price paid for capturing prey. The model is solved by applying two main assumptions:

- Organisms maximize their net energy. This condition is simulated by setting the partial derivative of the net energy equation with respect to the biomass transfer from each prey species equal to zero. For each species in the foodweb, the number of derivatives is equal to the number of its potential prey species.
- The system is in equilibrium when biomass supply is equal to demand in all biomass markets. A biomass market is a predator-prey interaction in the foodweb. The equilibrium condition is defined by setting the population of the predator times the prey biomass transfer the equal to the population of the prey times the prey consumption. For each species in the foodweb, the number of equilibrium conditions is equal to the number of its potential prey species.

The system of equations from the two assumptions is solved simultaneously for the energy prices and the biomass transfers. The net energy equation is solved for all the species in the foodweb for an individual representative of each species. If the individual is preyed upon, this is interpreted as an average loss to the species. Thus, the model combines individual "micro" behavior with the "macro" community structure (Tschirhart, 2000).

Some of advantages of the GEEM approach are:

- It is a foodweb model; thus, it can incorporate the effects of both food availability (energy flows) and impacts of environmental stressors.
- The fundamental theory is mechanistic and can be verified.
- It incorporates adaptive behavior by having the capacity to switch prey based on the relative energy costs of obtaining biomass.

- The output is simple. Changing the parameters of the system through model scenarios provides a functional way of comparing a system in two or more equilibrium states.

In reality, an aquatic foodweb consists of many species and it is difficult to model efficiently. However, many species have similar behavior in terms of where they live and what they eat and can be grouped into functional feeding groups (Allan and Castillo, 2007). Thus, it is a typical practice in foodweb modeling to group species into major taxonomic groups or compartments. Following the guidance of ecologists from the National Environmental Research Institute of Denmark (NERI) a foodweb representative of Danish streams ecosystems was selected which includes 13 taxonomic groups of macroinvertebrates and two fish compartments.

The response of the foodweb to the toxicity of a pesticide was simulated by changing the selected GEEM parameters based on an estimated toxic response. First, a test was performed using a simpler 2-species model to evaluate the response of the foodweb when changing some of the parameters. The results of the test indicated which parameters were the most appropriate for the application of the toxic response. The toxic response was calculated based on the simulated pesticide concentrations the Hove catchment streams. The input mass load of the pesticide was conceptually routed from the agricultural fields to the streams using a simple input-to-loss ratio model and calculating the amount of runoff that each stream location receives from the coupled MIKE SHE – MIKE 11 model. The toxic response is measured in toxicity units (4.7)

$$\log \mathrm{TU}_{D.magna} = \log\left(\frac{C_i}{\mathrm{LC50}_{D.magna\ i}}\right) \quad (4.7)$$

where C_i is the concentration of chemical i, and $\mathrm{LC50}_{D.magna}$ i is the concentration of chemical i that causes 50% mortality of D. magna after 48 hours of exposure. For each foodweb compartment the relative toxic sensitivities were calculated based on LC50 values in found in the literature. Detailed explanations of all these procedures are provided in paper **III**.

5 Results

This chapter highlights some of the most important results of the research. The first section presents results from the Wood River Valley flow model (papers **I** and **II**). The second sections presents some of the temperature model results (papers **I** and **II**). The third section shows results from the fish bioenergetics model and the forth section from the GEEM model (paper **III**).

5.1 Wood River Valley flow model

The Wood River Valley flow model was calibrated for a period of seven years (2003-2009). As previously mentioned, the calibration efforts were mostly focused on the Silver Creek flows, particularly on the low summer baseflows. The exchange flows between Silver Creek and the aquifer are relatively small. Most of its flow comes from the springs that are located in the northern areas of the basin and feed the Silver Creek tributaries. Thus, the parameters that control seepage losses from the Big Wood River Basin, the groundwater flow, and the surface water – groundwater exchange with the Silver Creek tributaries were the main changes made during the calibration. The runoff peaks that occur mostly during the spring months from the mountain tributaries were under-estimated by the model. These flows were simulated using a rainfall-runoff model (NAM) that is linked to the MIKE 11 streams; however, there was very limited data available to properly calibrate the model. As discussed in paper **I**, the temperature calibration is very sensitive to the flow calibration and the periods of the lowest temperature errors coincided with periods of low flow errors. Since the main focus of the study are the critical summer periods, the performance of the model was considered acceptable.

