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THE MESOHABITAT EVALUATION MODEL APPLIED AT AN AUSTRIAN AND IBERIC RIVER

by

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supervised by

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I owe my deepest gratitude to my parents, who have presented me the opportunity of an education throughout my life.

ABBREVIATIONS

MEM Mesohabitat evaluation mode

HMU Hydromorphologic unit

EFM Environmental flow methodology

EFR Environmental flow requirement

EFA Environmental flow assessmen

HEP Habitat evaluation procedure

FDC Flow duration curve

GIS Geographical information syster

HSI/HSC Habitat suitability index/curve

MSI Mesohabitat suitability index

IFIM Instream flow incremental methodology

USFS United States Forest Service

WUA Weighted usable area

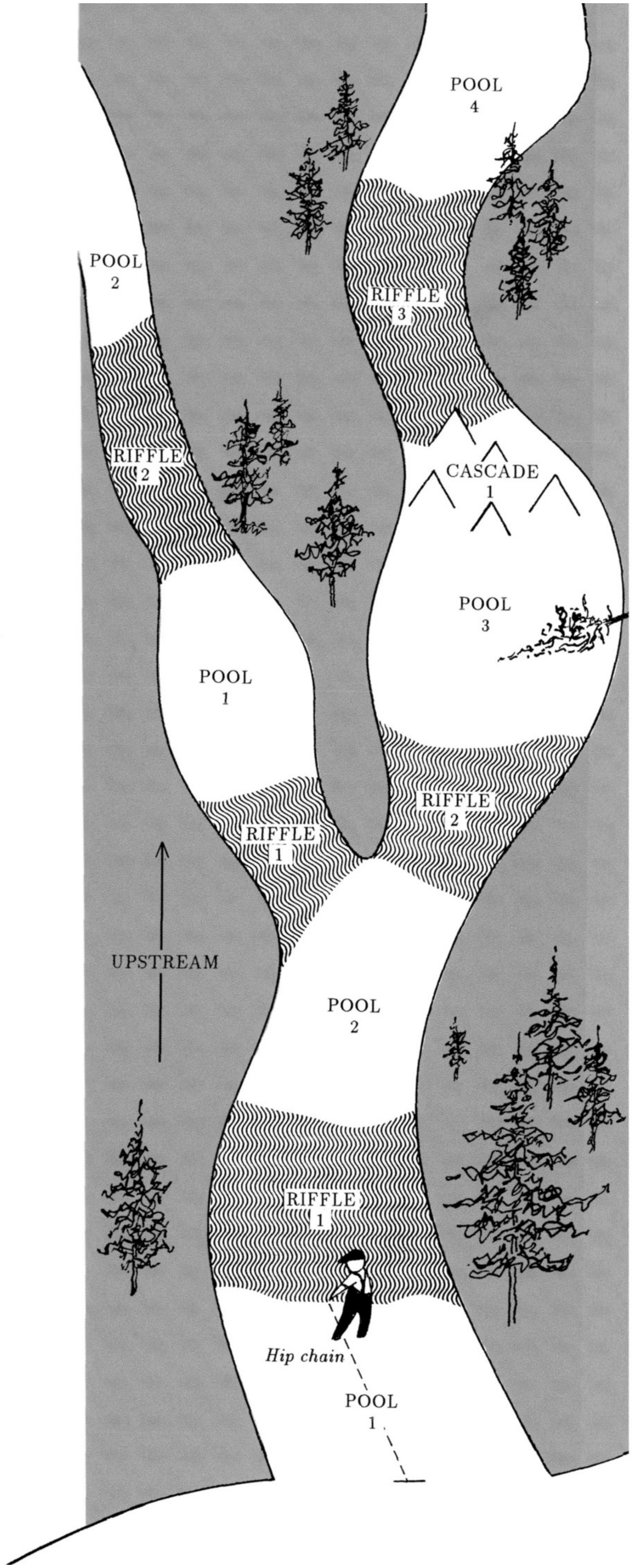
UMA Usable mesohabitat area

WSP Water surface profile

WFD Water framework directive

WB Water body

CMS Cubic meters per second



ABSTRACT

Habitat simulations play an important role in environmental flow assessments (EFA). Originating from pure hydrological methods or hydraulic rating methods, habitat simulations assess environmental flows based on modeling quantity and suitability of physical habitat available to target species under different flow regimes. EFA should be a key element in integrated water resources management tasks, like facing residual flow problems.

Nowadays, the estimation of fish abundance by using mesohabitat availability often presumes an in situ visual mesohabitat classification. The execution of the fieldwork depends on the discharge and, thus, on time. Moreover, the results obtained are subjective and costly. These are all disadvantages, since additional simulations for different flow regimes cannot be realized without additional fieldwork, in contrast to classical microhabitat modelling.

This master thesis investigates the possibility to model mesohabitat availability by using only common abiotic input variables, such as depth, flow velocity and bed shear stress, to omit extra fieldwork. For this purpose, the use of an Austrian mesohabitat model (MEM) in a Spanish and an Austrian river reach is evaluated. At first, selected mesohabitat types used by the US Forest Service (USFS) are described. Subsequently, a mapping of these USFS types to hydromorphological units (HMU) used in the MEM model is undertaken. One of the central aims of this master thesis was the automatic mesohabitat classification of the MEM software. The results are compared with sampled visual mesohabitat classifications during mean flow and low flow condition. A comparison of various calibration approaches is carried out, before the question whether the MEM classification approach would be able to substitute visual mesohabitat site samplings is answered: at the Cabriel the approach produced pleasing outcomes under mean flow conditions, while it produced unsatisfactory results at the Ybbs due to the river's diverse morphology in the transversal direction.

ZUSAMMENFASSUNG

Habitatsimulationen spielen bei der Bestimmung von ökologischen Restwassermengen eine wichtige Rolle. Der in den letzten 30 Jahren zunehmend rasche Fortschritt, ausgehend von einfachen hydraulischen Methoden zur Abschätzung der ökologisch verträglichen Restwassermenge, führte zur Modellierung verfügbarer Fischhabitate unter verschiedenen Abflussregimen als Indikator für die ökologische Güte eines Gewässers.

Die Abschätzung der verfügbare Mesohabitate setzt derzeit eine visuelle Klassifizierung derselben durch Feldarbeit voraus. Der Zeitpunkt der Durchführung hängt vom herrschenden Abfluss ab. Dies nimmt Flexibilität, da im Gegensatz zur klassischen Mikrohabitatmodellierung eine Abschätzung unter geänderten Abflussbedingungen weitere Feldarbeiten erfordern.

Diese Diplomarbeit untersucht die Möglichkeit, Mesohabitatverfügbarkeit unter Verwendung von rein abiotischen Eingangsparametern wie Wassertiefe, Fließgeschwindigkeit und Sohlschubspannung zu modellieren, um auf zusätzliche Feldarbeit verzichten zu können. Zu diesem Zweck wird die Verwendung eines österreichischen Mesohabitat-Modell (Mesohabitat Evaluation Model) in einem spanischen (Río Cabriel) und einem österreichischen Fluss (Ybbs) evaluiert. Begonnen wird mit einer Beschreibung der von der Forstverwaltung der Vereinigten Staaten verwendeten Mesohabitattypen. Danach wird versucht, dieses Klassifizierungssystem auf Mesohabitattypen des MEM-Modells umzulegen. Ein zentrales Ziel dieser Arbeit war die automatisierte Habitatklassifizierung der MEM Software mit der visuellen Klassifizierung durch Feldarbeit währen herrschendem Niederwasser und Mittelwasser zu vergleichen. Verschiedene Kalibrierungsansätze wurden getestet, ob die MEM-Klassifizierung in der Lage ist, Feldarbeit zu ersetzen. Der Ansatz zeigt im Cabriel bei Mittelwasser zufriedenstellende Ergebnisse, während er in der Ybbs bedingt durch die unterschiedliche Morphologie des Flusses in Querrichtung keine Ausreichenden Übereinstimmungen zu den Feldarbeiten liefert.

INTRODUCTION

GENERAL INTRODUCTION TO HYDRAULIC ALTERATION

The recognition of the escalating hydrological alteration of rivers on a global scale and the resultant environmental degradation has led to the ample establishment of the science of environmental flow assessment. EFA studies try to answer the question of how much water does a river need in terms of quantity and quality required for ecosystem conservation and resource protection. There is a consensus among environmental scientists that "on a worldwide scale, existing and projected future increases in water demands have resulted in an intensifying, complex conflict between the development of rivers (as well as other freshwater ecosystems) as water and energy sources, and their conservation as biologically diverse, integrated ecosystems" (THARME, R. E., 2003). Despite the basic need of water for living, intact aquatic ecosystems provide places for recreation, enable tourism and other cultural activities, support our livelihoods, life styles and help to reduce follow-up costs.

Many answers to the question of how much water a river needs are available. It is now widely accepted that a naturally variable regime of flow, rather than just a minimum flow, is a primary determinant of the structure and function of aquatic and riparian ecosystems for streams and rivers. According to POFF, N. L. et al. (2009), environmental flows are defined in the Brisbane Declaration[1] as the "quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems". Nevertheless, we should keep in mind, that an environmental friendly flow is nothing more than a satisfactory tradeoff in water allocation among all users of the resource and the resource base itself (the river).

To understand the whole problematic it is feasible to outline a chain of causal factors leading to the actual problem in its current state – the loss of vital river ecosystem services mainly caused by

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[1] http://www.riverfoundation.org.au/images/stories.pdfs/bnedeclaration.pdf

hydraulic alterations - using the **DPSIR** (**d**riving forces, **p**ressures, **s**tate, **i**mpacts, **r**esponses) model. This master thesis focuses on the loss of physical habitat. Physical habitat is considered in the European Water Framework Directive (WFD) as the interaction of several hydromorphological elements, i.e. water flow, morphology, sediment and connectivity (figure 1), that are "supporting the biological elements".

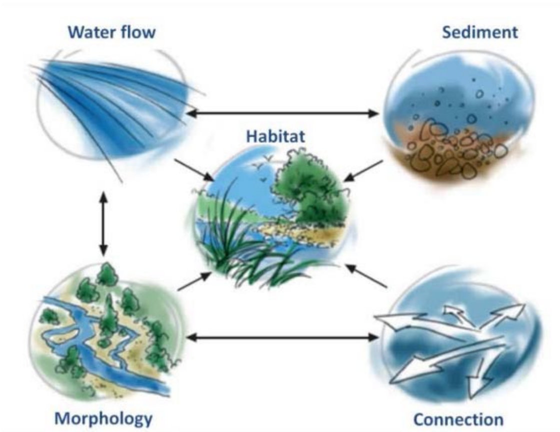

Figure 1: Hydromorphological elements forming physical habitat. (FEHÉR, J. et al., 2012)

Driving Forces:

Driving forces are anthropogenic activities that have an effect on physical habitat. Agriculture, urbanization, hydropower using reservoirs, navigation, flood protection, tourism, urban development can be seen as main driving forces behind hydromorphological alterations. All those are human activities driven mainly by the steady increasing human population and their needs for basic resources like drinking water, sanitation, energy and alimentation. In more developed regions the list can be extended by recreational needs, tourism demands and needs for cultural activities.

Figure 3 states the ongoing intensification of the driving forces. The graph, originating from CEDEX (2000), shows the temporal relation of the driving force human population, the watered surface for agricultural needs and the installed hydraulic power, as well as the relation to pressures, such as dam volume and ground water used in Spain. It has to be noted that, while the driving forces in some way are growing linear with the population, the pressures (groundwater used, dam volume) show a more exponential growth beginning at the mid-1950s.

Another driver, which can also be seen as an impact of the above stated drivers, is climate change. The long-term most natural response of human to climate change is resettlement. Nowadays, resettlement means urbanization requiring huge quantities of water to move or buffer. The rationale to transfer or buffer water is generally economic: "cities are accorded priority to water for domestic uses and industries, where the economic return to 1 cubic meter of water is much higher than elsewhere and political power is concentrated." (MOLDEN, D. et al., 2007) (also see figure 2). From a technical point of view, climate change is to cope with the increased variability in precipitation and temperature. A common strategy to satisfy a steady demand (e.g municipal water use) of a highly variable resource, as water is especially in dry areas, is increasing storage capacity, which in turn is a driving pressure for hydraulic alterations.

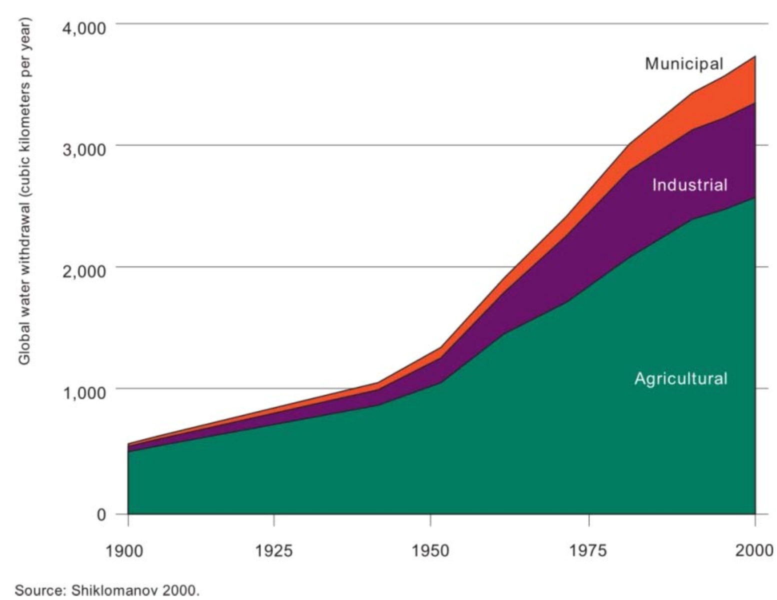

Figure 2: Sectoral split for blue water withdrawals (withdrawals from rivers, reservoirs, lakes and aquifers) for human uses (MOLDEN, D. et al., 2007)

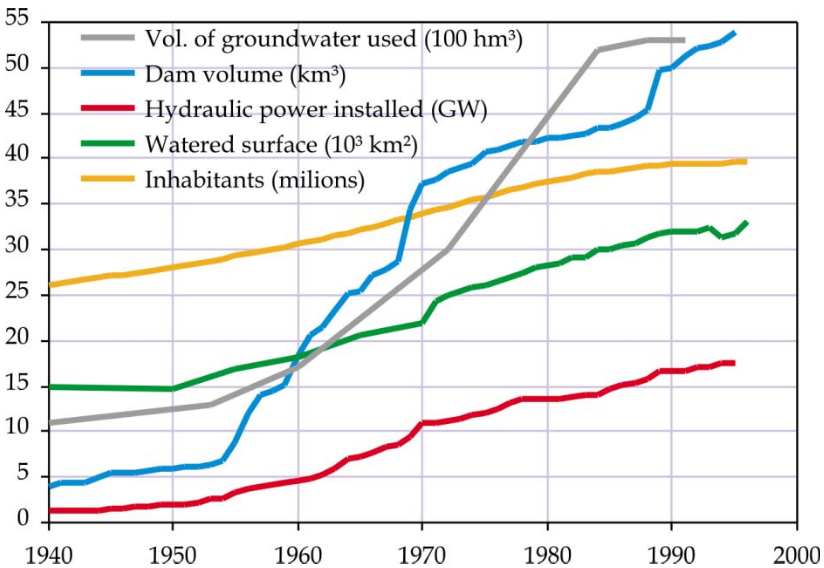

Figure 3: Development of hydraulic resources in Spain (CEDEX, 2000)

Pressures:

Pressures are the consequences of human activities. **Hydromorphological pressures** comprise all physical alterations/modifications of water bodies modifying their shores, riparian/littoral zones, water level and flow.

Before detailed pressures are stated, it is good to take a closer look at a pressure called basin closure or over allocation of the rivers renewable natural resources. The rivers renewable resource is the water, which is flowing downstream each year. Over-allocating this resource makes it more difficult to respond on the supply side because there will be no margin left to use more. Basin closure can be sketched schematically like in figure 4. The second diagram shows how over the years the development of facilities to abstract surface water (note: a pressure group defined in WFD) and groundwater allowed human water use to approach the total annual renewable water resources in the basin (figure 4, third diagram). "The fraction of water that can be stored or pumped under existing economic and technological constraints is generally under the total annual renewable resource when, for example, a large part of floods cannot be controlled and flows to the sea. But it may be higher in some cases when dams can capture all or most of the runoff and aquifers are overexploited" (MOLDEN, D. et al., 2007). To quote an example MOLDEN, D. et al. (2007) state the Lerma-Chapala basin. The basin is situated Mexico's central high plateau. Because of the overabstraction of groundwater and the excessive surface water withdrawals, it is a closed basin, with water depletion exceeding annual renewable water by 9% on average, even without including environmental flows. This example illustrates that a developing over-allocation of natural resources is putting a lot of pressure on the rivers ecosystem by restricting feasible responses or counter actions against hydraulic alterations like environment flows. Implementing environmental flows in an open basin is easier because it does not imply countermeasures on the demand side like in closed basin. Moreover, basin closure also means a tighter interconnection within the components of the water cycle, such as aquatic ecosystems and water users, making it more difficult to cope with an increasing variability in renewable water due to climate change.

> According to MOLDEN, D. et al. (2007) "the definition of closure depends on the definition of the flow that is committed to flushing, diluting, and sustaining ecosystems. This definition is controversial but challenges the idea that any water in excess of human requirements is 'lost,' often expressed in declarations by engineers (or politicians) that not a single drop of water should be lost to the sea. The opposite position argues that all the river flow is necessary to sustain ecosystems, as they are intricately attuned to the natural flow regime. In many cases the flood regime is indeed part of ecosystem functioning and crucial for inland fisheries and can be considered as part of the fraction of water 'used'." Moreover, "outflow to the sea has several often overlooked functions: flushing out sediments (Yellow River in China), diluting polluted water (Chao Phraya River in Thailand), controlling salinity intrusion (many deltas), and sustaining estuarine and coastal ecosystems".

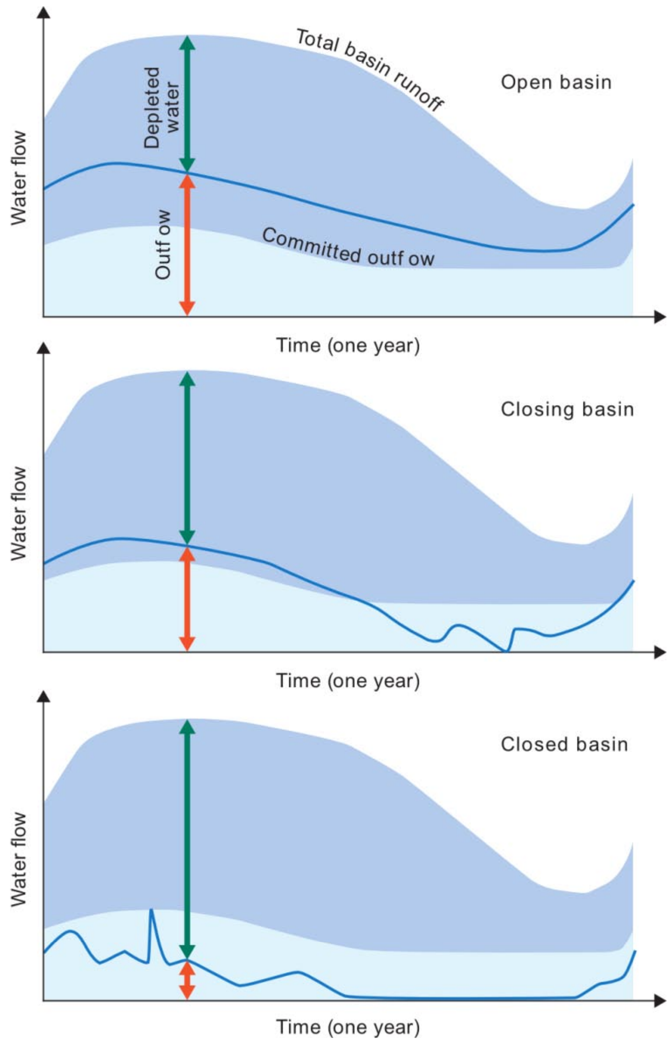

Figure 4: Closing and closed basins – rivers under stress (MOLDEN, D. et al., 2007). The third diagram shows that the committed out flow (to the sea or other catchments) is higher than available.