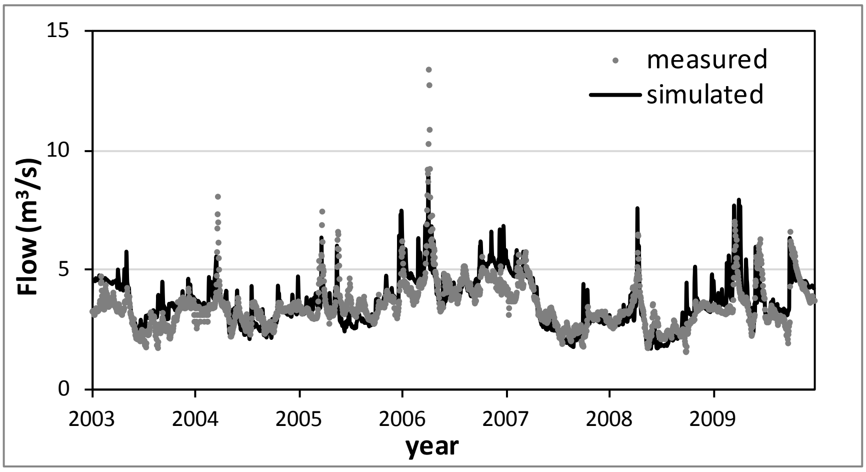

Figure 5.1 Simulated vs. measured flow at Silver Creek

The general water budget of the valley served to guide the model development and calibration. Data to perform a quantitative comparison of the water budget components were not available, but a qualitative comparison was performed of some of the model components for which limited data was available from previous studies (e.g., evapotranspiration, irrigation, seepage, subsurface flows) and adjustments made where necessary. The water budget calculation is useful for understanding the distribution of flows in the valley, which is important in understanding the results of the model scenarios. The largest inflow to the model is through the Big Wood River (BWR) at the northern boundary, which are measured flows at Hailey (Figure 3.2). This flow gage receives most of the runoff from the mountainous tributaries in the Big Wood River Basin. Approximately 25% of this flow is diverted from the BWR to an extensive network of irrigation canals. The BWR and the diversion canals lose a significant portion of the flow to the aquifer. Approximately a third of the total inflow volume flows from the BWR Basin to the Silver Creek Basin through groundwater flow discharges at the headwaters of the Silver Creek tributaries; another third is lost to evapotranspiration (mostly from crops); and the rest flows out of the valley through the Big Wood River.

Table 5.1 Simulated water budget of the Wood River Valley.

Water budget component	annual average (10^6 m^3/yr)
Inflows	
Precipitation	68
Runoff from mountain catchments	422
Subsurface inflow	32
Total inflows	521
Internal surface water-groundwater flows	
Surface water diversions	82
Groundwater abstractions	57
Total irrigation	128
Net seepage loss from the BWR and canals	185
Groundwater recharge from soils	45
Groundwater flow across the BWR-SCB divide	159
Total spring discharge	129
Outflows	
Evapotranspiration	151
Big Wood River surface water outflow	231
Silver Creek surface water outflow	101
Subsurface outflow (southeast)	48
Total outflows	531

As previously mentioned a set of scenarios were run. The details on the setup of these scenarios are found in paper **II**. For the two land use change scenarios, the most water demanding crop, alfalfa, was converted to barley in one scenario and to grass in another scenario. For the water use scenarios, the total amount of water diverted out of streams and canals and pumped from the ground was reduced by 10%, 20%, 30%, while the crop demand remained the same.

For these five scenarios the differences between the simulated present conditions water table and each scenario (scenario x – present conditions) were calculated. The increasing effect of the water use reduction in the water table can be seen in Figure 5.1. From the average and maximum water table differences, the change in the water table increased with increasing 10% water reductions. The land use scenarios reduce the use of water by a lower crop demand, thus, less evapotranspiration losses. The changes in water table in the first land use scenario (alfalfa to barley) fall somewhere in between the 10% and 20% water savings scenarios in terms of magnitude and the changes in the second land use scenario (alfalfa to grass) are similar in magnitude to the 30% savings.

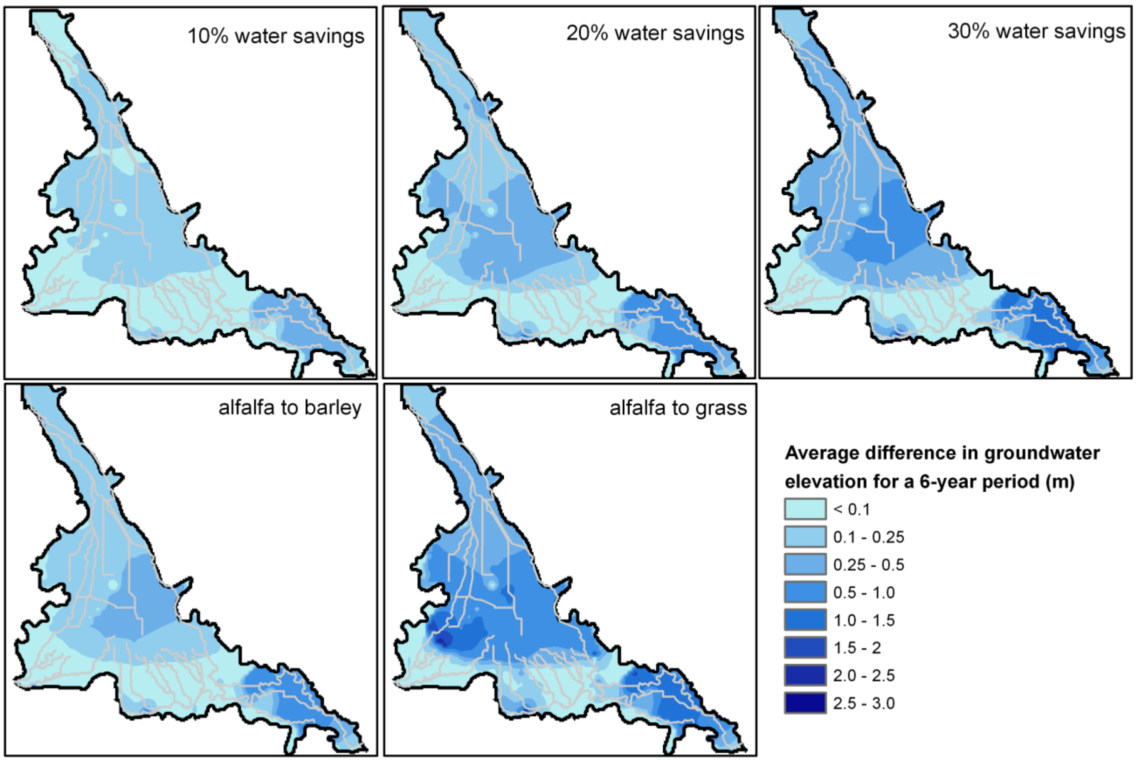

Figure 5.2 Water table differences for water use and land use scenarios (scenario - present conditions).

Flow duration curves were calculated to evaluate the impact of the water table reductions on the Silver Creek flow. The red dash line in the plots represents an assumed ecological minimum flow line, which is equal to the water right flows granted to the Idaho Department of Fish and Game for Silver Creek (Idaho Water Resources Board, 2010). From the water savings scenarios flow curves it is estimated that it takes ~86 Mm^3/yr of water savings in the Wood River Valley to increase the average flow in Silver Creek by 1 m^3/s. Changing alfalfa crops to barley produced an average increase of 0.3 m^3/s in Silver Creek flows, similar to the 20% water savings results. And changing alfalfa to grass produced an average increase of 0.7 m^3/s, the largest increase out of all the scenarios.

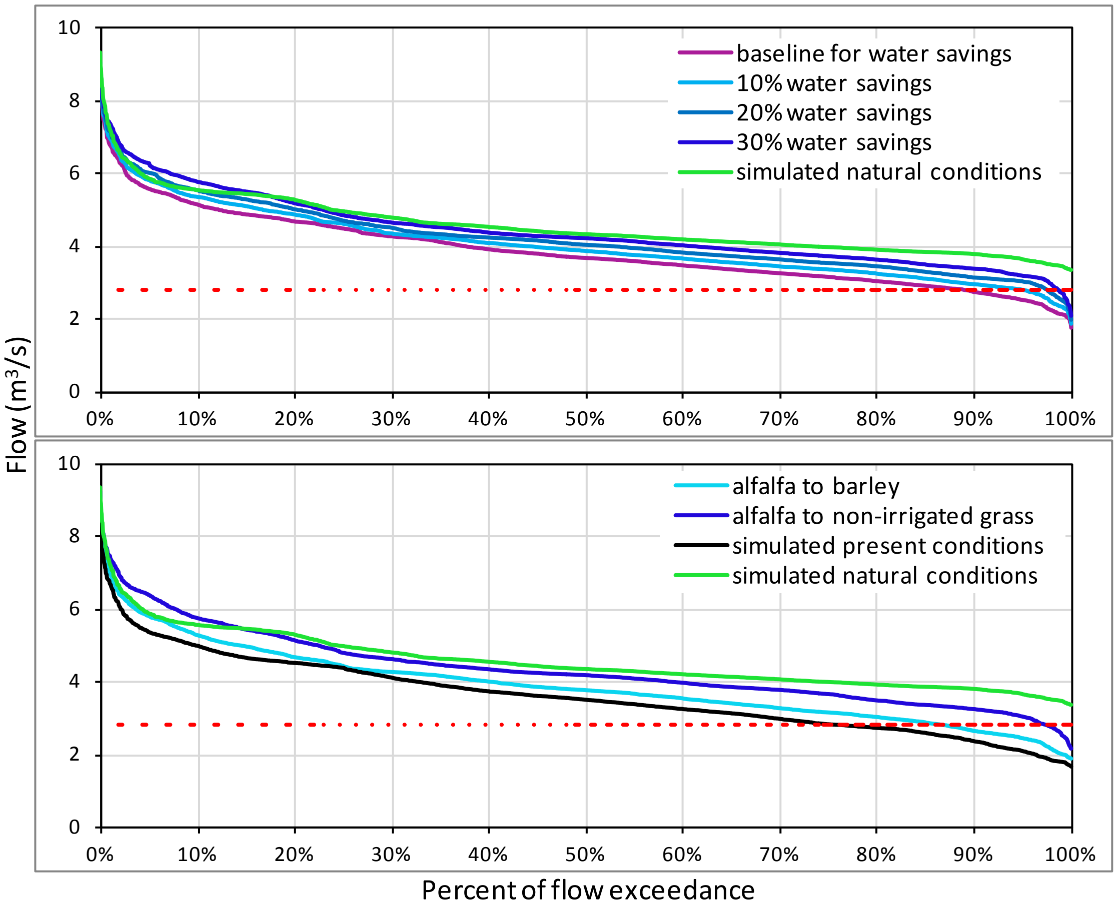

Figure 5.3 Flow duration curves for simulated present conditions, simulated natural conditions, water use and land use scenarios and estimated minimum ecological flows (red dash line).