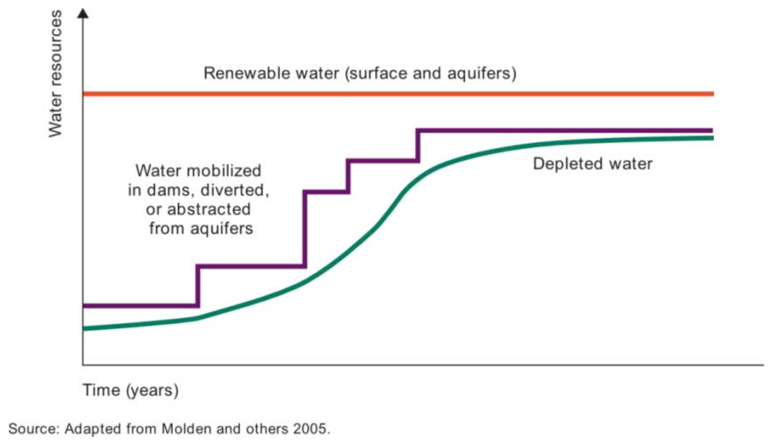

Figure 5: Development of water resources can lead to basin closure (MOLDEN, D. et al., 2007)

Going back to more obvious pressures, the technical report of FEHÉR, J. et al. (2012) identifies the following six main pressure groups: Water abstraction (modifying significantly the flow regime) (a), water flow regulations and morphologic alterations (b), river management (c), transitional and coastal water management (d), other morphological alterations (e), and other pressures (e.g. land drainage) (f). Especially relevant for this master thesis are the pressure groups **water abstraction** (hydraulic alterations), which include pressures from agriculture, public water supply, manufacturing, electricity cooling, fish farms, hydroenergy, navigation and water transfer; **morphologic alteration and water flow regulations** including pressures from groundwater recharge, hydroelectric dams, water supply dams, water flow regulation, diversion, locks and weirs and **river management** cumulating pressures like river channelization, dredging, land drainage and barriers due to bridges, etc..

Hydraulic alteration refers to pressures resulting from water abstraction and water storage that in turn leads to the change of the natural flow regime, e.g. changes in seasonal flow, changes in daily flow (hydro-peaking), water level fluctuations as well as modifications of sediment composition.

Examples of specific pressures are damming, embankment, channelization, non-natural water level fluctuations, disconnection of riverine floodplains, and so on. All these hydromorphological pressure arise in response for the need of hydropower, water supply, flood control, irrigation, navigation, recreation, fish breading, etc. (driving forces).

State:

The current state of hydraulic alterations is the result of what happened during much of the 20th century. The water needs of a growing population were met through the construction of infrastructure to increase water withdrawals from rivers and aquifers to enable urban, industrial, and agricultural growth (MOLDEN, D. et al., 2007, chapter 16). "The results are overbuilt river basins and basin closure, the situation where more water is used than is environmentally desirable or, in some cases, than is renewably available" (MOLDEN, D. et al., 2007, chapter 16).

> "During the second half of the century multipurpose development of river basins focused primarily on the construction of large dams. … Enthusiastic - and optimistic - large-scale development of river basins yielded unexpected results, however. River systems turned out to be interconnected transfer and transport systems … carrying not only water, but also sediment, nutrients, contaminants, and biota across space and time. Control of water, estimation of extreme events, and management of annual variability, surface water and groundwater interactions are posing many problems unanticipated by engineers, often leading to unexpected impacts and conflicts, while drastic alterations of the natural water regime provoked severe ecological degradation". (MOLDEN, D. et al., 2007, chapter 16).

To illustrate the current state of hydraulic alteration on a global scale, due to the lack of other meaningful statistics, it is feasible to look at worldwide dam constructions as an indication of hydraulic alteration. The World Commission on Large Dams (WCD) defines a large dam as having a height more or equal than 15 m from foundation to crest. Major dams are defined as those meeting at least one of the following criteria: height > 150 m, volume > 15,000,000 m^3, reservoir storage > 25 km^3, electrical generation capacity > 1000 MW. The commission has published incomplete statistics of the world's large dams and estimated that there were ~45,000 large dams built in the world (WCD, 2000). The associated reservoirs are estimated to have a combined storage capacity of ~6,000 km³, which is - assuming that half of the design storage is achieved in reality - equivalent to the volume of water in all the world's rivers. Unfortunately, a similar dataset for small dams is not available and therefore it has to be kept in mind that this numbers are only estimated for large dams and may also be outdated (see figure 7).

In a recent survey (FEHÉR, J. et al., 2012) conducted by the European Environment Agency (EEA) about the status of the hydromorphological alterations of the union's water bodies (WBs), all member states had the possibility to report different hydromorphological pressures on their WBs. However, many member states (e.g. Austria, Germany, the Netherlands and the UK) did not report details on pressures and only reported that a WB was affected by a pressure group. In numbers, 22 member states reported that 48.2% of their total river WBs are being affected. Moreover, 42.7% of the total rivers reported by 16 member states having altered habitats. The member states, which classified the pressures in groups on which their rivers are suffering, reported that 37% of their river WBs are affected by water flow regulation and morphological alteration. This pressure group includes impacts from storage of water in reservoirs, but also change in hydrological regime and impacts by weirs and locks. The second most important pressure group is river management, affecting 23.2% of river WBs. The river management pressure group includes WBs with physical alteration of the river channel including the effects of dredging, land drainage and barriers due to bridges, culverts etc. Interestingly, only 8.3 % of the classified river water bodies are affected by water abstraction. (FEHÉR, J. et al., 2012)

In Austria up to 80% of the large rivers are in a moderately to heavily impacted state. "As water pollution is not the main problem anymore, the main impacts on Austrian running waters concern hydromorphological alterations. Whereas, the main pressure types are channelization, continuum disruption, impoundment, water abstraction, hydro peaking and land use. In Austria only about one third of the total length of the main rivers remains free flowing. The remainders have been impounded or modified for hydroelectricity generation or flood protection and erosion control" (FEHÉR, J. et al., 2012). In numbers, the river WBs of Austria are mainly affected by water flow regulations and morphologic alterations having affected 58% of river water bodies with known ecological status/potential (compare 37% in EU). Obviously, this will be the main cause for a reported 56% of altered habitats in Austrian river bodies.

In contrast, Spain reported that 21% of their national river water bodies (WBs) are affected by water flow regulations and morphologic alterations, and 11 % of the total river WBs have altered habitats. Unfortunately, another 21% of the Spain's rivers have to cope with water abstraction (Austria: 1%; EU: 8.3%).

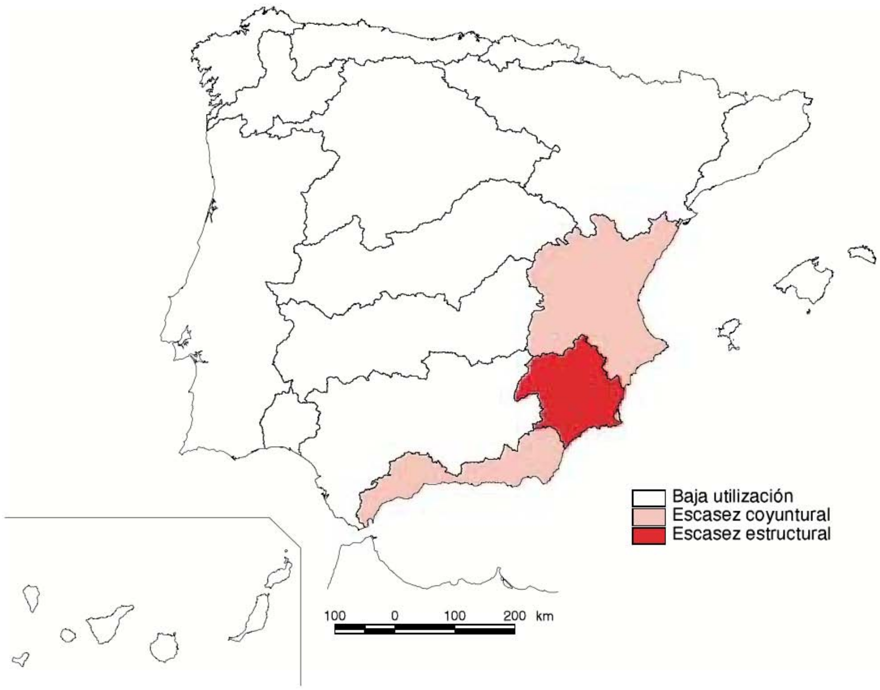

Figure 6: River basins in Spain under stress of overexploitation (CEDEX, 2000). Colored basins from north to south: Jucar river basin (mainly situated in the autonomous community of Valencia): cyclic deficit; Segura river basin (Murcia): structural deficit; Sur river basin (Andalusia): cyclic deficit

Despite notable scientific advances in the field of environmental flow assessment (EFA), "millions of kilometers of river and thousands of hectares of wetlands (and the human livelihoods dependent upon them) remain unprotected from the threat of over-allocation of water to offstream uses or to other alterations of the natural flow regime." (POFF, N. L. et al., 2009)

Unfortunately, the pace and intensity of flow alteration in the world's rivers greatly exceeds the ability of scientists to assess the effects on a river-by-river basis, thus may favor inappropriate responses, even when sophisticated EFMs are available.

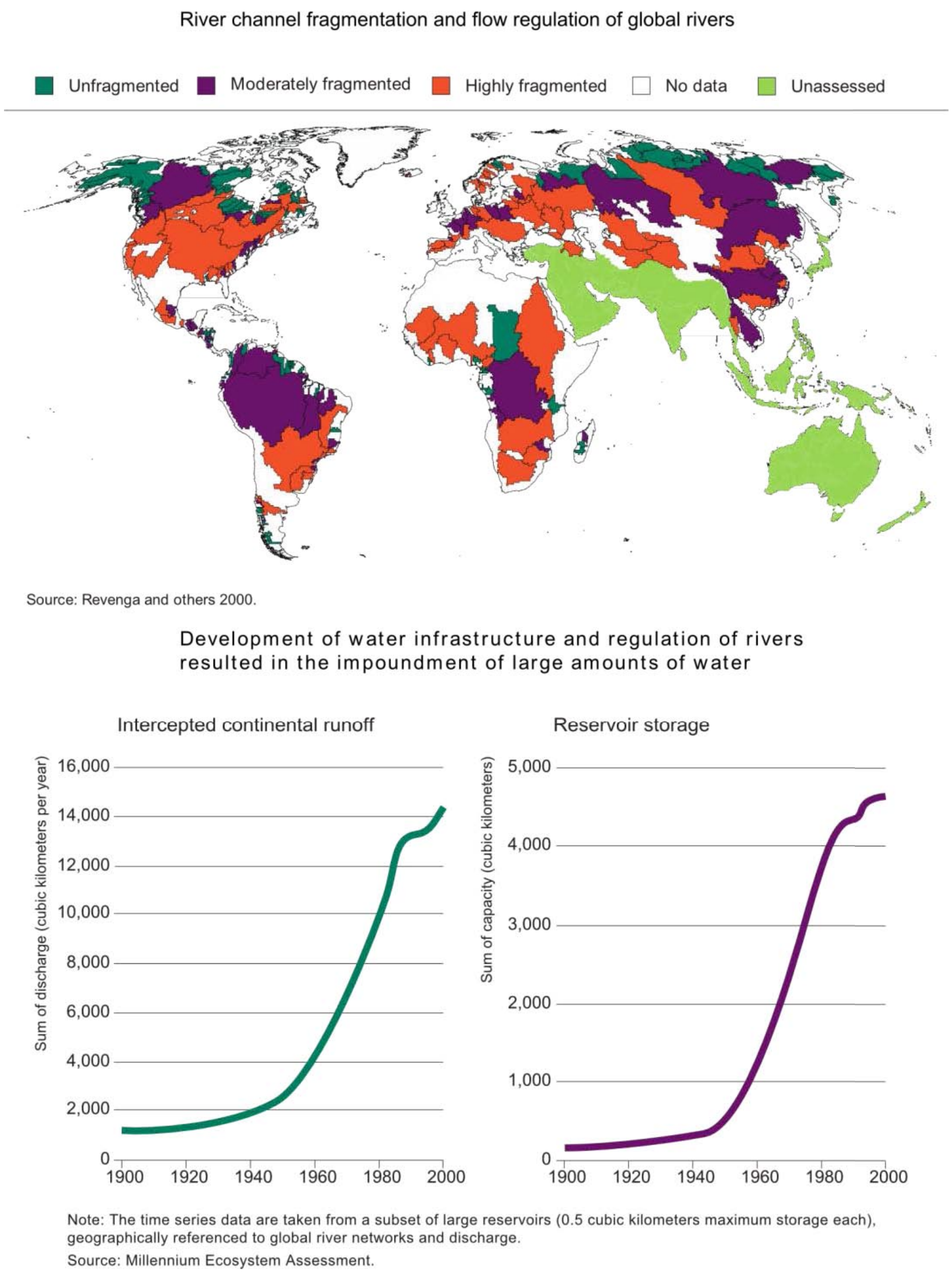

Figure 7: River channel fragmentation and flow regulation of global rivers (MOLDEN, D. et al., 2007)

Impacts:

The last 60 years have seen remarkable developments in water resources. Massive developments in hydraulic infrastructure have put water at the service of people. While the world population grew from 2.5 billion in 1950 to 7.1 billion today, the irrigated area doubled and water withdrawals tripled (MOLDEN, D. et al., 2007). These changes made many good things possible like propelling economies, improved livelihoods (unbalanced) and fighting hunger (still work to do), but are also accompanied by unwanted impacts on the ecosystem.

"Changes in the quality and functioning of the ecosystem or human condition have an impact on the welfare (well-being) of humans. Ecosystem services, in particular, are the benefits that ecosystems can provide" (EPA). Again, like in the previous sections, a general impact introduction on a global scale of hydraulic alteration and its main consequence habitat change is given before a more detailed introduction is stated. Above all, it is crucial to examine the linkage of human wellbeing to ecosystem services:

The Millennium Ecosystem Assessment, an international assessment done by more than 1300 scientists, showed that the well-being of human society was intimately linked to the capacity of ecosystems to provide ecosystem services (figure 8). Securing these multiple ecosystem services means ensuring for healthy ecosystems. Water plays a special role, because it connects ecosystems across the landscape. When agricultural activities (the main driver according to MOLDEN, D. et al. (2007)) or other driving forces, change the quality, quantity, and timing of water flows, this can have impact on the connected ecosystem's capacity to provide ecosystem services other than food. Some changes in ecosystems are unavoidable simply because of the amount of water needed to produce food or energy. However, much ecosystem can be avoided when water is managed well.

Whether an ecosystem is managed primarily for food production, energy production, water regulation or for other services (figure 8), it is possible to secure these for the long term only if basic ecosystem functioning is maintained[2].

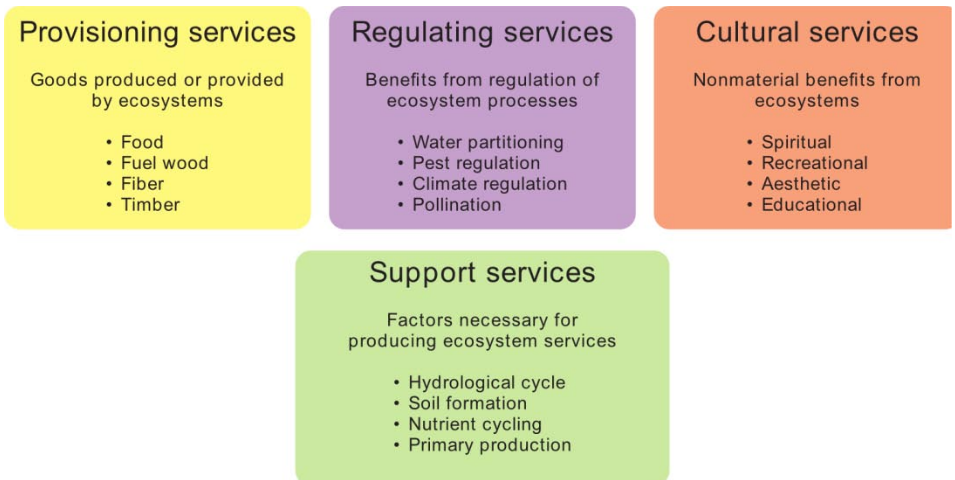

Figure 8: Types of ecosystem services (MOLDEN, D. et al., 2007)

Hydromorphological alteration causes numerous, deeply studied, impacts within the river reaches. The general impact of hydromorphological alteration is the reduction of complexity, dynamism and biodiversity (FEHÉR, J. et al., 2012). While biological diversity is in rapid decline in the entire world's major biomass, loss of biodiversity is greatest among freshwater-dependent species - almost twice as fast as for marine and terrestrial species (figure 9).

From the perspective of species conservation, the Mediterranean part of Europe has been recognized as a global biodiversity hotspot for freshwater fish species and for plant and terrestrial animal species (CUTTELOD, A. et al., 2008). However, an ongoing extinction crisis is affecting Europe's freshwater fishes, and ambitious conservation actions, including the adequate protection and management of key freshwater habitats, are urgently needed (FREYHOF, J. and Brooks, E., 2011). Conservation of fish diversity is one of the most critical issues facing the preservation of European biodiversity (ZITEK, A. et al., 2008).

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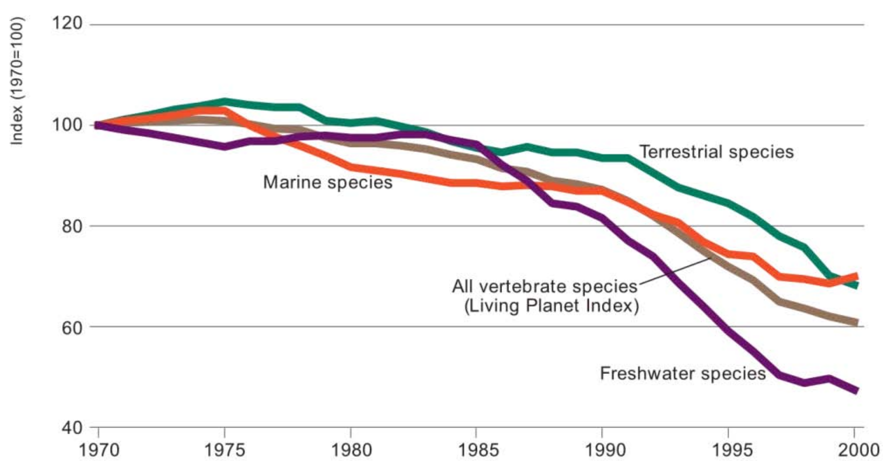
[2] A comprehensive list of ecosystem services supported by environmental flows can be found at http://www.eflownet.org, page "eFlows & Human Well-being". Last accessed (September 2014)

This has happened since biodiversity associated with inland waters is concentrated within limited areas (habitats) and many inland water-dependent species are especially vulnerable to changes in environmental conditions and because freshwater is subject to rapidly escalating threats from land-based impacts as demands are placed on water to meet growing populations and development pressures rises (MOLDEN, D. et al., 2007, chapter 2). More precisely, alterations to the flow regime degrade aquatic ecosystems through modification of physical habitat and of erosion and sediment supply rates resulting in habitat transformation and fragmentation (see figure 7). (MOLDEN, D. et al., 2007, chapter 6) Moreover, "there is increasing evidence that ecosystems play an important role in poverty reduction …. Many rural poor people rely on a variety of sources of income and subsistence activities that are based on ecosystems and are thus most directly vulnerable to the loss of ecosystem services" (MOLDEN, D. et al., 2007) .



Note: The index incorporates data on the abundance of 555 terrestrial species, 323 freshwater species, and 267 marine species around the world. While the index fell by some 40% between 1970 and 2000, the terrestrial index fell by about 30%, the freshwater index by about 50%, and the marine index by about 30%.