5.2 Stream temperature modeling

A map of simulated stream temperatures for all the streams in the Silver Creek Basin at the hour of the warmest water temperatures in Silver Creek (June 29th, 2008 16:00) is shown below (Figure 5.3). The headwaters of Stalker Creek, the stream that turns into Silver Creek after Grove Creek, shows extremely high and lethal temperatures (>25°C) due to the warm flows from Buhler Drain and Patton Creek. The stream cools as it receives the flow from Mud Creek. Grove Creek, which has larger spring flows, reduces the temperatures from Stalker Creek at the headwaters of Silver Creek. Loving Creek gets warmer as it flows toward Silver Creek, possibly because of the irrigation diversions by the Gillihan Ditch and higher exposure to solar radiation. The downstream areas of Silver Creek also get warmer due to irrigation diversions and large segments of open water areas.

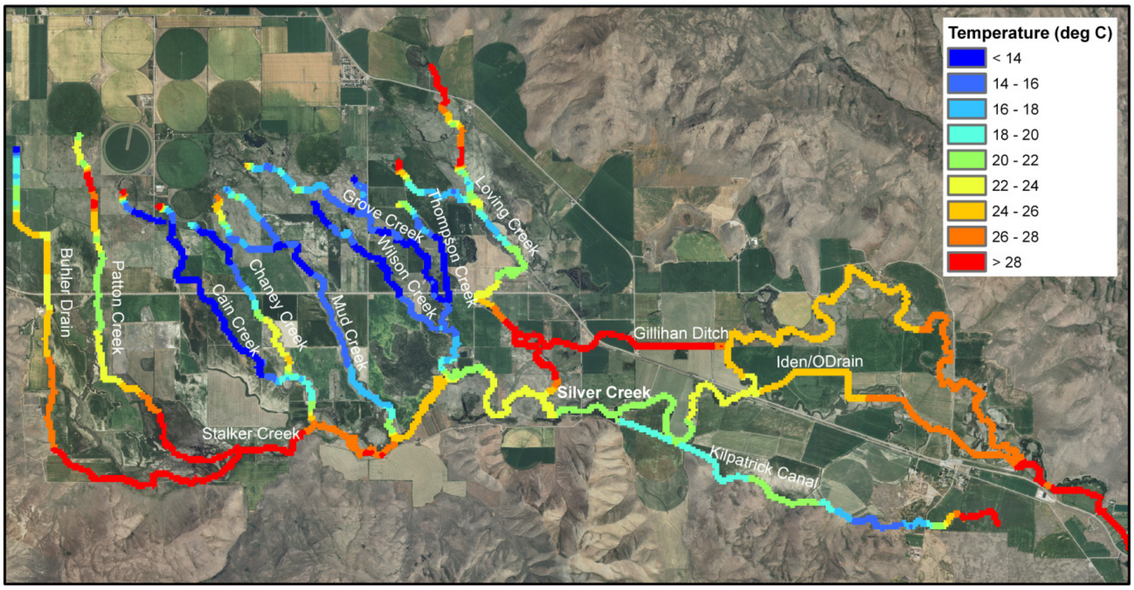

Figure 5.5 Simulated stream temperatures at the hour of warmest water temperatures in the downstream portions of Silver Creek (June 29th, 2008 16:00).

The spatial distribution of temperatures in the Silver Creek Basin can be better understood by examining the various heat balance components for the Silver Creek tributaries. The fraction of the incoming heat components of the total heat input for each of the tributaries was calculated for each day for the year 2008 (Figure 5.4). The incoming heat components are: solar, atmospheric, groundwater, and drainage runoff. For the calculation of total atmospheric heat input, the sensible heat was added to the atmospheric heat at the times when it is a heat gain to the stream (i.e., when the temperature of the air is higher than the water temperature). When the opposite is true then the sensible heat is added to the total heat loss. Figure 5.4 also shows the percentage of the total flow that each tributary contributes to the total flow in Silver Creek and the daily average temperature in the stream. The results reveal that besides the volume of flow, the source of heat and flow determines the stream temperature signal. Buhler Drain and Patton Creek have high summer temperatures (>20°C) because of low flow volume, with a high percentage of it from drainage runoff, and high solar radiation. Thompson Creek also has low flow volume (2% contribution), but the flow is almost exclusively spring-fed, thus the temperatures are much lower and have low seasonal variation. Moreover, all the streams for which groundwater heat is a larger fraction of the heat input, have much lower and stable temperatures (Cain, Grove, Thompson, and Wilson creeks). Chaney Creek and

Mud Creek, have similar heat source fractions, but Chaney Creek has a lower flow volume; thus, it has higher temperatures due to lower thermal capacity (paper **I**). Finally, Love Creek has the second largest flow but most of it is fed by drainage runoff; thus, it has high temperatures and a large seasonal variation. This model output reveals the strong influence of the flow volume and source in stream temperature, and therefore the value of the temperature model and temperature data in the flow model calibration.