Figure 9: The Living Planet Index shows that biodiversity is declining most rapidly in freshwater-dependent species (MOLDEN, D. et al., 2007, chapter 6)

In Europe FEHÉR, J. et al. (2012) identifies hydropower as one of the main drivers to hydromorphological alterations, loss of connectivity and reduced sediment flow.

As impacts of hydropower installations (dams, pumped storage, run-of-the-river stations) the report mentions:

- barriers to the movement of aquatic species; risk of fish entrainment in turbine intake

- altered flow regime in the river; altered water-level fluctuation in reservoirs, altered structure of reservoir shore zone habitat
- altered sediment transport and retention; altered structure and conditions of bed and banks downstream; altered physic-chemical conditions of water bodies

As impacts of navigation infrastructure FEHÉR, J. et al. (2012) states:

- physical removal, smothering or other alteration to habitats or species
- barrier to movement of aquatic species; loss of riparian connectivity
- removal of sediment from the river or its relocation within a river
- water quality changes due to release of particulate matter and/or contaminants
- loss of riparian habitats due to bank erosion/bank protection
- physico-chemical changes due to impoundment (e.g. salt to fresh; tidal to non-tidal)
- altered physical processes and/or sediment transport characteristics (e.g. erosion, accretion)

Furthermore as impact of flood defense measures like river channeling, deepening and dykes, the following main impacts are identified:

- alteration of (i) type-specific natural hydrological flood regime; (ii) river cross section, (iii) riverbed and banks structure and materials and (iv) river bed depth
- saturation of sediments in downstream parts of the river
- disruption of connection with groundwater, alteration of groundwater level
- detachment of riparian hydromorphological structures from river
- Decreased (i) environmental and species diversity, (ii) recreation potentials of river environment; self-purifying capacity, (iii) river corridor ecological functions and (iv) interconnectedness between surface and groundwater flow.
- fragmentation of riverine ecosystem and river corridor structure
- loss of (i) shades, detritus, food, canopy; aquatic and riparian habitat, (ii) natural flood plain, (iii) fragmentation of aquatic habitat
- damaged riverine landscape amenities

Other relevant impacts are produced by hydropeaking at different scales, including the mesohabitat scale. It occurs downstream of hydropower outlets. Characteristics of hydropeaking influenced regimes can be summarized by a higher rate of discharge change than natural (ramping rate, decrease rate), by more frequent changes than naturally, by featuring an element of periodicity, and/or by a max discharge value (much) lower than, for example annual flood. The cause of this impact is that reservoir power stations are operating when the price of power is high or there is a need to balance the power grid.

More possible impacts focused on fish (hypothesis of the authors in (POFF, N. L. et al., 2009) due to flow alteration) are first, a further reduction of extreme low flows in perennial streams and subsequent drying leading to rapid loss of diversity and biomass in invertebrates and fish due to declines in wetted riffle habitat, lowered residual pool area⁄depth when riffles stop flowing, loss of connectivity between viable habitat patches and poor water quality. As second example, a decrease in inter-annual variation in flood frequency will lead to a decline in overall fish species richness and riparian vegetation species richness, as habitat diversity is reduced.

Responses:

"Responses are actions taken by groups or individuals in society and government to prevent, compensate, ameliorate or adapt to changes in well-being due to the state of the environment or condition of human health." (EPA)

There are many levels to respond to hydraulic alterations. "**Driver-level**" responses attempt to prevent that it is even coming to the point where hydraulic alterations are generating problems. Responses to modify the quantity of water demand (as well as spatial and temporal) are management actions like agriculture or energy management, population control and population settlement management, to name only a few.

On the **pressure-level** side, responds attempt to control activities, which place pressure on the environment. One can name land-use management, resource use management (withdrawal limitations), technology improvements or behavior modifications (e.g. irrigation timing, human diet change) as responses. A pressure more detailed discussed was basin closure. Typically, the first response is/was the augmentation of supply – developing the resource. "When options for augmentation get scarcer or more costly, the emphasis is likely to shift to improved management and conservation. Once gains in efficiency have been realized, reallocation to higher value or other uses may appear necessary". (MOLDEN, D. et al., 2007, chapter 16) It should be noted that most of the responses listed in table 1 are no direct responses to hydraulic alterations. Related to hydraulic alteration and habitat loss, often they are originator of problems themselves but they are also responses to water scarcity, in which responses to hydraulic alterations have to be incorporated.

Table 1: Three types of responses to basin closure (MOLDEN, D. et al., 2007, modified)

Respond type	Respond
Developing	Reservoir building, groundwater abstraction, transbasin diversion, water treatment desalination, virtual water (e.g. importing goods)
Allocating	Sectorial reallocation (agriculture, industrial, municipal), quotas, water rights and markets, give up (release water), change of crops
Conserving	Improved dam management, canal lining, awareness campaigns and water management practices, the use of less water intense irrigation technics.

State-level responses directly attempt to restore, modify or maintain the condition of the environment. Here a direct modification of the ecosystem through revitalization or restoration (original state of the ecosystem hast to be known) can be mentioned. River revitalization/restoration incorporates also the removal of dams or new dam operation rules taking into account environmental flow requirements (EFRs). A comprehensive list of state-level responses can be found in (http://wiki.reformrivers.eu/index.php/Category:Measures). To remain more general, even the establishment of parks and reservation areas, general technology improvements (fish passes, habitat evaluation models, …), increased transparency in decision-making or legal frameworks - which address or incorporate ecological flow criteria for future projects in the planning phase - are appropriate state-level responses.

Impact-level responses attempt to monitor or quantify the loss of ecosystem services and their impact on human well-being. To be aware about the impacts and to measure them is crucial. Recognizing the impacts is the first starting point for counter measures. In the last 60 years environmental topics have been given to little value in planning and evaluation, hence we now have to deal with the impacts of not knowing or understanding the functioning of ecosystems and how dependent we are on the services they provide. Index developing as the Living Planet Index presented in the figure 9 can be seen as impact-level response on a global scale. In general, such indices attempt to study the cumulative effects of hydrological alterations; they are relatively recent compared to the studies of impacts of individual dams and reservoirs (ROSENBERG, D. M. et al., 2000). On a technical, master thesis relevant perspective, the development of indices likes the HSI (habitat suitability index) to measure potential habitat for a target fish species can be seen as an example of index development. Another challenging response to habitat loss is to give this special ecosystem service an economic value to make the hidden costs of interventions explicit to be able to influence cost-benefit analysis and feasibility studies in favor of environmental preservation. (MOLDEN, D. et al., 2007)

The fundamental challenge of the described negative effects of hydraulic alteration is how to deal with tradeoffs. In reality, win-win situations are hard to find and difficult choices have to be made. MOLDEN, D. et al. (2007) states five big tradeoffs we have to face in water management today: (1) water usage for the people (e.g. water storage for agriculture) vs. water for the environment, (2) reallocation vs. overallocation (new allocations of water in closed basins will require renegotiating water allocation), (3) upstream vs. downstream, (4) equity vs. productivity and (5) this generation vs. the next ones. Moreover, the following elements, which are critical for negotiating tradeoffs, are advised. First, foster social action and public debate. Next, share knowledge and information equitably and third, ***develop better tools for assessing tradeoffs***. In each planning state, decision support tools like those related or integrating hydraulic habitat modeling can help to develop satisfactory tradeoffs or at least can serve as a justification of decisions.

ENVIRONMENTAL FLOW METHODOLOGIES FOR RIVERS

In 2003, THARME, R. E. conducted a global review of the present status of environmental flow methodologies and revealed the existence of 207 individual methodologies, recorded for 44 countries within six world regions. The following sections outline the evolution of the science of environmental flow assessment (EFA) and provide classification of methodologies for EFA.

Evolution of the science of EFA

> "Recognition of the need to establish the extent to which the flow regime of a river can be altered from natural, for the purposes of water resource development and management, while maintaining the integrity …, or an accepted level of degradation, of the ecosystem has provided the drive for accelerated development of a relatively new science of environmental flow assessment … . An environmental flow assessment (EFA) for a river may be defined simply as an assessment of how much of the original flow regime of a river should continue to flow down it and onto its floodplains in order to maintain specified, valued features of the ecosystem. An EFA produces one or more descriptions of possible modified hydrological regimes for the river, the environmental flow requirements (EFRs), each linked to a predetermined objective in terms of the ecosystem's future condition. For instance, these objectives may be directed at the maintenance or enhancement of the entire riverine ecosystem, including its various aquatic and riparian biota and components from source to sea, at maximizing the production of commercial fish species, at conserving particular endangered species, or protecting features of scientific, cultural or recreational value. Typically, EFAs are performed for river systems that are already regulated or are the focus of proposed water resource developments, but more recently, attention has also been directed at the flow-related aspects of river restoration …. The resultant EFR may be specified at several levels of resolution, from a single annual flow volume through to, more commonly nowadays, a comprehensive, modified flow regime where the overall volume of water allocated for environmental purposes is a combination of different monthly and event-based (e.g. low flows and flood pulses) allocations. The scale at which the EFA is undertaken may also vary widely, from a whole catchment for a large river basin that includes regulated and unregulated tributaries, to a flow restoration project for a single river

> reach … Concerted development of methodologies for prescribing EFRs began at the end of the 1940s, in the western United States of America. … Outside the United States, the route by which environmental flow methodologies (EFMs) became established for use is less well documented …. In many countries, the process only gained significant ground in the 1980s (e.g. Australia, England, New Zealand and South Africa) or later (e.g. Brazil, Czech Republic, Japan and Portugal). Other parts of the world, including Eastern Europe, and much of Latin America, Africa and Asia, appear poorly advanced in the field, with little published literature that deals specifically with environmental flow issues." (THARME, R. E., 2003)

Methodologies in EFA

The survey conducted by THARME, R. E. (2003) differentiates into four main methodologies that are discussed more in detail later. The main groups of methodologies are hydrological methodologies (i), hydraulic rating methodologies (ii), habitat simulation methodologies (iii) and holistic methodologies (iv), which are used at two or more applications levels. (1) First, he identifies a "reconnaissance-level relying on hydrological methodologies … applied in all world regions. Commonly, a modified Tennant method or arbitrary low flow indices is adopted". These methodologies are the largest group and are applied in all world regions. (2) The second level of application is a more comprehensive scale of assessment, which he furthermore divides into avenues of application: "In developed countries of the northern hemisphere, particularly, the instream flow incremental methodology (IFIM) or other similarly structured approaches are used. As a group, these methodologies are the second most widely applied worldwide, with emphasis on complex, **hydrodynamic habitat modeling**" (2a). The holistic methodologies, originating and mostly applied in Australia and South Africa, shortly explained as scenario-based methods, addressing the flow requirements of the entire riverine ecosystem, based on explicit links between changes in flow regime and the consequences for the biophysical environment, mark an alternative route (2b). (THARME, R. E., 2003)

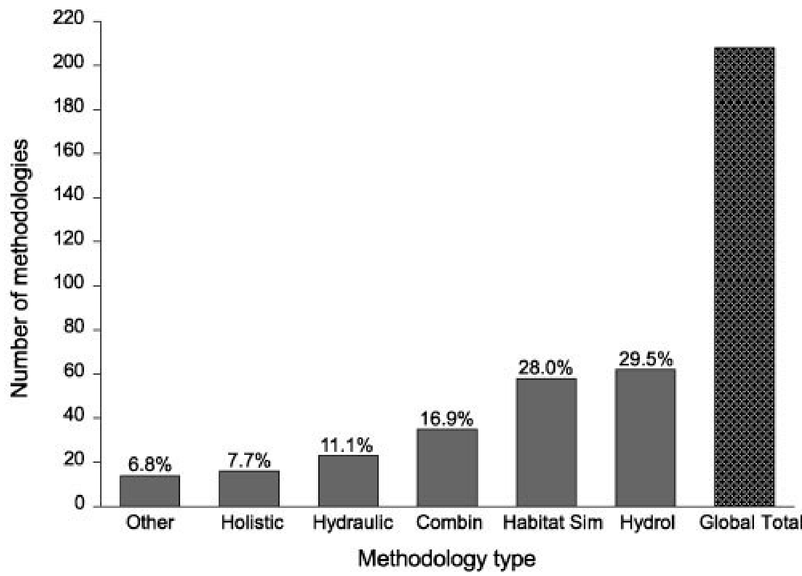


Figure 10: Number of EFMs of each type in use worldwide and their relative proportions compared with the global total. "Hydraulic" refers to hydraulic rating; "Combin" to combination; "Habitat Sim" to habitat simulation and "Hydrol" to Hydrological methodologies. (THARME, R. E., 2003)

Hydrological Methods:

> "The simplest, typically desktop EFMs, hydrological methodologies, rely primarily on the use of hydrological data, usually in the form of naturalized, historical monthly or daily flow records, for making environmental flow recommendations. They are often referred to as fixed-percentage or look-up table methodologies, where a set proportion of flow, often termed the minimum flow represents the environmental flow requirement intended to maintain the freshwater fishery, other highlighted ecological features, or river health at some acceptable level, usually on an annual, seasonal or monthly basis." (THARME, R. E., 2003)

THARME, R. E. (2008) states simplicity, rapidness, low data needs (primarily flow data), suitability for water resource planning purposes and the potential of regionalization for different river ecotypes as strengths of hydrological methodologies, whereas on the other hand the inflexibility, the low resolution output (comment: one dimensional), the absence of a direct link to ecosystem indicator (e.g. discharge to an instream resource, such as fishery habitat) and an in general insufficient approach to address the dynamic nature of flow regimes are mentioned as deficiencies. Furthermore, THARME, R. E. (2003) concludes, that "as a result of their rapid, non-resource-intensive, but low resolution environmental flow estimates, hydrological methodologies are considered to be most appropriate at the planning level of water resource development, or in low controversy situations where they may be used as preliminary flow targets".

Recently, one hydraulic EFM called Range of Variability Approach (RVA), primarily its component indicators of hydrologic alteration (IHA), a software tool, has been applied intensively since its inception. The RVA aims to provide a comprehensive statistical characterization of ecologically relevant features of a flow regime, in which the natural range of hydrological variation is described using 67 different hydrological indices derived from long-term, daily flow records. These indices are divided into two groups, the IHA parameters and the Environmental Flow Component (EFC) parameters and are grouped into five categories based on regime characteristics with flow management targets set as ranges of variation in each index, which can be monitored and refined over time. "In the majority of cases the methodology has been used in trend analysis of pre- and post-regulation scenarios, to characterize the flow-related changes experienced by regulated rivers". However, in several instances, such changes have been correlated with ecological factors (e.g. fish populations, vegetation, water quality, geomorphological processes and species habitat) or have been used to supplement the results of physical microhabitat, as done in this master thesis. (RYBICKI, T., (2009) and THARME, R. E. (2008))

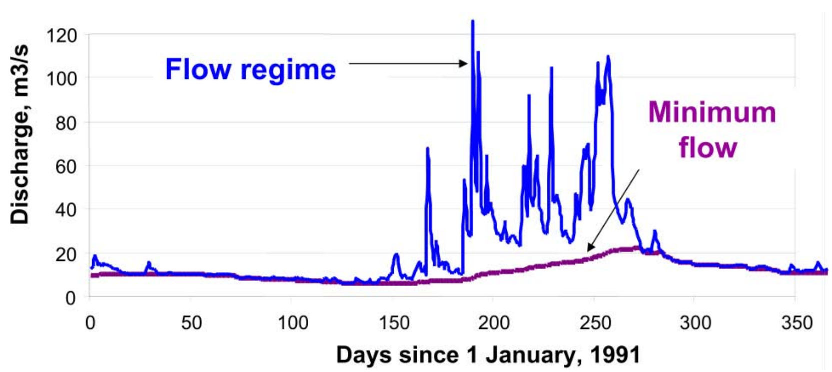


Figure 11: Minimum flow as a percentage of average flow (DE FREITAS, G. K., 2008)

Hydraulic rating environmental flow methodologies (EFMs):

To address one drawback of hydrological methods, the absence of a relationship between the discharge and an instream resource (e.g. fishery habitat) to calculate EFRs, hydraulic rating methods examine the effects of specific increment, decrement in discharge on instream resources. To sum it up, hydraulic rating methods uses changes in hydraulic variables (such as wetted perimeter or maximal depth) to assess habitat factors known or assumed to be limiting to target biota, thus a threshold value of the selected hydraulic parameter will sustain biota/ecosystem integrity. In general as target biota, a target fish species (target fish concept), identified as economically or recreationally important fish species, is used. THARME, R. E. (2008) and DUNBAR et al. (1998) consider "these methodologies to be the precursors of more sophisticated habitat rating or simulation methodologies, also referred to as microhabitat or habitat modeling methodologies." (THARME, R. E. (2008) and PYRCE, R. (2004))

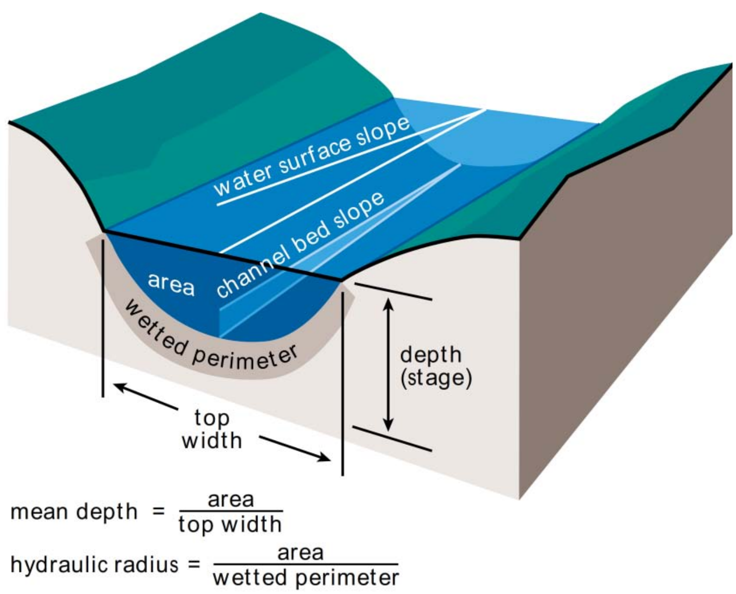


Figure 12: Hydraulic parameters (FISRWG, 2001)

Habitat simulation EFMs:

> "These techniques attempt to assess EFRs on the basis of detailed analyses of the quantity and suitability of instream physical habitat available to target species or assemblages under different discharges (or flow regimes), on the basis of integrated hydrological, hydraulic and biological response data. Typically, the flow-related changes in physical microhabitat are modelled in various hydraulic programs, using data on one or more hydraulic variables, most commonly depth, velocity, substratum composition, cover and, more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within the river study reach. The simulated available habitat conditions are linked with information on the range of preferred to unsuitable microhabitat conditions for target species, lifestages, assemblages and/or activities, often depicted using seasonally defined habitat suitability index curves. The resultant outputs, usually in the form of habitat–discharge curves for the biota, or extended as habitat time and exceedence series, are used to predict optimum flows as EFRs." (THARME, R. E., 2003)

To illustrate how these methodologies generally work, basic steps for finding an environmental friendly flow using the **ph**ysical **hab**itat **sim**ulation **m**odel (PHABSIM) are outlined. PHABSIM represents the habitat evaluation component within a larger instream flow incremental methodology (IFIM) for incorporating fish habitat consideration into flow management. The IFIM not only scopes technical procedures but also an organizational framework useful for evaluating and formulating alternative water management options. The two basic components of the PHABSIM model are a hydraulic simulation for predicting water surface elevations and flow velocities at unmeasured discharges and a habitat simulation model for predicting habitat change through discharge change. (FISRWG, 2001)

At the beginning, a target fish species or a set of target fish species (fish guilds) is selected for the habitat evaluation procedure (HEP). This is a crucial step, because it heavily influences the complexity of the evaluation. Keeping in mind that the complexity of the analysis varies along a number of important dimensions, like for example single place (e.g. spawning habitat) and single time (e.g. spawning season) versus a temporal sequence of spatially complex requirements (e.g. different life stages require different habitat requirements), as well as analysis for a single target species versus fish guilds. Next, fieldwork is done to set up the hydraulic model for the investigation site. Fieldwork can also include the development of habitat suitability curves (HSI) for target fish species and life stages. The HEP is founded on two fundamental ecological principles described in FISRWG (2001): "Habitat has a definable carrying capacity, or suitability, to support or produce wildlife populations …, and the suitability of habitat for a given wildlife species can be estimated using measurements of vegetative, physical, and chemical traits of the habitat. The suitability of a habitat for a given species is described by a habitat suitability index (HSI) constrained between 0 (unsuitable habitat) and 1 (optimum habitat)". The PHABSIM model uses physical properties like depth, velocity, substrate material and cover for which HSI have to be developed. The spatial discretization of the hydraulic model in PHABSIM is one dimensional as can be seen in figure 13. The transects are the same like in the hydraulic simulation, so for each patch defined in between of two cross sections, averaged velocity, depth, substrate and cover values are assigned and translated into habitat suitability weights using the specific HSI. The total weighted usable area (WUA) for the target fish in its specific life stage and at a specific discharge is calculated by the sum of the WUA of each patch, which is the area of the patch times the product of the velocity index, depth index, substrate index and cover index. The procedure is repeated for different flows to evaluate habitat change caused by flow change.

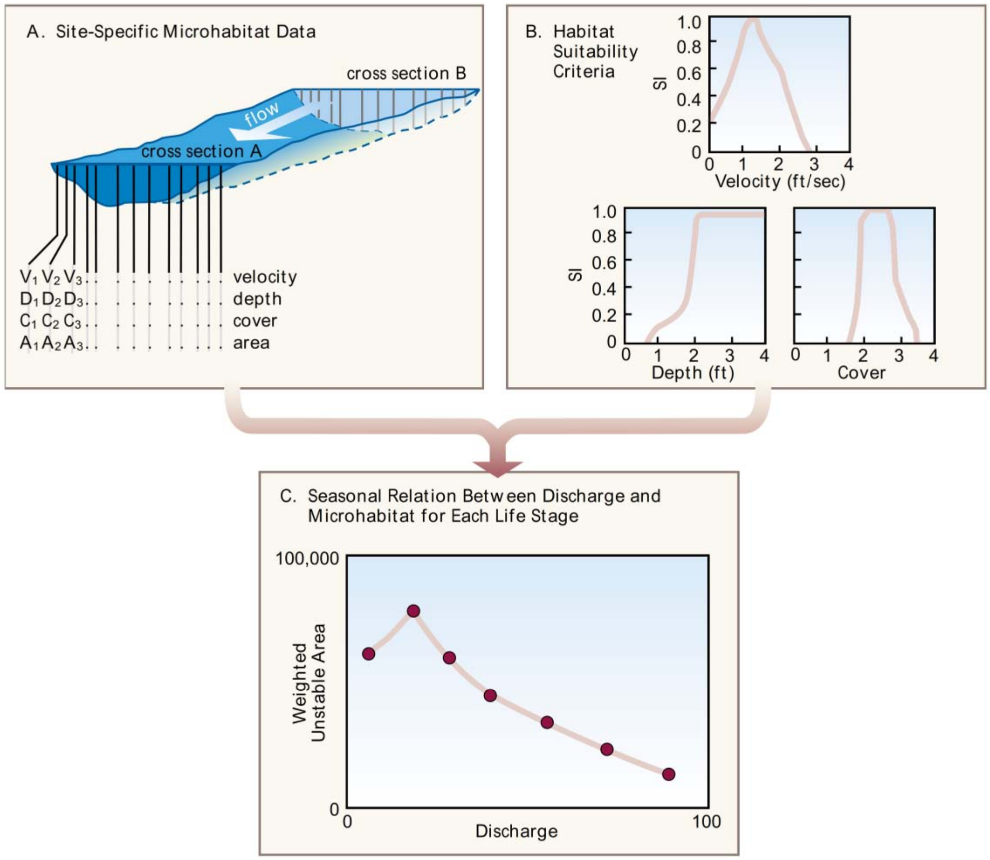


Figure 13: PHABSIM WUA concept (FISRWG, 2001)

Description of figure 13: "Conceptualization of how PHABSIM calculates habitat values as a function of discharge. Ad A) First, depth (Di), velocity (Vi), cover conditions (Ci), and area (Ai) are measured or simulated for a given discharge. Ad B) Suitability index (SI) criteria are used to weight the area of each cell for the discharge. The habitat values for all cells in the study reach are summed to obtain a single habitat value for the discharge. Ad C) The procedure is repeated for a range of discharges ..." (FISRWG, 2001)

In a minimum flow project scenario the outcome of the HEP is a plot of WUA versus discharge, in which a threshold value is searched to justify the potential habitat loss in a quantitative way. Two strategies for finding the "best" tradeoffs are commonly applied. Assuming a non-linear decreasing WUA curve, there might by a break in the decline, which can serve as recommendation for the minimum flow. The other one is using a percentage of the optimum as limit or minimum recommendation. One can imagine that finding the optimal solution is not straight forwarded if a set of target species at their different life stages is taken into account.

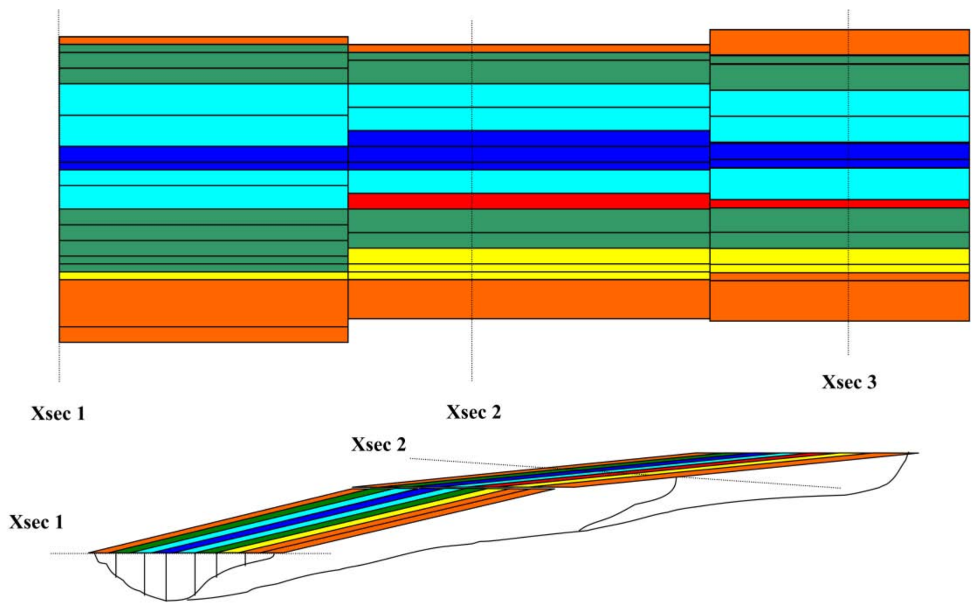


Figure 14: Reach discretization in 1D hydraulic models

Before discussing the strengths and weaknesses of this EFM, some things have to be remembered about the PHABSIM approach and especially about the WUA value:

> "First, it provides an index to microhabitat availability; it is not a measure of the habitat actually used by aquatic organisms. It can be used only if the species under consideration exhibit documented preferences for depth, velocity, substrate material, cover, or other predictable microhabitat attributes in a specific environment of competition and predation. The typical application of PHABSIM assumes relatively steady flow conditions such that depths and velocities are comparably stable within the chosen time step. PHABSIM does not predict the effects of flow on channel change." (FISRWG, 2001)

Choosing the optimal spatial discretization in size and dimension not only depends on the river type but also on the available budget. While a 1D hydraulic simulation can be sufficient in homogenous rivers with a dominating longitudinal character, it is clear that for example in a braided river system a 2D flow simulation is more suitable. On the other hand, a 1D simulation is more economic in terms of fieldwork, equipment costs and computing power than a 2D simulation.

The high-resolution habitat-flow relationships for target species and the possibility to generate alternative environmental flow scenarios for different species are forming main strengths of this approach. However, too little focus on the whole ecosystem, the biological meaning of the weighted usable area (WUA) value, the problems of describing the river morphology (spatial discretization), the relatively high amount of needed information and the interpretation of HSI curves can be seen as deficits.

It is feasible to take a closer look at the critics of the habitat simulation approach, especially at microhabitat modeling, to carry over into the discussion of mesohabitat modeling. A more detailed review of the problems of microhabitat modeling can be found in (HUDSON, H. R. et al., 2003), which are summarized as follows:

Problems describing the river:

- "For particular reaches of river, a wide divergence outcome is possible because of sampling problems …, hydraulics modeling problems …, choice of habitat curve for a particular species and life stages … and weight given to particular species and life stages in recommending a flow regime."
- No confidence intervals of the divergent WUA are stated to help interpretation.
- Transect placement: complex reaches are avoided due to locations too deep to wade or to shallow to jetboat; hydraulic modeling transects are placed tens to hundreds or more meters apart, while the actual area of use by fish and other aquatic animals is often in the order of meter;
- For many animals (e.g. salmoids, many cyprinides) the habitat structure may have a stronger influence on habitat suitability than the occurrence of a particular range of microhabitat conditions, like depth, velocity and substrate, does.

Problems with habitat suitability curves (HSC):

- Significant problems in translating observations into biologically meaningful HSCs; different methods of deriving those produce different results
- "Widely used habitat suitability curves were developed from a limited range of environments and from a narrow range of conditions, but the indices have been applied generally, without testing."
- "Critical requirements such as groundwater upwelling in salmon spawning areas are known but not modeled resulting in unrealistically high estimates of habitat availability and use …."

Problems with biological meaning of WUA:

- "The index of habitat availability that PHABSIM generates—WUA in m^2/m is difficult to imbue with biological meaning."
- The positive relationship between biomass (in terms of fish abundance) and WUA has to be demonstrated before the PHABSIM method can be considered valid for assessment of instream flow requirements.

Problems with a two narrow definition of minimum flow:

EFA projects with the application of microhabitat simulations tend to focus on a to narrow definition of minimal flow (survival flows) for target fish species without consideration of critical elements, such as flow variability and maintenance of ecosystem processes, and overriding constraints on habitat availability like water quality and stream temperature, which are again depended on flow condition. Rather than minimum flows, environmental flows should be the focus. "Environmental flows provide a flow regime for the river corridor (i.e. the channel itself as well as the floodplain, and the transitional upland fringe) and receiving waters (e.g. coastal zone), for the purpose of maintaining ecosystem structure (e.g. wetlands, oxbow lakes) and processes (e.g. nutrient cycling; sediment flux) in their own right ..." Therefore, environmental flows, not minimum flows, are required. (HUDSON, H. R. et al., 2003)

Despite, all the mentioned critics, the PHABSIM implementation of habitat evaluation EFMs (28% on a global scale, see figure 10) and all it's derivate, is the mostly used approach in at least

20 countries and "has been considered by some environmental flow practitioners as the most scientifically and legally defensible methodology available for assessing EFRs" (THARME, R. E., 2003). However, concerning the legal defensibility, HUDSON, H. R. et al. (2003) state a court case in North America, where a court convened expert panel conclude, that currently no scientifically defensible method exists for defining the instream flows needed to protect particular species of fish or aquatic ecosystems. Moreover, the panel's opinion was split on the future role of physical habitat simulation, as undertaken in IFIM, into two views: a) with modification and careful use, IFIM-habitat simulation might produce useful information; and b) IFIM-habitat simulation should be abandoned.

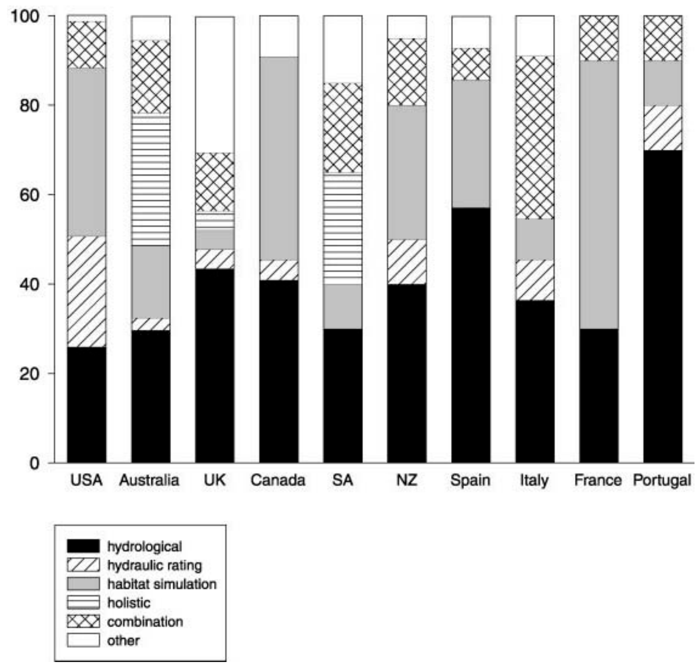


Figure 15: Methodology types per country (THARME, R. E., 2003).

Holistic EFMs:

"Holistic methodologies emerged from a common conceptual origin … to form a distinct group of EFMs focused from the outset towards addressing the EFRs of the entire riverine ecosystem. They rapidly took precedence over habitat simulation EFMs in South Africa and Australia, countries that lack the high profile freshwater fisheries characteristic of North America and where the emphasis is on ensuring the protection of entire rivers and their often poorly known biota." (THARME, R. E., 2003). Holistic methods try to integrate the complete ecosystem requirements (including the river channel, source areas, riparian zones, floodplains, etc.) and use the natural regime of the river as a fundamental guide that has to be incorporated into the modified flow regime (figure 17). Furthermore, critical flow criteria are identified for some or major components of the riverine ecosystem (figure 16). The basis for most approaches is a systematic construction of a modified flow regime on a month-by-month and element-by-element basis, which defines features of the flow regime to achieve particular ecological, geomorphological, water quality, social, or other objectives of the modified system. This is done through a bottom-up or, more common recently, a top-down or combination process that requires considerable multidisciplinary expertise and input. (PYRCE, R. (2004) and THARME, R. E. (2003))

> "Although centered in Australia and South Africa, holistic methodologies have stimulated considerable interest elsewhere. They may be especially appropriate in developing world regions, where environmental flow research is in its infancy and water allocations for ecosystems must, for the time being at least, be based on scant data, best professional judgment and risk assessment." (THARME, R. E., 2003)

An extensive overview of selected holistic methodologies can be found in (THARME, R. E., pp.41-45).

As proven by THARME, R. E. (2003) the emergence of holistic methods do not substitute habitat simulation methodologies but instead incorporate them:

> "Advanced holistic methods routinely utilize several of the tools found in hydrologic, hydraulic and habitat rating methods. The most advanced holistic methodologies routinely utilize several of the tools for hydrological, hydraulic and physical habitat analysis featured in the three types of EFM previously discussed, within a modular framework, for establishing the EFRs of the riverine ecosystem ... Importantly, they also tend to be reliant on quantitative flow-ecology models as input, especially if they are to possess the predictive capabilities required in EFAs nowadays." (THARME, R. E., 2003)

Turning now to the strengths of the holistic approach, DE FREITAS, G. K. (2008) lists the whole-ecosystem focus (i), the use of interdisciplinary expert judgment in a structured and consistent process (ii), the usability in a data rich as well as in a data poor context (iii) and the existence of explicit links between characteristics of flow regime, biological and social responses to flow change (iv). On the contrary, the dependence on expert judgment and the difficulties in reconciling opinions of different experts and the moderate to high resource demands are stated as deficiencies by (DE FREITAS, G. K., 2008).

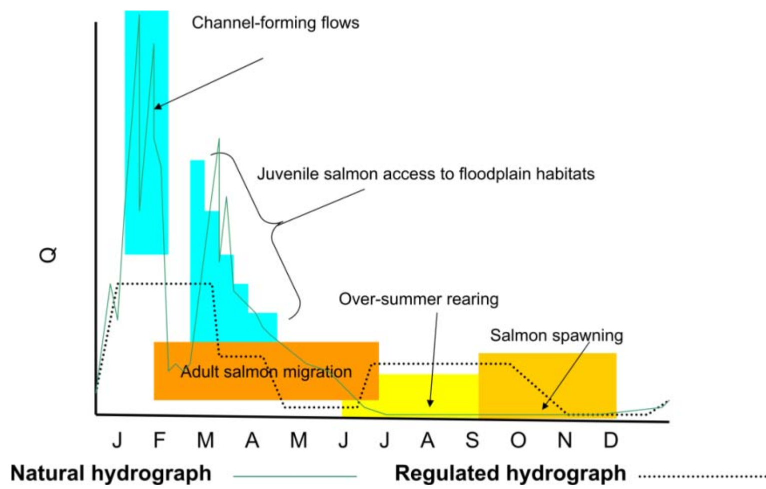


Figure 16: Determining flow needs for various ecosystem processes (DE FREITAS, G. K., 2008)

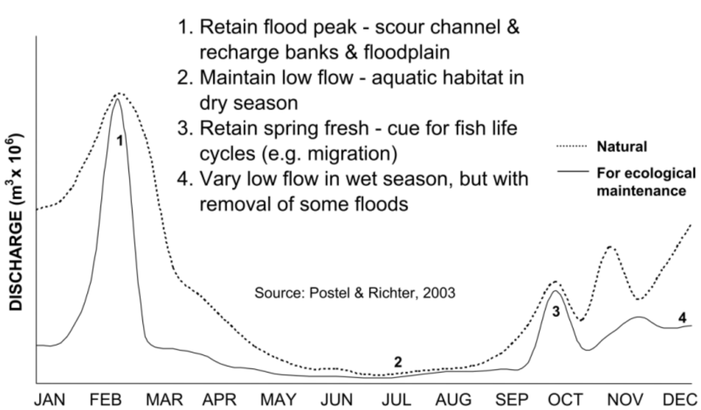


Figure 17: Natural flow paradigm (DE FREITAS, G. K., 2008)

HYDROMORPHOLOGIC PHYSICAL HABITAT MODELING AT MESO SCALE

A habitat is an ecological or environmental area that is inhabited by a particular species of animal. It is the natural environment in which an organism lives, or the physical environment that surrounds a species population. Surveying potential habitat areas is an essential component in examining the ecological state of running water ecosystems. Habitat can be structured into different spatial scales that stand in a hierarchical relationship to each other (figure 18). The extent in space requires a correlated temporal evolution. The macro level considers the whole catchment area, and larger parts of the river network. This scale is affected by very slow change processes due to tectonic, geological, and climatic activities. A further subdivision is the meso- and microhabitat level. Those levels are subject to dynamic change processes caused by the flow and sediment regime. The microhabitat level describes the habitat very local and on a small scale. It is defined by factors, such as water depths, flow velocities and bed shear stress. Meso- and microhabitats are to be understood as possible whereabouts of an individual. “Because of the natural mobility of fish, observation at the meso-scale is less affected by coincidence than at the micro-scale and can be expected to provide relatively meaningful clues about an animal’s selection of living conditions …” (PARASIEWICZ, P., 2007). The underlying philosophy of mesohabitat modeling is the recognition that fauna reacts to the environment at different scales related to the size and mobility of the species as well as the time of use. The mesohabitat simulation software used in this master thesis defines a fish habitat through hydromorphological units (HMUs) (compare figure 1). The focus on few physical parameters, like flow velocity, depth, and bed shear stress to describe a HMU, enables rapid surveying at arbitrary flows. After the site inspection is done, all these parameters can be simulated at different flow stages using a state of the art two-dimensional hydraulic model. As shown in many studies mentioned in PARASIEWICZ, P. (2007), “hydromorphic units (HMUs) and mesohabitats commonly correspond in size and location, at least for adult resident fish. Subsequently, ‘mesohabitat’ has almost become a synonym for HMU…”. PARASIEWICZ, P. (2007) justify the limitation on adult resident fish as follows:

> … the size of mesohabitats depends on the size and mobility of the investigated individuals, hence mesohabitats of juvenile fish or macroinvertebrates are usually smaller than those of

adult fish. In contrast, HMUs reflect only the interplay between hydraulics and riverbed topography, and their size is dependent upon the size of the river. Still, because hydraulics drives the organizational framework for riverine habitat, the correspondence between the HMUs and mesohabitats is not coincidental. Consequently, the spatial distribution of HMUs accompanied by associated cover attributes can be used for the quantification of summer habitat use by adult fish. For other life stages or seasons the functional habitats may be different and need to be considered separately.