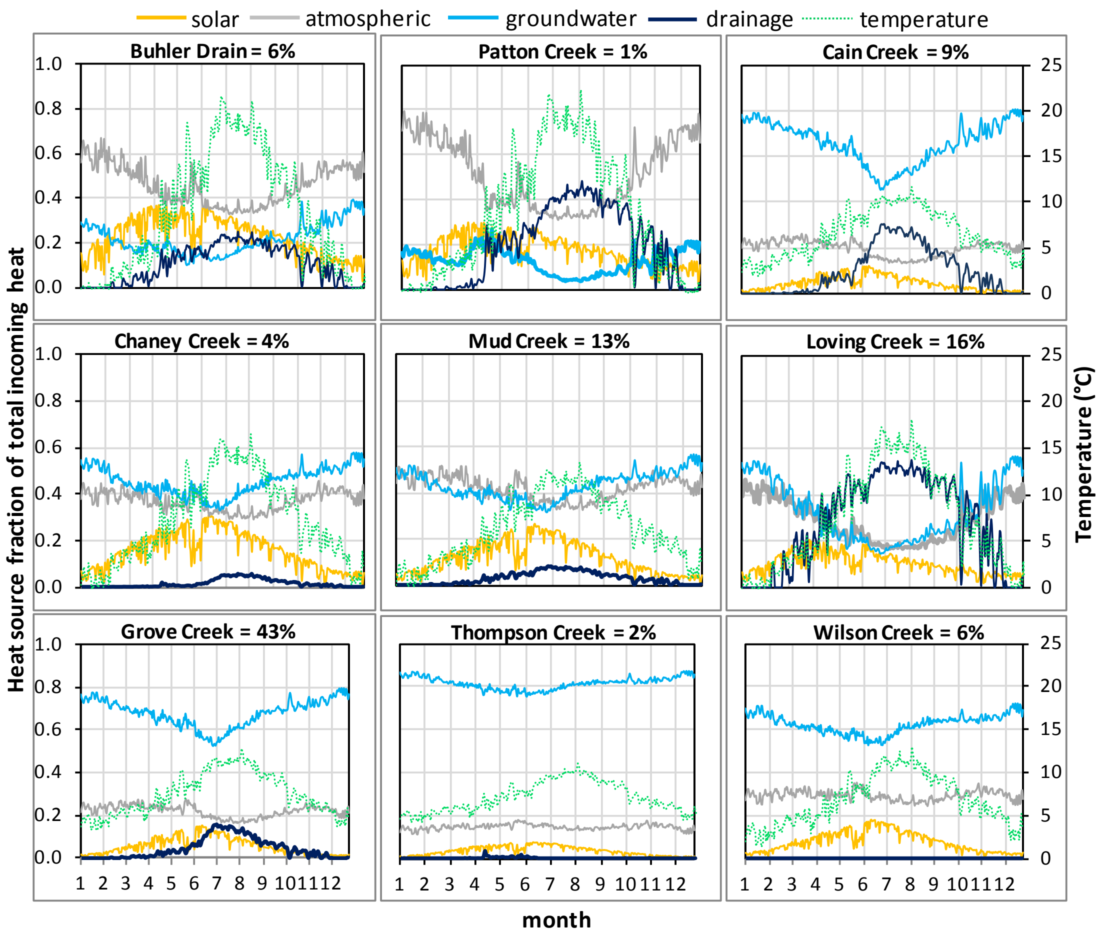

Figure 5.6 Simulated fraction of heat sources and temperature in 2008.

Stream maps of the differences in maximum stream temperatures for all the model scenarios are included in paper **II**. In general, the streams located near large agricultural areas show the largest reductions in temperatures in most scenarios (Buhler Drain, Loving Creek, and the downstream portions of Silver Creek). And the streams with the least change are those that are in relatively good present conditions, i.e., have a large portions of shaded areas and are mostly groundwater-fed (e.g., the Grove Creek system). All scenarios lowered the temperatures in Silver Creek. Temperature statistics for all the scenarios are shown in Table 5.2 and are explained in paper **II**. The natural conditions scenario had a much higher impact in lowering the temperatures than the scenarios because it combines all the effects simulated by the individual scenarios, except for the past climate. This outcome supports the idea that a combination of restoration strategies might be optimal. Nevertheless, the results of the fish model illustrate that point statistics are not enough to determine the optimal conditions for fish growth.

Table 5.2 Temperature statistics at Silver Creek.

Scenario	Max hr (°C)	Max daily (°C)	Avg. summer (°C)	% TC[a]	% TL[b]
Natural conditions	21.9	16.9	13.3	4.4	0
Present conditions	28.8	19.6	15.7	11.2	1.60
Baseline for water savings	27.3	19.0	15.3	10.6	0.82
10% savings	25.9	18.5	15.0	10.2	0.38
20% savings	25.6	18.4	14.9	10.2	0.31
30% savings	25.3	18.4	14.9	10.1	0.26
Alfalfa to barley	28.5	19.4	15.4	10.9	1.21
Alfalfa to grass	26.0	18.7	15.1	10.3	0.47
Restored morphology	27.1	19.2	15.3	10.7	1.18
Restored vegetation	27.4	19.1	14.7	7.2	0.64
Past climate	27.9	19.4	15.1	10.5	0.79

[a]Percent exceedance of critical temperature (13°C)
[b]Percent exceedance of lethal temperatures (22°C)

5.3 Fish bioenergetics

Stream maps of the differences in the ecological indicator for all the model scenarios are included in paper **II**. Table 5.3 provides a summary of the change in the maximum daily and average summer temperatures and the change in ecological indicator from present conditions for each scenario. A positive increase in the ecological indicator means that there is more fish growth under the scenario than under present conditions. The scenarios with the largest change in ecological indicator were the conversion of alfalfa to grass and the restored morphology. The restored vegetation scenario had a negative change because of the lower winter temperatures. The large improvement under the restored morphology scenario is likely caused by increases in thermal stability.

Table 5.3 Summary of main results at Silver Creek.

	10% savings	20% savings	30% savings	Alfalfa to barley	Alfalfa to grass	Restored morphology	Restored vegetation	Past Climate
dTmax d [a] (°C)	-0.5	-0.6	-0.6	-0.2	-0.9	-0.4	-0.5	-0.2
dTavg summer d [b] (°C)	-0.3	-0.4	-0.4	-0.3	-0.6	-0.4	-1.0	-0.6
dEind [c] (%)	3.8	4.4	4.9	2.8	8.4	8.9	-7.7	5.6

[a]Change in the maximum daily average temperature average along the length of Silver Creek
[b]Change in the average summer daily temperature average along the length of Silver Creek
[c]Change in the ecological indicator

Figure 5.7 shows the fish growth curves in response to the corresponding temperature signal for the simulated present conditions and natural conditions. For each model four different locations that had similar growth at the end of the 3-year simulation were selected. In the case of the lowest growth (black line), the temperature is always under 5°C in the natural conditions model and always above 20 in the present conditions model. This shows the upper and lower temperature limits for rainbow trout. The second case (gray line) shows high seasonal variability in both the natural and present conditions, but lower maximum temperatures under natural conditions (~5°C less). These results indicate that low maximum daily temperatures are not sufficient for optimal growth. The highest growth occurs for the most stable temperature signal in case 4 (light blue).