It should be kept in mind, that the inclusion of cover parameters to describe mesohabitats involves more fieldwork because fish shelter are discharge dependent habitat features and cannot be simulated.

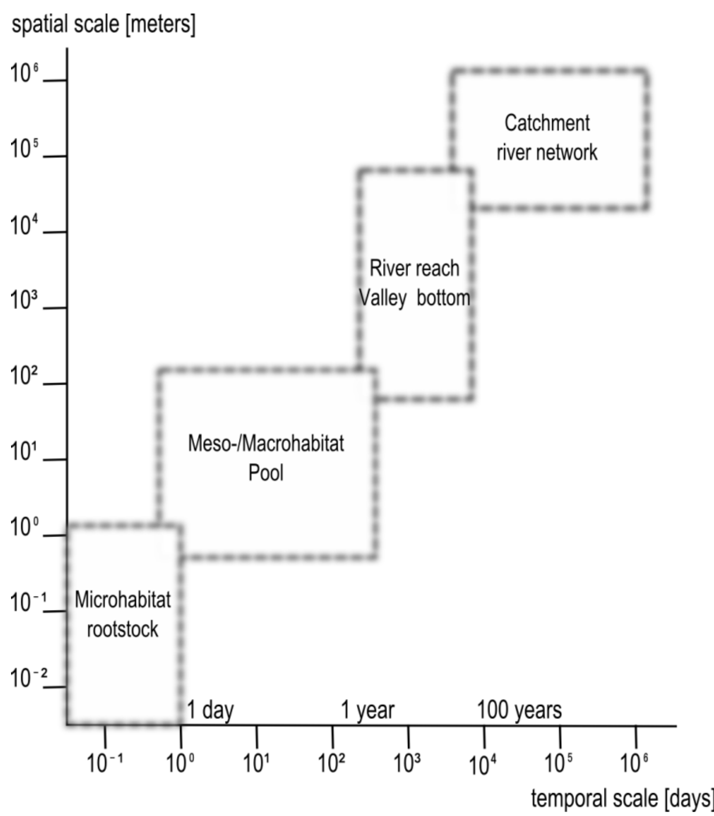


Figure 18: “River Scaling Concept“ (HABERSACK, H., 2000) in (AUER, H., 2012)

The typical structure of habitat models described by Parasiewicz and Dunbar (2001) in PARASIEWICZ, P. (2007) is an aggregation of three models (compare PHABSIM, figure 13):

1. A hydromorphologic model that describes the spatial mosaic of fish-relevant physical features.
2. A biological model describing habitat use by animals.
3. A habitat model quantifying the amounts of usable habitat and relating it to flow.

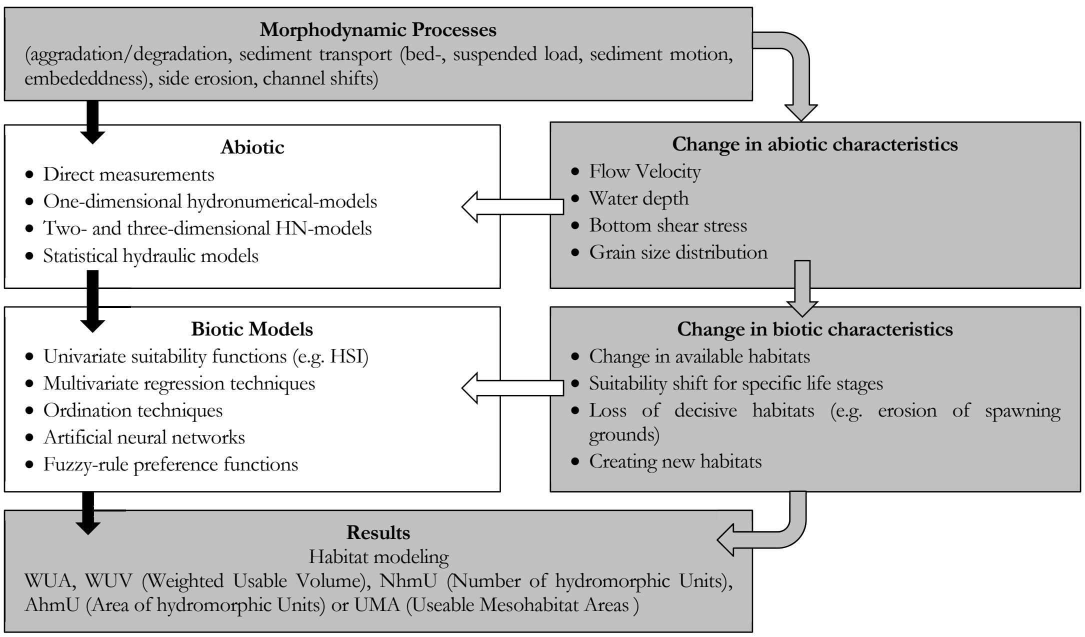


Figure 19: The role of river morphology and sediments in hydromorphological habitat modeling; impact of morphodynamic processes (grey bars and arrows) on hydraulic- and habitat suitability models (HAUER, C., 2014)

Figure 19 states on the one hand the components of a hydromorphological habitat model (white boxes) and the impact of morphodynamic process on the model's components (grey boxes). Without explaining all the implementation techniques in detail, the core message is that we can separate between an abiotic model component, which is providing input information for the biotic model.

The following presents the biological model (point 2 and 3) of the MEM approach. A detail introduction of the hydromorphologic model used in MEM is given in section "The hydromorphologic model and its calibration", p. 75ff.

Other than in microhabitats, HMUs are composed of a range of flow, depth and bed shear stress conditions forming a type of mesohabitat unit. To map fish abundance to a mesohabitat units (habitat evaluation procedure, HEP), two different concepts were developed (HAUER, C. et al., 2009). The fish guild concept (FGC) evaluates habitat suitability for spawning, juveniles, sub-adult and adult life stages, whereas the target fish concept (TFC) is concentrating on a specific fish species (figure 21). The linkage of numerical mesohabitat evaluation and fish guilds/target fish species has to be discussed with regard to the different fish region. In HAUER, C. et al. (2011) the FGC is applied in the Sulm River, which he outlines as follows:

> This first step involved determining the analysed fish region (e.g. metarhithral or. hyporhithral) and/or identifying target fish species (guilds) …. In a second step, electro fishing data (point abundance, meso-units) were used to assign mesohabitat suitability (preferred/useable/avoided) concerning the various hydromorphological units of the MEM-concept. To clearly differentiate between the three suitability classes, a numerical step of 0.5 was selected (Mesohabitat Suitability Index: preferred = 1, useable = 0.5, avoided=0). By multiplying mesohabitat suitability (preferred, use-able, avoided) with spatial extents of hydromorphological units, so-called Useable Mesohabitat Areas (UMA) could be determined (Equation 1), where UMA stands for Useable Mesohabitat Area (m²), A_{MEM} is the spatial extent of various mesohabitat (m^2) and MSI is the Mesohabitat Suitability Index (-).

$$UMA = A_{MEM} \times MSI$$

Equation 1: Useabel Mesohabitat Area

Developing MSIs is an evidence based or expert driven process. Most likely, a combination of both will yield economic success. The setup of the biological model (target fish/fish guild, HIS/MSI development) and the habitat model (UMA/WUA aggregation) is heavily influencing the complexity of the habitat evaluation procedure and their application in environmental flow studies (minimum flow, hydropeaking) (also see section Hydromorphologic physical habitat modeling at meso scale; “complexity discussion”, p 37ff).

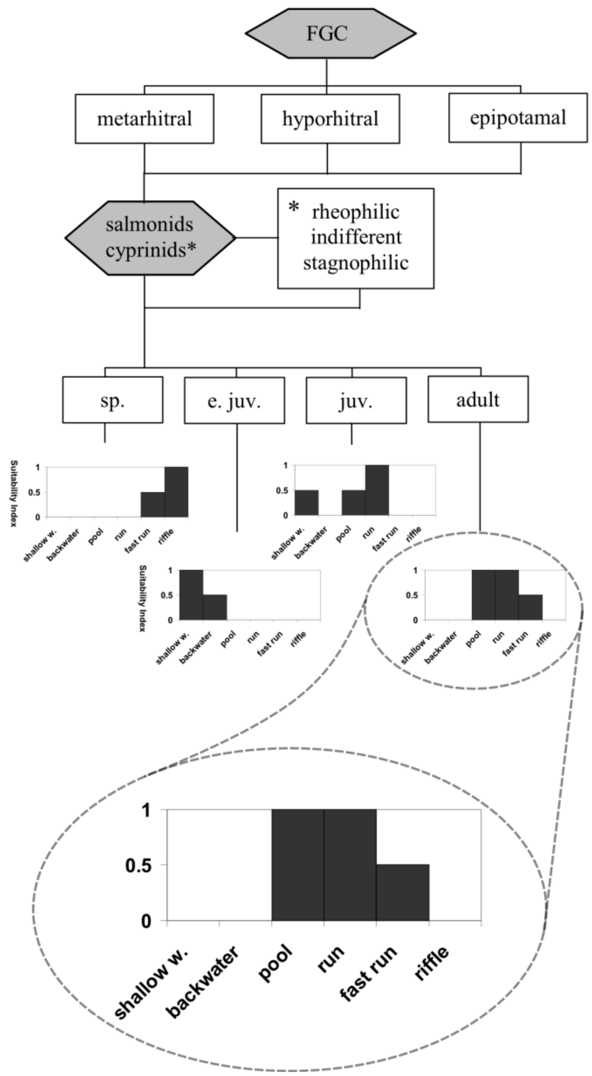


Figure 20: Fish Guild Concept (FGC); sp. = spawning; juv. =juveniles; s. ad. =sub-adults

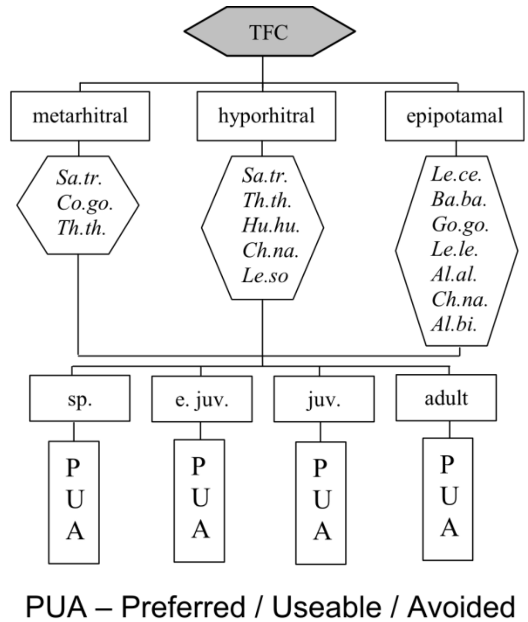


Figure 21: Target Fish Concept (FGC)

PROBLEM DEFINITION

The superior problem – hydraulic alterations with its entire negative effects was outlined in the introduction. The main motivation for this master thesis is to **develop better tools to mitigate the impacts of hydraulic alteration**. The concrete tool investigated in this work is called MEM – Mesohabitat Evaluation Model. It was developed at the University of Applied Life Sciences in Vienna at the Water Management, Hydrology and Hydraulic Engineering institute. The idea of this master thesis originated during the authors student exchange stay at the Polytechnic University of Valencia, where the interest to apply the MEM approach in Spanish river reaches was declared. Before detailed information about the tool and its purpose is given, a more EU centric legal justification of the need for such tools is given.

From a legal perspective, the development goal of a river is defined by the European Water Framework Directive (Directive 2000/60/EC). Some of the goals of the WFD are conflicting with other important EU Directives particularly the EU Floods Directive and the EU Renewable Energy Directives (Directive 2009/28/EC). To work out the conflicts of these directives, a short summary of the WFD goals is given:

> **Article 3-WFD:** Member states should achieve the objective of at least good water status by defining and implementing the necessary measures within integrated programs of measures.
>
> **Article 4-WFD:** Member States shall **protect, enhance and restore** all bodies of surface water, subject to the application of subparagraph (iii) for artificial and heavily modified bodies of water, with the aim of **achieving good surface water status** at the latest 15 years after the date of entry into force of this Directive, in accordance with the provisions laid down.
>
> The objective of achieving good water status should be pursued for each river basin, so that measures in respect of surface water and groundwater belonging to the same ecological, hydrological and hydrogeological system are coordinated. For the purposes of environmental protection, there is a need for a greater integration of qualitative and

quantitative aspects of both surface water and groundwater, taking into account the natural flow conditions of water within the hydrological cycle. (HAUER, C., 2014)

For the classification of the ecological status of a river, quality elements are defined and grouped into (compare figure 1):

A) biological elements
  - composition and abundance of aquatic flora
  - composition and abundance of benthic invertebrate fauna
  - composition, abundance and age structure of fish fauna

B) hydromorphological elements supporting the biological elements
  - hydrological regime
    - quantity and dynamics of water flow
    - connection to ground water bodies
  - river continuity
  - morphological conditions
    - river depth and width variation
    - structure and substrate of the river bed
    - structure of the riparian zone

C) Chemical and physicochemical elements supporting the biological elements

The hydromorphological quality components are of special interest in this master thesis. Although chemical and physicochemical elements are the basis for biological elements (e.g. water temperature), without river appropriate hydromorphological elements a site specific original aquatic fauna and flora cannot be sustainable established. A "high" hydromorphological status (remark: at least good is demanded by the WFD) is defined for the quality elements:

Table 2: Hydromorphological quality elements; requirements for status "high"

Element	High Status
Hydrological regime	The quantity and dynamics of flow, and the resultant connection to groundwater, reflect totally, or nearly totally, undistributed conditions.
River continuity	The continuity of the river is not influenced by anthropogenic activities and allows undistributed migration of aquatic organisms and sediment transport.
Morphological conditions	Channel patterns, width and depth variations, flow velocities, substrate conditions and both substrate the structure and condition of the riparian zones correspond totally or nearly totally to undisturbed conditions.

However, most of the European river systems are heavily impacted by multiple pressures within the main channel banks (e.g. run-off hydropower plants) and/or feature significantly altered conditions in former inundation areas, the floodplains (PIÈGAY, H. et al., 2008). Beside the ecological degradation, the intensified use of these overbank areas close to the river increases the risk of human tragedy and high economic losses if the design discharge (e.g. hundred years recurrence interval) of the regulated river will be overtopped, or if flood protection measures fail (DE KOK, J. and Grossmann, M., 2010). To cope with this specific natural hazard the European Parliament released a second directive, the European Floods Directive (Directive 2007/60/EC), relevant for managing river systems. Beside those clear stated flood management issues, one of the main tasks in the upcoming decades in Europe has to be seen in the integrative evaluation of our river systems due to the various interests represented by the different European directives. The specific need, however, for an integrative approach was already considered by the European Parliament and the Council of the European Union in some aspects, exemplarily for the Floods Directive and WFD in form of several operative relevant items like (i) the catchment scale is valid for both, (ii) definitions of the WFD are valid for both, (iii) integrative management plans should be achieved, (iv) participation and (v) subsidiary should be given. (HAUER, C., 2014)

The third and youngest European directive for water management issues is dealing with important aspects of energy supply based on hydropower production. The Renewable Resource Directive (Directive 2009/28/EC) claims for 20 % gross energy consumption of every Member State based on renewable energy until 2020 (Article 3). Thus, as part of the

EU´s Climate and Energy Policy 20/20/20, the increase in hydropower production on the energy market (beside an increase of wind, photovoltaic, etc…) will be a consequence of those targets. The extension of hydropower use has already been implemented as an objective in federal energy strategies. Although, hydropower has to be seen as a renewable form of energy, the intensified use of the kinetic energy of river systems stay (very often) in contrast to the aims of the European Water Framework Directive (preserve / achieve the 'good ecological status' or the 'good ecological potential'). To underline this conflict, STIGLER, H. et al. (2005) states that the implementation of the Directive 2000/60 /EC (WFD) would cost 90 Mil. € for fish passes at small hydropower plants in Austria. Moreover, for power plants > 10 MW an estimation of 144 Mil. € investments was calculated. The most cost effective measure, however, was determined for the reduction of hydropeaking effects, due to possible restrictions for peak flow (e.g. maximum ramping ratio for discharge fluctuations = 1:3 between base- and peak flow). The loss in productivity was calculated up to 85 % for selected storage power plants, with an economic deficit of 4.5 Mil. € per year. (HAUER, C., 2014)

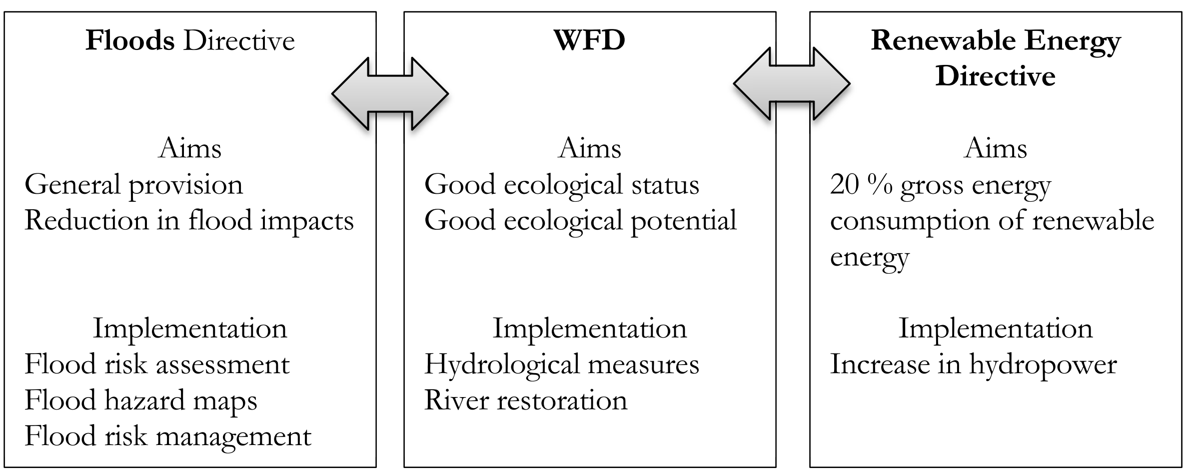


Figure 22: EU Directives: conflicts of interests

Before turning to the specific problem definition of the master thesis's project, figure 22 exhibits the conflicts of interests in the EU Directives stated before. Linking to the introduction, one can see the Renewable Energy Directive as a new pressure caused by the ever-increasing demand of cleaner energy (driver) maybe even more degrading the hydromorphological state of our rivers that result in more floods (impact) and degenerated aquatic ecosystems. These impacts ask for appropriate responses (WFD, Floods Directive) for mitigation. To balance all these different aspects, appropriate tools are needed. MEM is one of those.