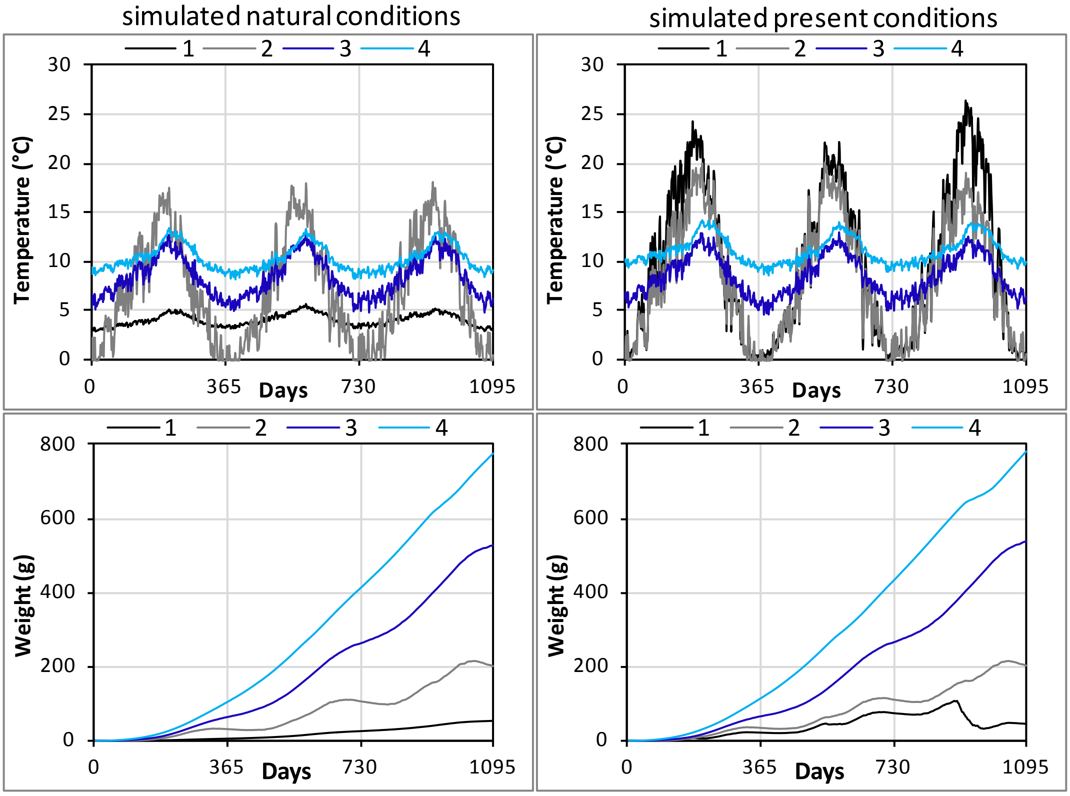

Figure 5.7 Temperature and fish growth under natural conditions and present conditions.

5.4 GEEM

A number of simulations were performed that test the sensitivity of the GEEM parameters, the effect of higher vs. lower pesticide concentrations, and the effects of changes in food (or energy) availability (paper **III**). The GEEM parameters to which the toxic response was applied were the basal (or resting) metabolism and a parameter that controls the biomass supply rate to predators. Both parameters were increased with toxicity, which physically implies that the amount of respiration losses per unit consumed increases and the ability to avoid predation decreases. The results show that the simulated populations in the foodweb are highly sensitive to the changes in these parameters.

Increasing both parameters for all the organisms in the foodweb, by using their relative toxic sensitivities, causes the populations of the lower trophic levels to decrease and the higher trophic levels to increase because the effect of increasing the biomass supply parameter, is stronger than the toxic effect on the respiration parameter. In other words, by increasing the food available to the predators in the foodweb, which is the outcome of increasing the supply parameter of the prey compartments, had a net positive effect in the predators despite their higher respiration losses. However, this outcome is based on the assumption that both parameters react in exactly the same way to the pesticides, i.e., both the parameters were multiplied by the same fractional toxic response. If only the respiration parameter is changed, then all populations decrease with toxicity. When the food availability (or energy source) increases/decreases for the lower trophic levels, it also had a stronger effect than the effect of respiration losses in demining the direction of the population change (paper **III**).

Figure 5.8 shows two maps of the Hove catchment streams, one with values for the toxic units calculated from the maximum pesticide concentrations simulated and the other with values for the calculated SPEAR change. SPEAR (SPEcies At Risk) are species that have traits that make them more susceptible to pesticide harm (Liess and von der Ohe, 2005; Liess et al., 2008). The relationship between the SPEAR abundance and pesticide concentrations has been estimated from the results of a study in Danish streams (Rasmussen et al., 2012; paper **III**). These taxonomic groups have the highest relative sensitivity to the chemical. The indicator was calculated from the total population change of these groups (#SPEAR individuals toxic conditions/#SPEAR individuals reference conditions). The results show that the spatial distribution of SPEAR change correspond to the spatial distribution of the $\log TU_{D.magna}$. The change in SPEAR is greater in the locations where the simulated pesticide concentrations are high, which are the areas that receive a greater amount of agricultural runoff in the catchment.

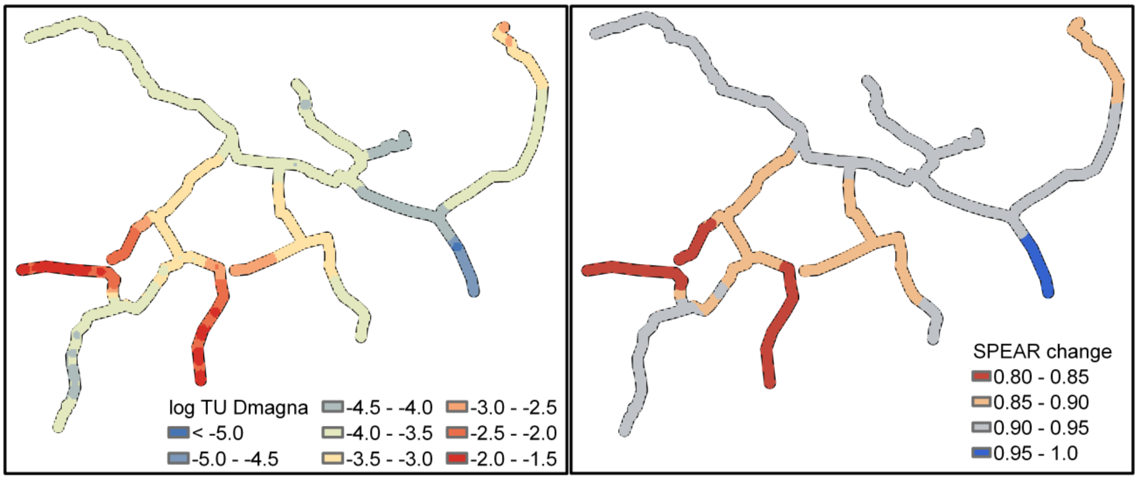

Figure 5.8 Simulated toxicity and SPEAR change (#SPEAR individuals toxic conditions/#SPEAR individuals reference conditions) in Hove catchment streams.