MEM is a tool for Environmental Flow Assessment. The main purpose of MEM is to classify hydromorphological units (HMU) at meso scale. The output of the model can serve as processing inputs for biological models/tools for the assessment of biological quality elements. The assessment of the effectiveness of, for example a restoration project, is demanded by the WFD, therefore MEM is not only useful to make a snapshot of the current state of the hydromorphological variety of a river, it can also be used as a planning or decision tool. The MEM model with its extension HEM (Habitat Evaluation Model; the biological model of MEM) is applied in the following uses cases:

- Hydropeaking investigations
- Spawning habitat restoration projects
- Environmental friendly minimum flow investigations
- Evaluating habitat diversity in longitudinal and lateral direction for various discharges

The MEM model is of special interest because of its ability to **automatically** classify patches of hydromorphological units (mesohabitats), which are inputs for biological model to predict fish abundance. Manual site inspection can be a very cost effective task. The advantages and disadvantages compared to a manual mesohabitat inspection using the MEM are:

+ easily repeatable for different discharges, therefore less cost effective
+ less field work
+ time independency: no need to wait for project relevant discharges at the sampling site
+ extendable; the length of the river site to investigate does not matter[3]
+ consistent abiotic classification; no subjective estimation

[3] if the costs for a 2D hydraulic simulation is not taken into account

- river type dependent calibration required
- a digital terrain model is required (cost effective data acquisition)
- a 2D hydraulic model is required (computation intensive)
- no biotic features are taken into account for mesohabitat classification; e.g. plant cover

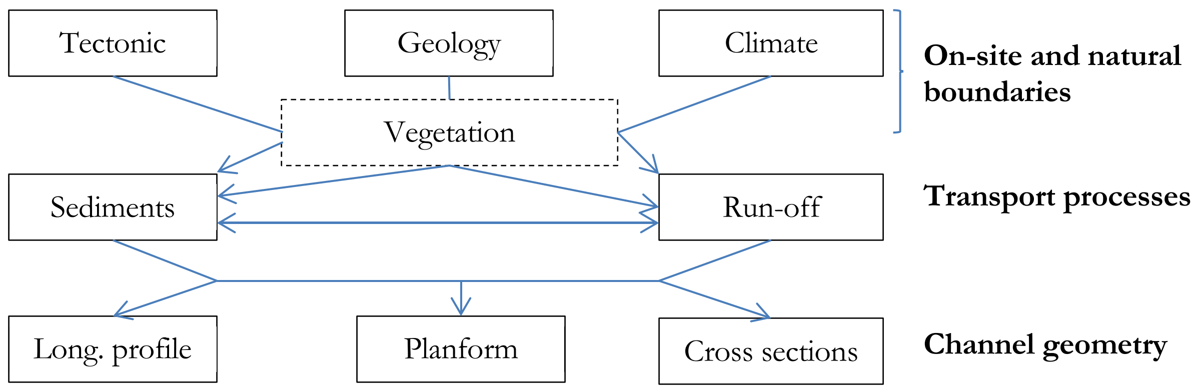
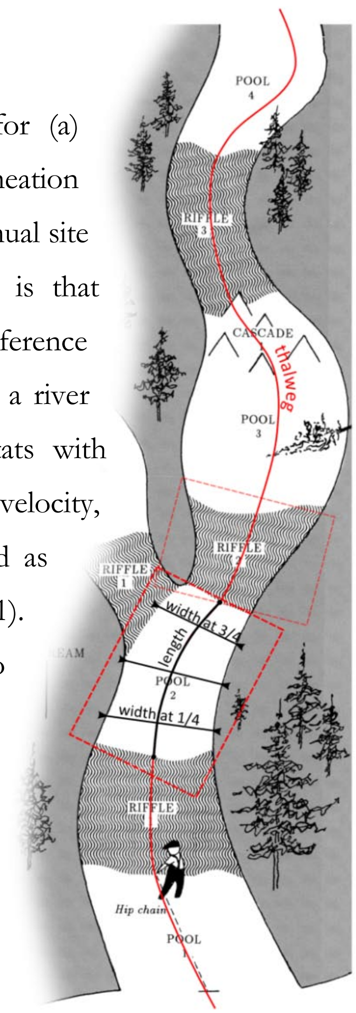


Figure 23: System river morphology (HAUER, C., 2014)

AIMS OF THE MASTER THESIS

The aim of the master thesis is to apply the MEM's habitat classification approach at a selected Spanish river (Cabriel) and an Austrian river (Ybbs) to compare the model performance. The idea behind this is to apply the MEM approach in Spanish Rivers as the abiotic component of an existing biotic mesohabitat model.



Hence, evaluate the use of a mesohabitat evaluation model for (a) automatic mesohabitat delineation or (b) manual mesohabitat delineation in terms of substituting or partial substituting the cost effective manual site inspections. In this master thesis the investigation prerequisite is that mesohabitats are factually non-overlapping sections on a linear reference (thalweg) where no side-by-side mesohabitats are allowed so that a river reach can be represented as a logical sequence of mesohabitats with properties like the length of the habitat, the average width, average velocity, depth, bed shear values and more. Those parameters are needed as inputs for biological models like in MOUTON, A. M. et al., (2011). Streamlining the derivation of the input parameters is crucial to extent the application of mesohabitat models on a higher spatial or temporal scale while keeping the survey efforts low. Therefore, the performance of the classification approach used in MEM is evaluated to answer the following objectives.

For both testing sites:

Automatic detection of the predominant mesohabitat type: For the testing sites, visual sampled mesohabitat classifications were available serving as prediction aim (nominal condition).

For the Spanish testing site:

- Evaluate mesohabitat classification performance of MEM with default parameters.

- Evaluate mesohabitat classification performance of MEM using manual derived classification parameters.
- Evaluate mesohabitat classification performance of MEM with automatic derived classification parameters.

For the Austrian testing site:

- Manually deduce mesohabitat borders from the DTM, longitudinal water surface thalweg, velocity, depth and bed shear stress plots.
- Evaluate mesohabitat classification performance of MEM using sampled classification parameters.
- Evaluate mesohabitat classification performance of MEM with automatic derived classification parameters.

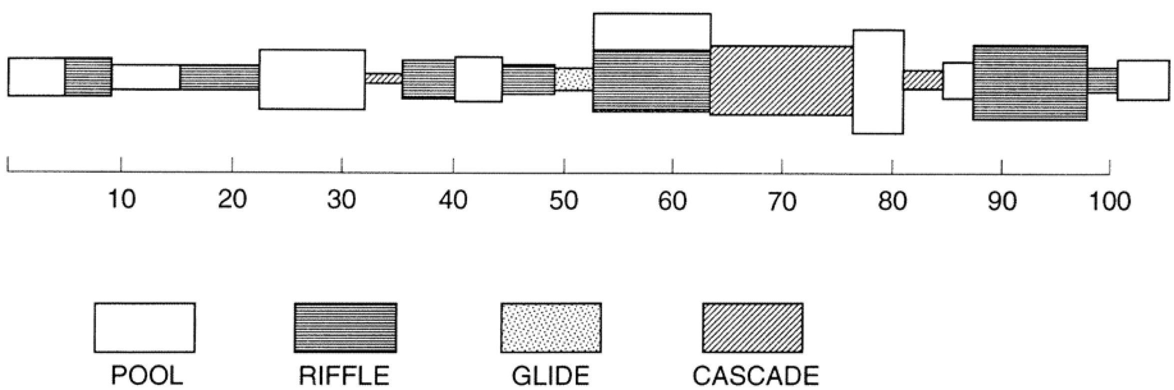


Figure 24: Schematic map of a river reach that show the size, sequence of occurrence, and position of all habitat units. (DOLLOFF, C. A. et al., 1993)

SURVEY SITE DESCRIPTIONS

LOCATION AND MORPHOLOGY

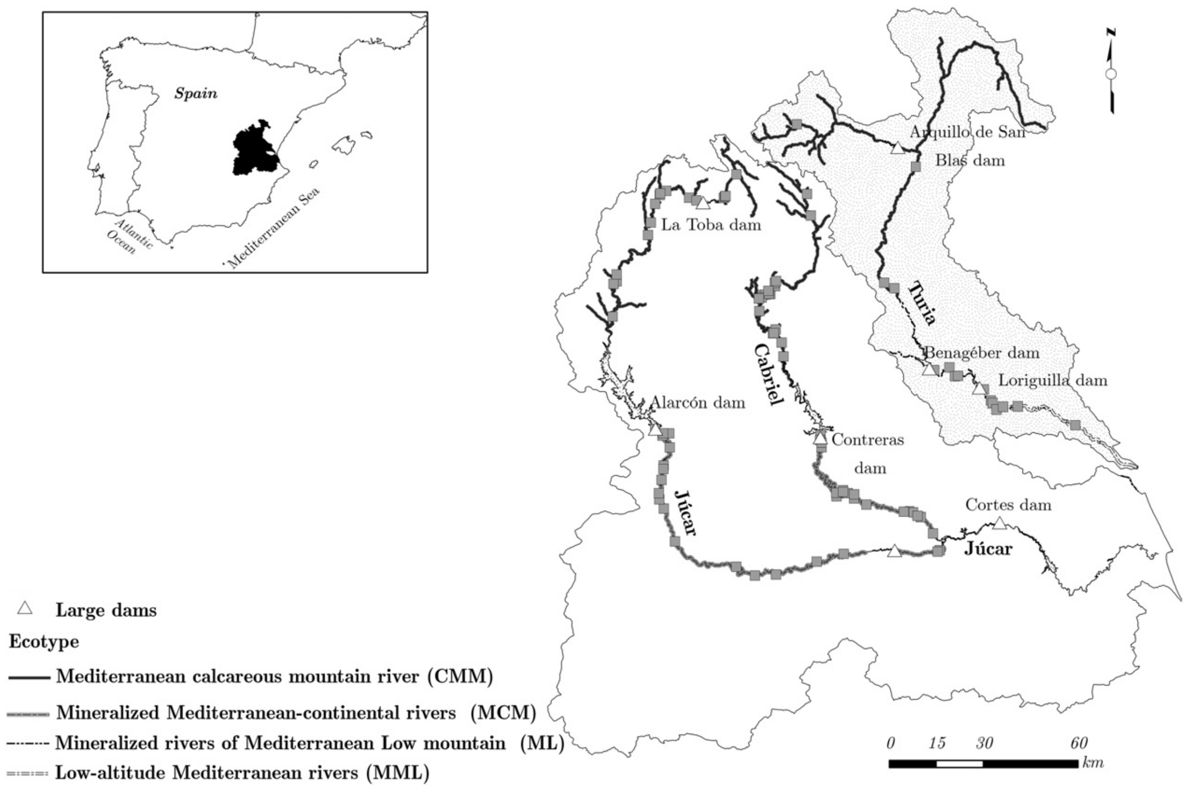


Figure 25: Location of the Júcar, Cabriel and Turia River Basins in the Iberian Peninsula, the large dams (triangle) and the river's ecotypes) sensu the European Water Framework Directive. (OLAYA MARÍN, E. J. et al., 2012)

The Spanish testing site is situated at the Cabriel River (province of Cuenca, Spain). The location was elected due to its reference habitat conditions (no or little human impact), natural flow regime and the availability of relevant project data like a digital terrain model and various 2D hydraulic simulations at different flows. The whole Cabriel River is 220 km long and drains an area of 4750 km². The catchment is part of the Júcar River Basin, which is characterized by a typical mediterranean climate (i.e. low flows and high evapotranspiration in summer and high flows in spring and autumn). The mean elevation is 1016 m.a.s.l. (elevation ranges from 490 to 1790 m.a.s.l.) and the mean annual precipitation in the catchment is about 500 mm. The testing site is located in the upper part of the Cabriel catchment, upstream of the large Contreras dam and close to the forsaken village "El Cañizar". The nearest gauging station Pajaroncillo is situated 4 km downstream. In this part of the catchment, the land cover is mainly represented by forested areas (86%) and crops (12%). The water quality of the river is outstanding. Due to the significant depopulation of the basin and the absence of economic activities that may influence water quality, it is one of the cleanest rivers in Europe. The mesohabitat composition was surveyed three times (2006 to 2008; 74 sampled mesohabitats) and is as follows: 41% pools, 37% riffles, 14% rapids and 8% glides. Additional relevant mesohabitat properties sampled were the mean depth (0.83 m), the maximum depth (2.4 m) and the average mesohabitat width (7.5 m). (SOARES COSTA, R. M. et al., 2012)

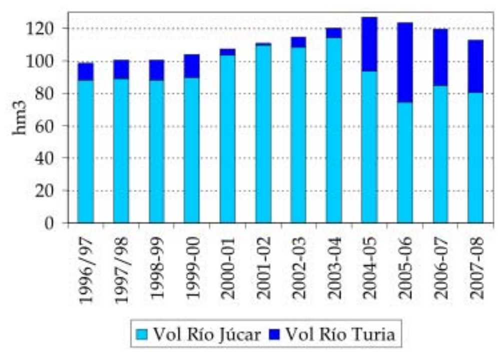


Figure 26: Sources of drinking water for Valencia (UPV gestion).

The large Contreras dam divides the Cabriel river into two segments. The dam is used for energy production and to allocate water for the Júcar-Turia canal, which supplies Valencia with drinking water. In Spain two-thirds of the large populations (> 20,000 habitants) take their urban water supply from rivers, whereas smaller populations use to two-thirds sub terrestrial waters for their supply. Figure 26 states the urban water need of Valencia. The River Cabriel contributes 220 hm^3 each year[4]. The whole catchment: has about ~3088 hm^3 long term average (last 50 years) run off per year. The urban water demand in 2004 was about 626 hm^3, the agricultural 2,820 hm^3 and the industrial 147 hm^3 per year (PÉREZ MARTÍN, M. A. and Estrela Monreal, T., 2013). The total storage capacity of the whole catchment is 2,349 hm^3 having retained 813 hm^3 of water in

[4] Wikipedia: River Cabriel; accessed May 2014

average in the last ten years[5]. Hence, it is easy to imagine how difficult it is in this catchment to negotiate for environmental friendly flows, given the fact that the water supply of the third largest city of Spain is dependent on the river and that each cubic meter of water could be turned into agricultural revenues (PÉREZ MARTÍN, M. A. and Estrela Monreal, T., 2013).

Figure 27: Rio Cabriel: Surveying activities. The photo shows a pool mesohabitat and was taken at the beginning of the testing reach. flow

[5] http://www.chj.es/es-es/ciudadano/salaprensa; accessed May 2014

Figure 28: Rio Cabriel: Surveying activities. The photo shows a transition area from a pool to a rapid mesohabitat. The photo was taken about 60m downstream.

Figure 29: Location of the Ybbs river in Austria

The Austrian testing site is located at the Ybbs river, which springs in Lower Austria in the Ötscher area at about 1,200 m a.s.l.. The Ötscher area belongs to the Ybbstal Alps, which are part of the Northern Limestone Alps. The Ybbs flows 138 km wide and overcomes a height - difference of approximately 1,000 m before it flows into the Danube at "Ybbs an der Donau". The total catchment area is about 1,300 km². From the river's origin to the confluence with the

"Lunzer Seebach" the Ybbs is called Ois. The gauging station used is located shortly before the confluence with the "Lunzer Seebach" and approximately 2 km farther downstream from the testing site. The area of the subcatchment upstream the gauging station is 118 km^2 large (76% forest), with an area-weighted average elevation of 1045 m. a. s. l.. The annual precipitation in this zone is about 1680 mm. (Water balance calculations for the case study regions in Austria, Hungary and Romania, 2001-2005)

The climate of the studied section of the Ybbs is located in the temperate transition zone in the transitional climate. The characteristics of the transitional climate are moderate temperatures and year-round precipitation with a peak in summer. The northern edge of the Alps is characterized by a humid climate. The mean annual precipitation is above 1,500 mm. Among 1,200 m altitude most of the snow falls in January and in even higher altitudes between March and April, hence the regime is strongly influenced by snowmelt processes.

Like the Cabriel river, the location was elected due to their reference habitat conditions (no or little human impact), natural flow regime and the availability of project relevant data like a digital terrain model.

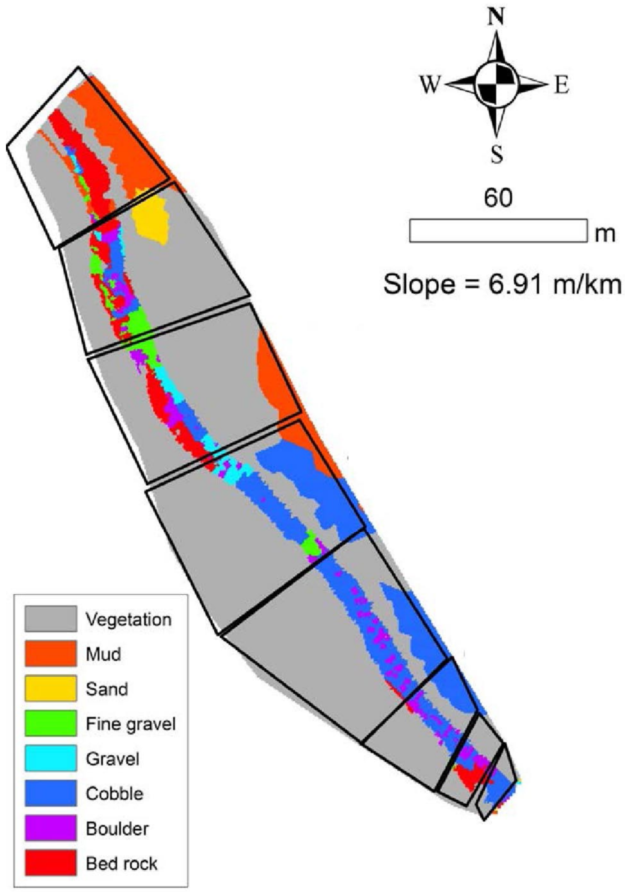


Figure 30: Cabriel: Stream bed particle distribution

Table 3:American Geophysical Union: Size gradation for sediment in the range of sand to boulders (Wentworth scale) (BUNTE, K. and Abt, S. R., 2001)

Particle size	*Range*
Boulder	4096 - 256 mm
Cobble	256 – 64 mm
Gravel	64 – 8 mm
Fine Gravel	8– 2mm
Sand	2 – 0.063 mm
Mud	< 0.063 mm

The following subsection presents a comparison of two daily/inter-daily discharge time series. Widely available averaged monthly discharge values are less helpful for EFA, because the temporal variability in flow cannot be seen. The comprehensive comparison was created to underline the important linkage between discharge and mesohabitat availability. The focus is on EFA relevant parameters. Tools used in the hydrological analysis are the IHA software and the statistics software R with the libraries IHA and HydroTSM. The IHA is designed to compare pre-impact to post-impact flow regimes therefore the usable overlapping timespan for analysis done with the **IHA software is 1985/10/1 to 2010/9/30**. On the contrary, statistics created in **R use the full available time spans**. To distinguish between R and IHA results, all results are prefixed either with "R" or with "IHA" in their descriptions.

Table 4: Time series properties

Properties	*Ybbs (Ois)*	*Cabriel*
temporal resolution	inter-daily	daily
measures	total 859917; 9237 (daily)	21901 (daily)
start date	1984-10-01	1949-10-01
end date	2012-09-30	2010-09-30
source	on request from „Hydrografischer Dienst Niederösterreich"	online available at http://saih.chj.es/chj/saih/
gauge	Lunz am See (Seestraße)	Pajaroncillo
water year	10/01 – 09/30	10/01 – 09/30
notes	Many missing values in the years 1986 until 2003; e.g. 114 daily values have been interpolated in year 1994 (done by the IHA software)	

The river morphology, the monthly discharge mean and median average discharge are parameters for overall habitat availability for aquatic organisms (table 6). Furthermore, the average discharge, influences water temperature, oxygen levels and photosynthesis in water column are overriding constraints on habitat availability. The second IHA parameter group (table 6), states parameters important for the (i) structuring of river channel, morphology and physical habitat conditions, the (ii) measurement of duration of stressful conditions, such as low oxygen and concentrated chemicals in aquatic environments, and (iii) for the aeration of spawning beds in channel sediments (duration of high flow) (RYBICKI, T., 2009). For minimum flow studies relevant parameters, like “1 day flow min” and “7 day flow min”, show a higher variance in flow for the Cabriel than for the Ybbs (figure 31 and figure 32). These parameters are calculated from moving averages of the appropriate length for every possible period that is completely within the water year. Aside from the magnitude of low flow, its average duration and its timing of annual extreme water conditions are of interest.

Figure 36 and table 6 state the timing of the minimal flow event: In the Ybbs the minimum flow event can occur all year long, in the Cabriel it is most likely to happen in late summer or autumn. How often low flow periods occur and their durations can be seen in figure 33 and figure 34. A low flow pulse is a fall below of the 25% quartile of all daily flows in the water year (default configuration). According to low flow events and their duration, the river comparison shows that low flow periods in River Cabriel take longer (up to 123 days). In the Ybbs they occur more often, however, for a shorter period of time (20 days). RYBICKI, T. (2009) states that low flow condition are in most rivers the dominant flow:

> In natural rivers, after a rainfall event or snowmelt period has passed and associated surface runoff from the catchment has subsided, the river returns to its base- or low-flow level. These low-flow levels are sustained by groundwater discharge into the river. The seasonally-varying low-flow levels in a river impose a fundamental constraint on a river's aquatic communities because it determines the amount of aquatic habitat available for most of the year. This has a strong influence on the diversity and number of organisms that can live in the river.

Recently, habitat simulations are applied for hydropeaking problems. In that context, the rate and frequency of water condition changes, especially rise and fall rates, may be of interest (entrapment of organisms on islands) (figure 35). Rise rates are the mean or median of all positive differences between consecutive daily values.

Table 5: R: Monthly flow in cms (also see boxplots in appendix figure 19 and appendix figure 20)

	median Ybbs	*mean Ybbs*	*median Cabriel*	*mean Cabriel*
October	1.88	2.16	2.42	2.59
November	2.36	2.79	2.70	3.27
December	2.26	2.57	3.26	4.46
January	2.44	2.39	3.77	6.06
February	2.07	2.41	5.57	6.70
March	4.18	4.39	5.24	6.82
April	7.41	8.49	5.72	6.14
May	5.98	6.19	4.91	5.70
June	3.22	3.50	4.35	4.69
July	2.30	2.88	2.59	2.90
August	2.27	2.39	2.16	2.33
September	2.22	3.01	2.28	2.36

Table 6: R: Magnitude and duration of annual extreme water conditions (IHA parameter group 2) in cms

	median Ybbs	*mean Ybbs*	*median Cabriel*	*mean Cabriel*
1 Day Min	0.95	0.96	1.27	1.46
1 Day Max	43.45	53.28	32.59	41.50
3 Day Min	0.98	1.00	1.54	1.63
3 Day Max	30.83	36.26	23.71	30.86
7 Day Min	1.02	1.07	1.65	1.68
7 Day Max	19.76	22.83	18.21	23.07
30 Day Min	1.36	1.47	1.76	1.85
30 Day Max	11.60	11.90	12.78	13.72
90 Day Min	2.46	2.61	2.32	2.37
90 Day Max	8.29	8.50	9.07	9.61
Zero flow days	0.00	0.00	0.00	0.00
Base index	0.21	0.22	0.37	0.37

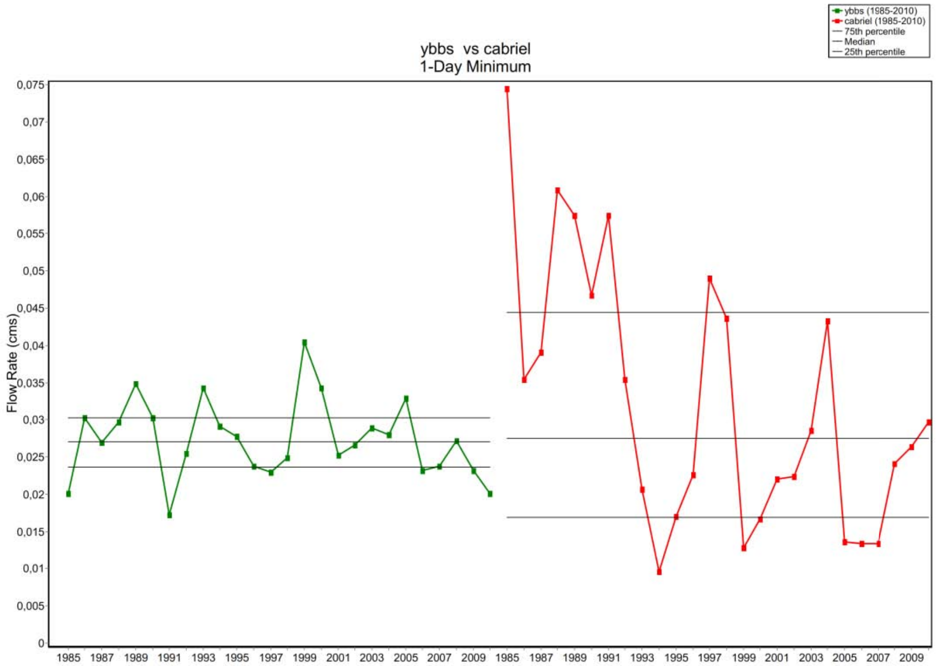


Figure 31: IHA: 1 day min flow compared

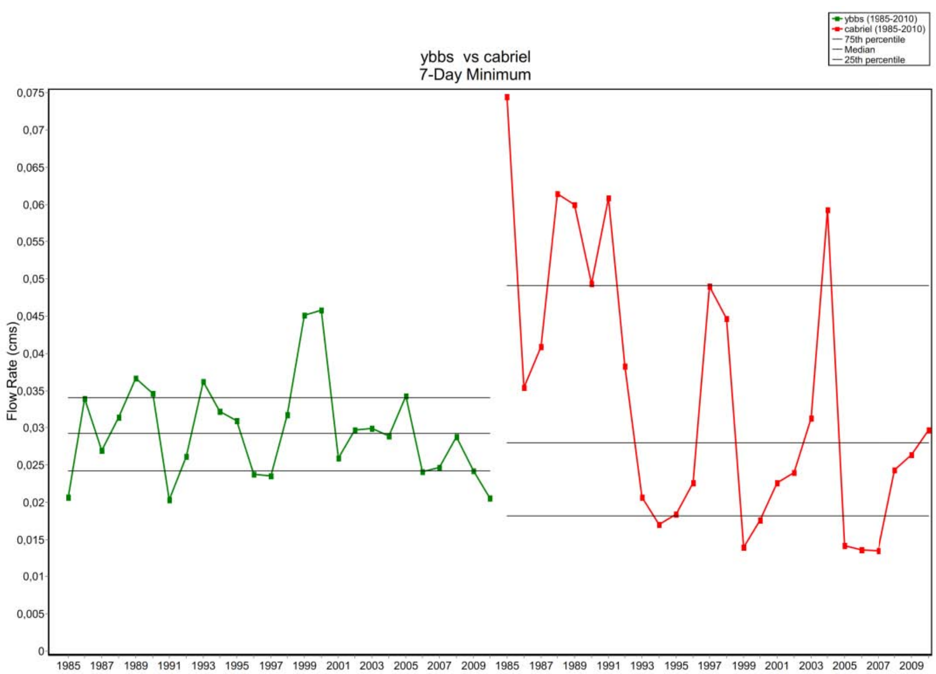


Figure 32: IHA: 7 day min flow compared

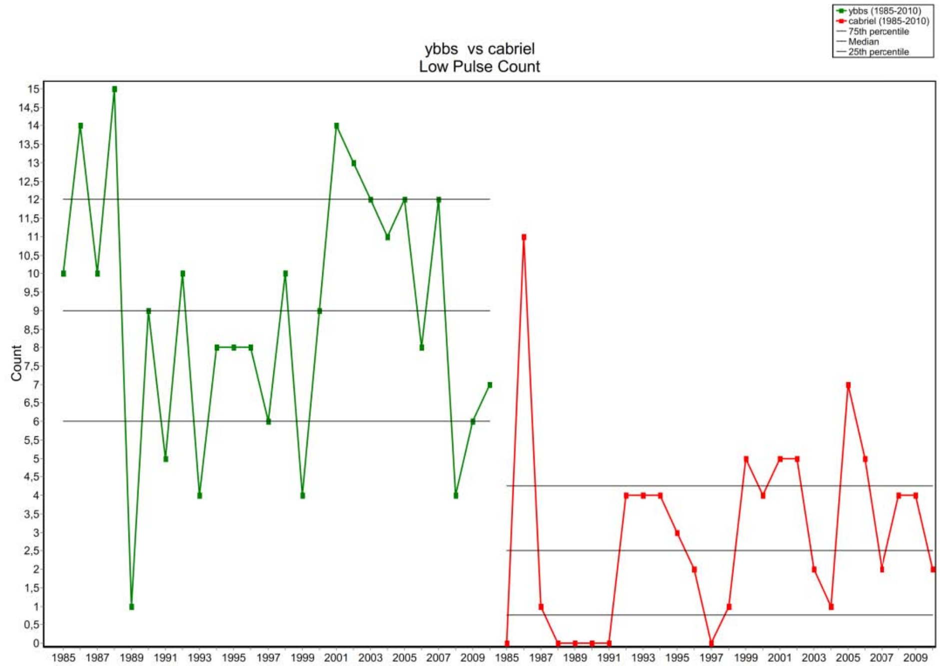


Figure 33: IHA: low flow pulse count compared

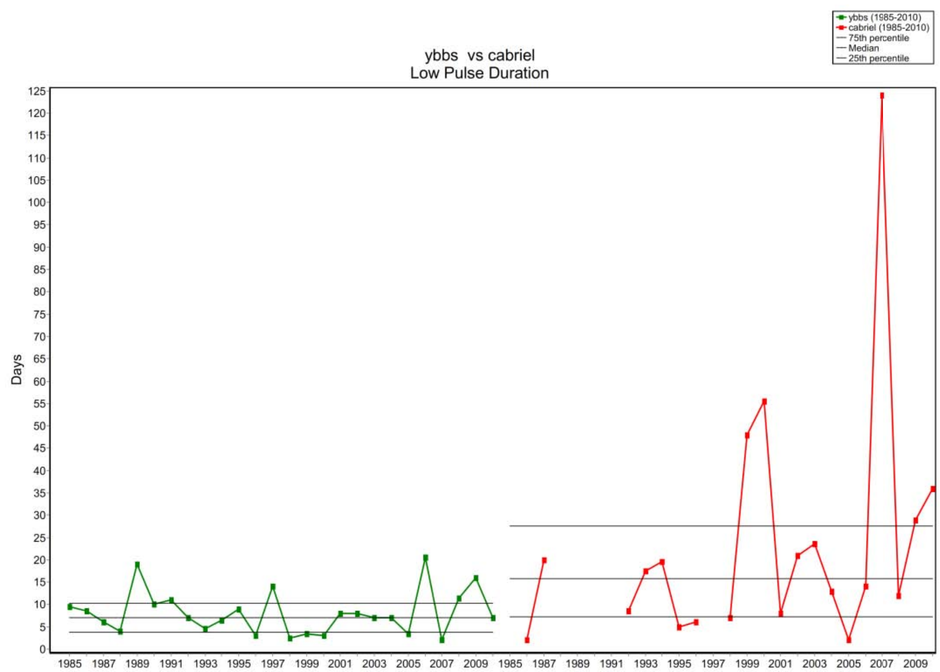


Figure 34: IHA: low flow pulse duration compared

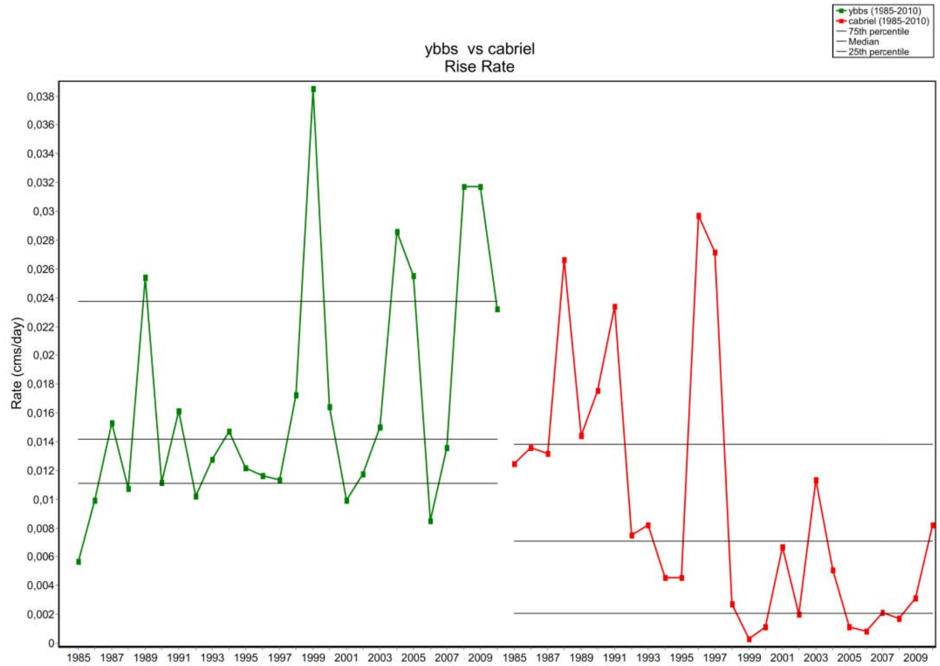


Figure 35: IHA: Rise rates compared

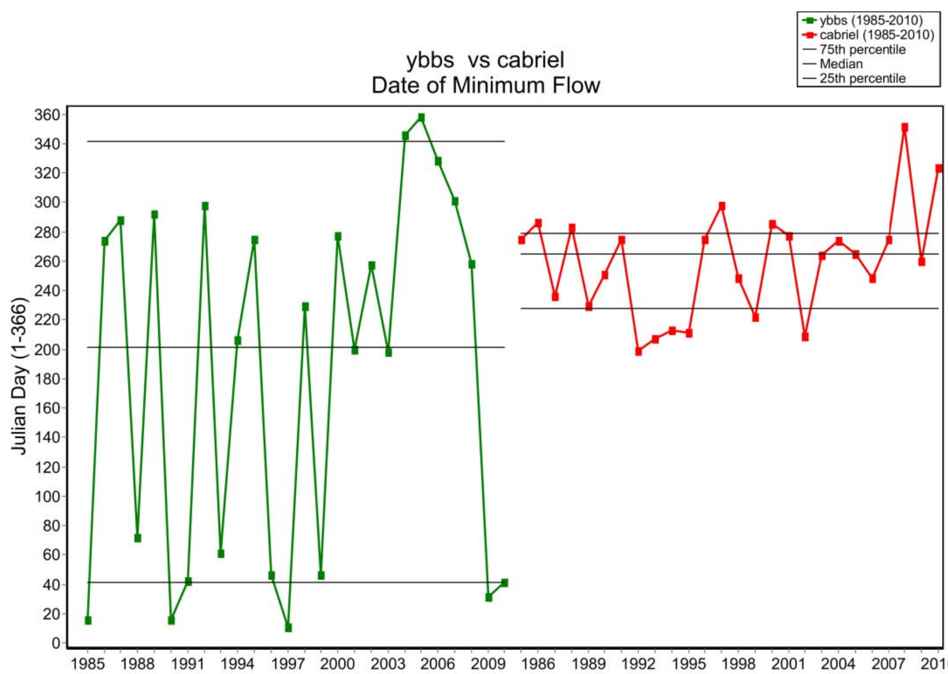


Figure 36: IHA: Date of minimum flow

HABITAT CLASSIFICATION SYSTEMS

Numerous mesohabitat classification systems exist. The one used by the US Forestry Service is also used by Francisco Martínez Capel, my host professor at UPV. The mesohabitat classification system used by MEM is slightly different to the one used at UPV. Therefore, each US forestry mesohabitat type used in the visual site inspection at river Cabriel has to be mapped to a corresponding MEM mesohabitat typ.

Table 7: Hierarchy of spatial river delineation used in this master thesis (PARASIEWICZ, P., 2007); modified

Spatial unit	*Description*
Study area, Investigation area	Encompasses entirely the investigated river length, preferably from the headwaters to the river mouth; it can also include the entire watershed
Reach or segment	River length with prevalent macro-morphological characteristics between larger tributaries, gradient discontinuities, etc.; (cascade, step pool, riffle-pool reach, …)
Sections	Portions with uniform hydromorphologic patterns and therefore a specific HMU mosaic
Representative site	The shortest portion of a section encompassing HMU distribution
Hydromorphologic units	Areas with consistent hydraulic patterns described by water velocity and depth

US Forest Service

USFS Pool habitat

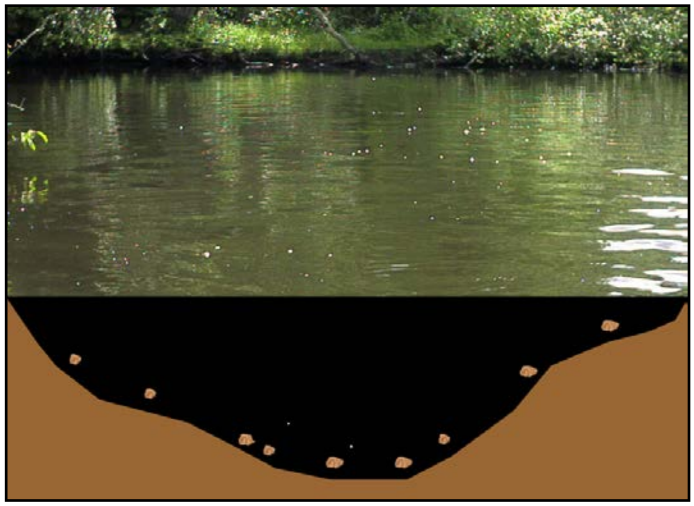


Figure 37: USFS Pool habitat

Pools are situated in areas with a gentle slope, are generally deep (> 0.6 m) and have flow velocities below the average of the reach. The substrate can be highly variable that often features accumulations of fine sediments. Typically, deeper pools have an asymmetric cross-section. In Spain, this mesohabitat is called "Poza". (DOLLOFF, C. A. et al. (1993) modified by SOARES COSTA, R. M. et al. (2008))

PASTERNACK, G. B. (2011) describes a pool as "deep water impounded by channel blockage or partial channel obstruction. Slow. Concave streambed shape".

USFS Backwater habitat

Figure 38: Backwater habitat (1)

Figure 39: Backwater habitat (2)

"Slack areas along channel margins, caused by eddies behind obstructions" (PARASIEWICZ, P., 2007).

USFS Run habitat

Figure 40: USFS run habitat

Runs refer to stream segments with a straight downstream sloping bed surface and relatively homogeneous bed material. (BUNTE, K. and Abt, S. R., 2001)

Runs are habitats within moderately sloping areas, with average depth and a moving water kernel with a steady surface. May also be defined as glide (see USFS Glide habitat , p. 68) but runs feature a higher water velocity and cross sections similar to glides, with depths approximately homogeneous in cross sections. Very easy to find in regulated rivers. (SOARES COSTA, R. M. et al., 2008)

Compared to low flow conditions on riffles, runs have deeper flows, and lower flow velocities. (BUNTE, K. and Abt, S. R., 2001)

USFS Riffle habitat

Figure 41: USFS riffle habitat (1)

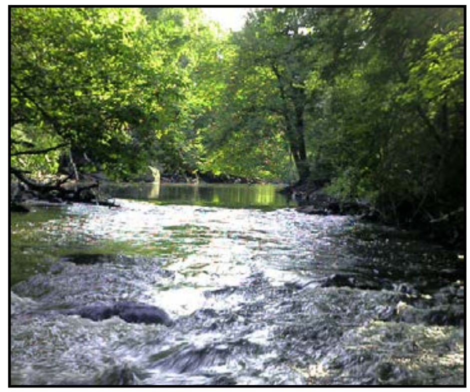


Figure 42: USFS riffle habitat (2)

Riffles are found in areas with moderate slopes, have shallow depths and feature surface ripples. Furthermore, average to high water velocities are present (> 0.4 m/s) and the bed substrate is dominated by gravel and fine gravel. The Spanish group calls this habitat "CORRIENTE". (SOARES COSTA, R. M. et al., 2008)

PARASIEWICZ, P. (2007) states riffles as "shallow stream reaches with moderate current velocity, some surface turbulence and higher gradient. Convex streambed shape".

USFS Rapid habitat

Figure 43: USFS rapid habitat (1)

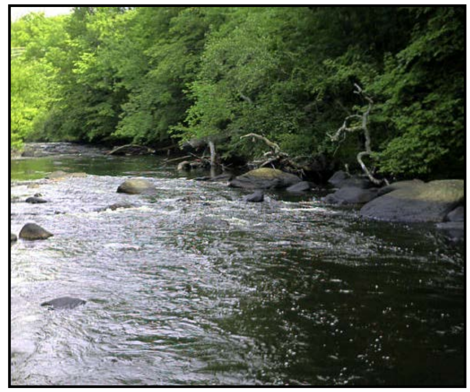


Figure 44: USFS rapid habitat (2)

Rapids have a steeper slope than riffles. The substrate shows cobbles abundantly, which stay out of the water surface. Supercritical flow (white waters) dominates this habitat type. A convex streambed shape is present. Rapids are found in areas with water depths less than the average of the reach and where the water velocity is higher than average. The substrate is thicker than in other units (generally boulders or greater). Sometimes small jumps can be found; therefore, its slope is high and dominated by white water, rough, with supercritical flow and frequent hydraulic jumps. Moreover, it is usually located in straight sections between two river bends. The Spanish group calls this habitat "RAPIDO". (SOARES COSTA, R. M. et al., 2008)

BUNTE, K. and Abt, S. R. (2001) further states that riffles might include a few nontransferable large particles protruding through low flow but these are not organized into transverse as they tend to be on rapids. Riffles have local gradients of less than 0.02, while rapids have local gradients of about 0.02-0.04.