6 Conclusions

The development and calibration of an integrated flow and stream temperature model has demonstrated the significant role of groundwater in stream temperature dynamics in a spring-fed environment. During the calibration process it was found that a 10% reduction of groundwater flow to the Silver Creek Basin can cause average temperature increases of approximately 0.5°C in Silver Creek. This finding was based on the relationship between average flow errors versus average temperature errors (paper **I**). In addition to the reduction in temperatures, the seasonal variations were much lower in the streams that receive most of their flow from groundwater than in streams that receive a larger percentage of flow from excess agricultural runoff, which was assumed to be in equilibrium with atmospheric temperatures. Therefore, simulating the spatial distribution of flow and temperatures in the basin helps to identify the areas where restoration efforts can be prioritized according to relative contribution of flow and heat from the tributaries. Moreover, these findings also illustrate that temperature data serves to provide constraints on the flow sources and volumes and thus decrease model uncertainty.

The application of the model to an area of intensive agricultural practice, low precipitation, and a highly valued ecosystem has demonstrated why it is important to manage this ecosystem by considering the upstream influences. All of the catchment scale land use and water use management scenarios simulated cause large changes on the stream temperatures and the calculated ecological indicator. Stream scale scenarios also produced large changes. Linking the results of the temperature model to the fish biogenetics model demonstrates how the changes in temperatures from the different scenarios benefit the fish growth. This gives us a more complete picture of the habitat requirements than temperature statistics and can help guide regulations. Past restoration practices implemented in Silver Creek have consisted of local scale solutions, such as canal dredging for accumulated sediments and stream vegetation management. However, while these may provide temporary solutions, they will not solve the problem in the long-term. Catchment scale restoration practices may include mitigation of excess agricultural drainage, increased efficiency of irrigation technology, changing the types of crops, restoration of the stream network altered morphology (e.g., channelization, artificial ponding, and dam removal).

In addition to the higher water use demand that comes with increasing population and food demand, long-term precipitation and air temperature records show evidence of climate change in Idaho in the recent decades, with decreased precipitation and increased temperatures particularly in the critical summer months. A past climate scenario resulted in reductions in the stream temperatures and the improvements in the ecological indicator, even though the impact of the simulated climate change on the water budget was underestimated (as discussed in paper **II**). Therefore, with the added pressure of climate change it will become even more critical to evaluate the potential benefits from combining restoration practices at the catchment scale.

The European Water Framework Directive (WFD) has established a priority for European countries to develop predictive tools that link measures of ecological quality to physical and chemical conditions in a basin. As pesticides are major contaminants of surface waters it is important have the capability to predict their transport and effect in a catchment. A spatially distributed integrated hydrological model is able to quantify the runoff from agricultural fields, which is one of the main pathways of pesticide transport. Moreover, the simulation of the spatial distribution of pesticide concentration in streams is important in catchment management not only because it can help focus mitigation efforts but also because the ecological impacts in certain areas may propagate into downstream areas. The WFD also requires that major anthropogenic stressors significantly impairing the ecological quality of targeted surface water bodies are identified, quantified and their specific effects on the biota are determined. Due to the cost and difficulty associated with continuously monitoring entire stream networks, tools that can predict the impact of physicochemical stressors in a catchment on aquatic ecosystems are highly valuable. The novelty of coupling a general equilibrium ecosystem model to a hydrological and pesticide transport model of an agricultural catchment was investigated for this purpose.

The application of the GEEM to a stream foodweb can provide insight into the ecosystem structure by simulating the energy flows in a foodweb and the way in which these are altered in the event of stress. The model results were consistent with observations in that the trophic compartments with the highest sensitivity to pesticides were those more negatively impacted by toxicity. The model results also help to illustrate that energy availability and flow can help explain why some species are more sensitive than others. However, in order to improve the parameterization it is necessary to have a better understanding of the physical mechanisms that impact organisms under toxic stress.

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9 Papers

I. Loinaz, M.C. Davidsen, H.C., Butts, M., Bauer-Gottwein, P., Integrated Flow and Temperature Modeling at the Catchment Scale. *Journal of Hydrology*, under revision.

II. Loinaz, M.C., Gross, D., Unnasch, R., Butts, M., Bauer-Gottwein, P., Ecohydrological impacts of land management and water use in the Silver Creek Basin, Idaho. *Journal of Geophysical Research - Biogeosciences*, submitted.

III. Loinaz, M.C., Hartmann, M.J., Rasmussen, J.J., McKnight, U.S., Butts, M., Bauer-Gottwein, P., Coupling a general ecosystem equilibrium model to a catchment-scale hydrologic model to evaluate ecological status in streams, *Ecological Modelling* , submitted.

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