USFS Glide habitat

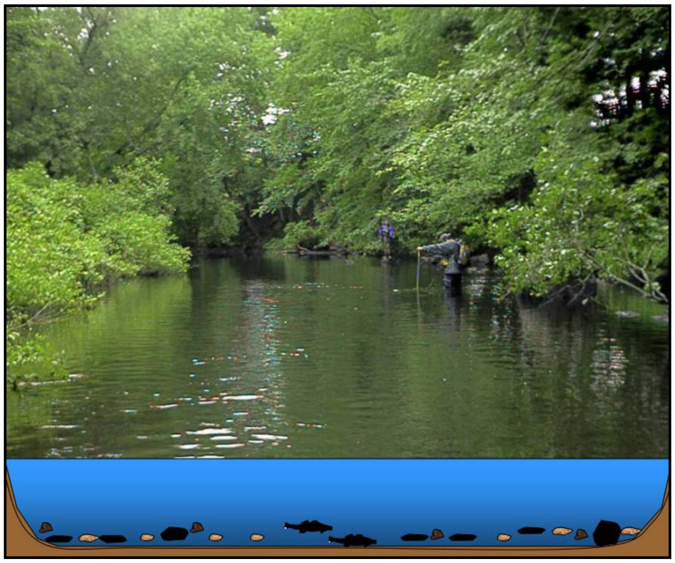


Figure 45: USFS glide habitat

PARASIEWICZ, P. (2007) describe this mesohabitat type as “moderately shallow stream channels with laminar flow, lacking pronounced turbulence. Flat streambed shape”. The term glide is sometimes used synonymously with run:

> “A glide may refer to the transitional area between the deep part of the pool and the crest of the riffle in which stream width increases while flow depth decreases …. This transitional zone may be termed pool-exit-slope …, especially if the stream gradient is sloping upward over this area. Bed material on the glide or pool exit slope tends to be less coarse than on the riffle crest. Church (1992) applies the term glide to a former pool that has been completely filled with sediment. If a differentiation is made between runs and glides, glides have deeper flows and lower flow velocities than runs and have a closer resemblance to pools than to riffles (i.e., a nearly horizontal water surface)”. (BUNTE, K. and Abt, S. R., 2001)

This mesohabitat is only mentioned for completeness. In this master thesis, no distinction between glide and run is made.

MEM habitat types

"The conceptual MEM-model allows differentiating between six different mesohabitat types (riffle, pool, shallow water, runs, fast runs and backwaters). These habitat types are well described by Parasiewicz, (2001), Bissonet al. (1981) and Dollof et al. (1993)." (HAUER, C. et al., 2009). The paper summarizes the habitats as follows:

Riffles: shallow stream reaches with moderate current velocity, some surface turbulence and higher gradient and a convex streambed shape.

Fast runs: uniform fast flowing stream channels.

Runs: monotone stream channels with well-developed thalweg. The streambed: is longitudinal flat and laterally concave shaped.

Pools: deep, slow or still region of water between riffle units. The flow type is scarcely perceptible flow.

Shallow waters: low water depth habitats with low-flow velocities.

Backwaters: quiet pools that accumulate on the side of a stream channel due to an obstruction or opposing current.

In his presentation HAUER, C. et al., (2009), categorizes the mesohabitats in three different energy classes: Riffles and fast runs are classified as high-energy habitats, whereas shallow water and backwater habitats as low energy and runs and pools as moderate energy habitats.

Due to the different classification systems and their overlapping habitat definitions, a one to one mapping is difficult. In this master thesis, the types are related as seen in table 8. Especially, the mapping of the habitat type fast run to rapid is problematic. Under a low flow condition we would map a rapid to a riffle but under the medium flow situation present at river Cabriel during visual site sampling it turned out that a mapping to fast run seems more appropriate. MEM was developed for riffle-pool reaches and therefore it does not consider the flat-bed rapid mesohabitat type.

Table 8: Mapping of habitat types

MEM classification	*US Forrest Service classification*
riffle	riffle
fast run	rapids
run	run/glide
pool	pool
shallow water	shallow water (not used)
backwater	backwater (not used)

Visual classification of mesohabitats

In general, identifying the different mesohabitat types in the field is not a difficult task. Problems arise if the mesohabitat shows features of distinctive mesohabitat classes. Trying to get consistent mesohabitat classifications over a long period can be quite a challenge because of changing assessment personal. Some useful advices for mesohabitat surveying are presented (SOARES COSTA, R. M. et al., 2008):

- Each mesohabitat unit should be having at least the length of the average width.
- The borderline between the different mesohabitat units usually occurs in hydraulic control sections (transitions from pool or glide to fast-water habitats) or by sudden changes in slope (transition from fast-water habitats to glide or pool).
- In river side arms where under the current conditions no water is flowing, only the presences of wood in the channel and erosion symptoms that may affect the channel in other flow conditions are registered.
- Channels, usually parallel, forking from the main channel or channels in a braided river system, where the circulating flows are less than in the main channel are called secondary river channels. Parallel channels are ordered from high to low flow and the percentage of discharge in each is estimated. When a channel has less than 10% of the estimated total flow, it is considered as not significant enough to separate the mesohabitat it may have and so it is treated as one unit.

Morphology of riffle-pool sequences

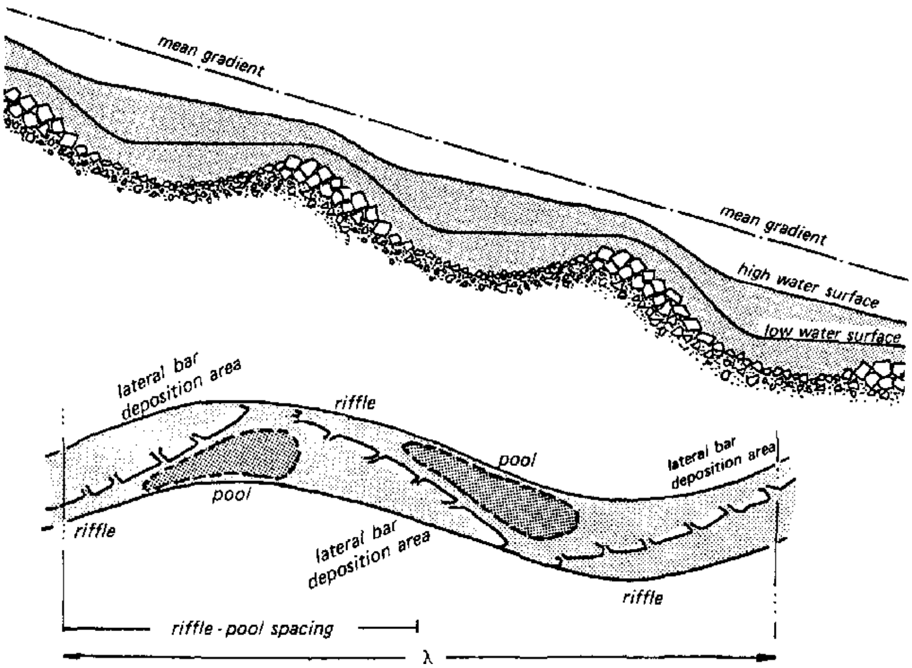


Figure 46: "Longitudinal (top) and plan view (bottom) of a riffle-pool sequence. The diagonal front lobe of the bar, the submerged part of which is the riffle." (BUNTE, K. and Abt, S. R., 2001)

The longitudinal stream profile along the thalweg of regular riffle-pool sequences is undulating; pools form topographic lows and riffle crests topographic highs (figure 46). In plan view, the morphological units pools, riffles, and bars are part of a single three-dimensional bedform called the pool-riffle-bar triplet. The bar unit for a straight, a meandering, and a braided stream is shown in figure 48. The upstream end of the bar unit is the pool that widens and shoals downstream until it terminates in an oblique shallow lobe front that extends diagonally across the stream. The downstream part of this front lobe is usually above the water line during low flows and forms the exposed bar. Farther upstream and towards the other side of the stream, the lobe front becomes inundated. The deepest and submerged part of the lobe front is the riffle crest. The bar unit extends over the length of two visible bars. Bar patterns that are repeated along opposite banks are called alternate bars in straight streams or riffle bars and point bars in meandering streams (figure 48, top and center). (BUNTE, K. and Abt, S. R., 2001)

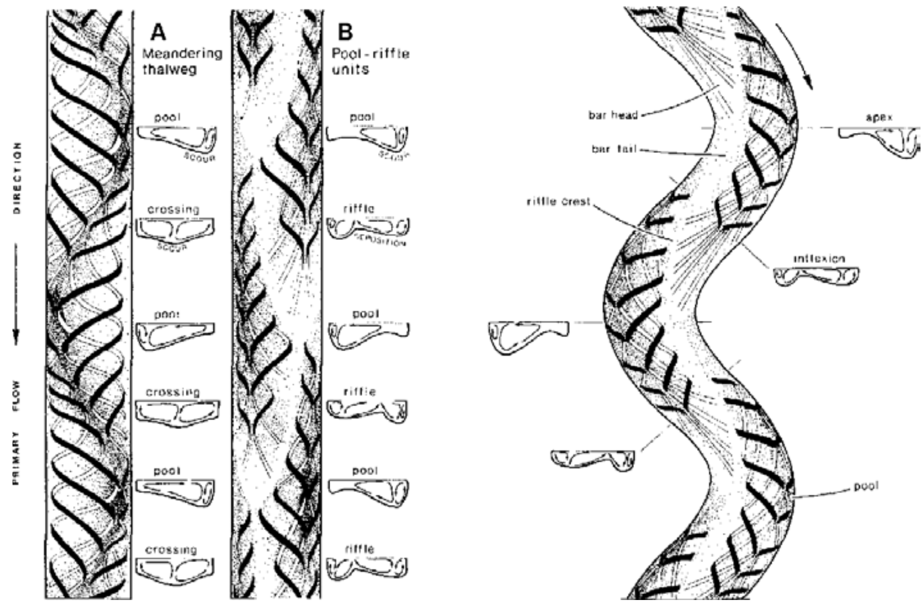


Figure 47: Model of helical flow in a straight stream with a meandering thalweg (left), in a straight stream with riffle-pool units (alternate bars), and in a meandering stream (BUNTE, K. and Abt, S. R., 2001)

Table 9: Morphological, hydraulic, and sedimentary features characteristic of riffles, pools and bars during low and high flows in streams with riffle-pool morphology. (BUNTE, K. and Abt, S. R., 2001)

Criterion	Riffles	Pool	Bar
Longitudinal form	ridge, or locally steep	depression, or locally flat	evenly inclined, but less steep than thalweg
Cross-section shape	± symmetrical or asymmetrical	asymmetrical	asymmetrical
Low flow situation:			
Flow depth	shallow	deep	mostly exposed
Flow velocity	relatively fast	relatively slow	n/a
Water surface	locally steep and	nearly horizontal,	n/a
Stream width	wide	narrow	n/a
Bed-material size	coarse scour lag	coarse scour lag, or deposit of fines	transition from coarse to fine
Surface fines	not likely	possible	possible
Spatial variability	------------------- lateral & longitudinal -----------------		
High flow situation:			
Flow depth	shallow	deep	shallow
Flow velocity	slow	fast	slow
Water surface	------------- evenly inclined over the reach -------------		
Stream width	-------------------- ± even over the reach --------------------		
Bed-material size	coarse deposit	coarse scour lag	transition from coarse to fine
Surface fines	not likely	not likely	possible

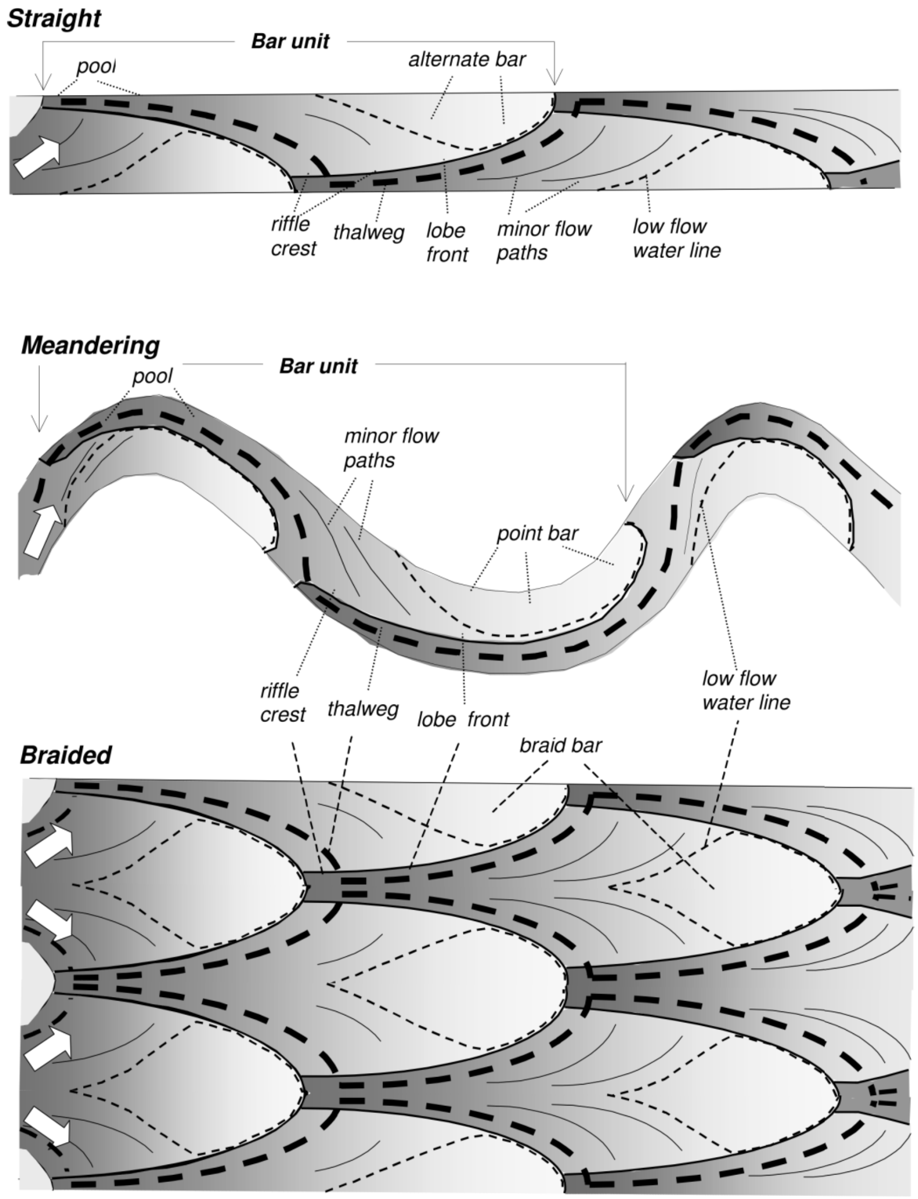


Figure 48: "Morphology of a bar unit in straight (top) and meandering (bottom) streams. Water depth is deepest in the areas with darkest shading, while areas of lightest shading are bars that are exposed during low flows." (BUNTE, K. and Abt, S. R., 2001)

To classify mesohabitats, the MEM software needs at least a depth averaged velocity value and a water depth value for each mesh/grid node. A bed shear stress value is optional; if it is missing, MEM is calculating the shear stress values. Above the, in the most cases, irregular mesh a regular grid of patches is overlaid and the mesh values (velocity, depth and bed shear stressed) are interpolated on the regular grid.

The first step in the determination of the mesohabitat class of a patch is the automatic computation of the numerical class for each of the three input parameters. The numerical class ranges from 1 (class a) to 5 (class e) for the flow velocity, from 5 (class f) to 1 (class j) for the water depth, and from 0 (class k) to 2 (class m) for the bed shear stress. MEM / HEM determines the respective numerical class by comparing the actual value for flow velocity, water depth or shear stress with the corresponding class boundaries that were defined during the mesohabitat calibration procedure. Afterwards the model evaluates the equation (HAUER, C., 2007)

$$MHC = [NC(v) + NC(d)] \times NC(t)$$

Equation 2: Mesohabitat classification value

, in which NC denotes the numerical class operator, v the flow velocity, d the water depth and t the bed shear stress, in order to obtain MHC, the mesohabitat class. (Mesohabitat Evaluation Model (MEM) Manual, 2010)

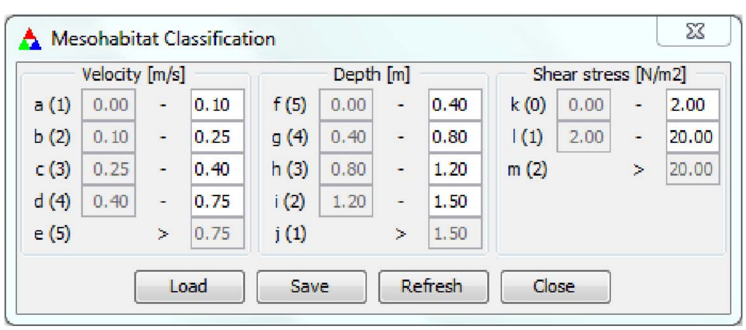


Figure 49: MEM Mesohabitat classification default parameters

Another possibility to represent these classes is through step functions (figure 50). Step functions are piecewise constant functions having only finitely many pieces.

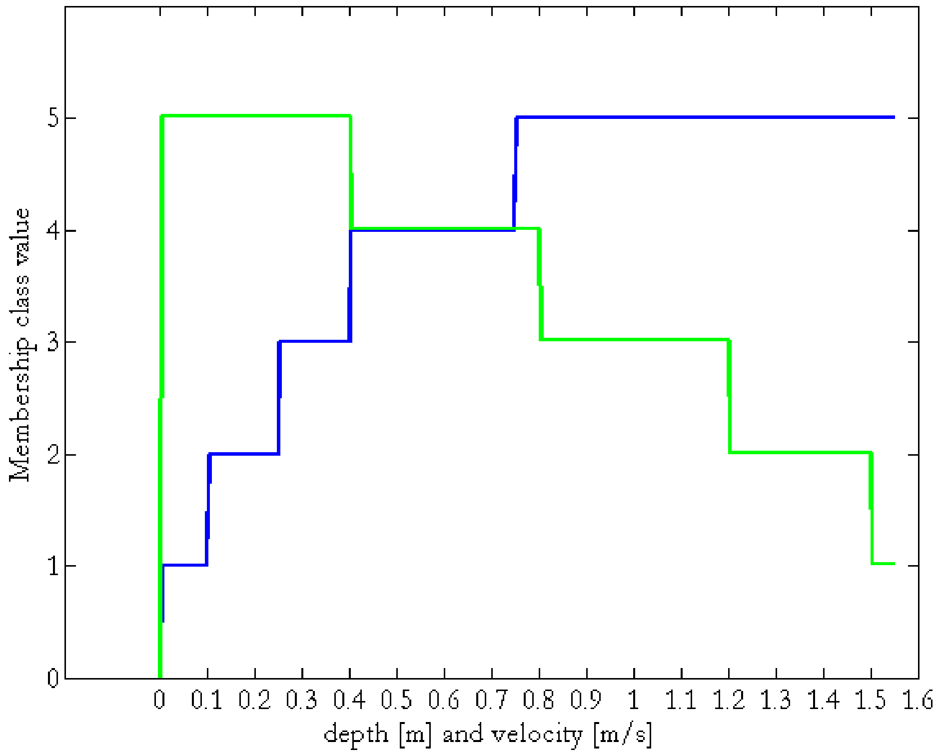


Figure 50: Class value step functions for depth (green) and velocity (blue) [default parameters see figure 49]

The result of this equation is a value for MHC in the range of 0 to 20. Mesohabitat types are then found according to table 10. If the shear stress class is fixed to one (shear stress between parameter l and m), the MHC values for velocity and depth can be plotted like in (figure 51).

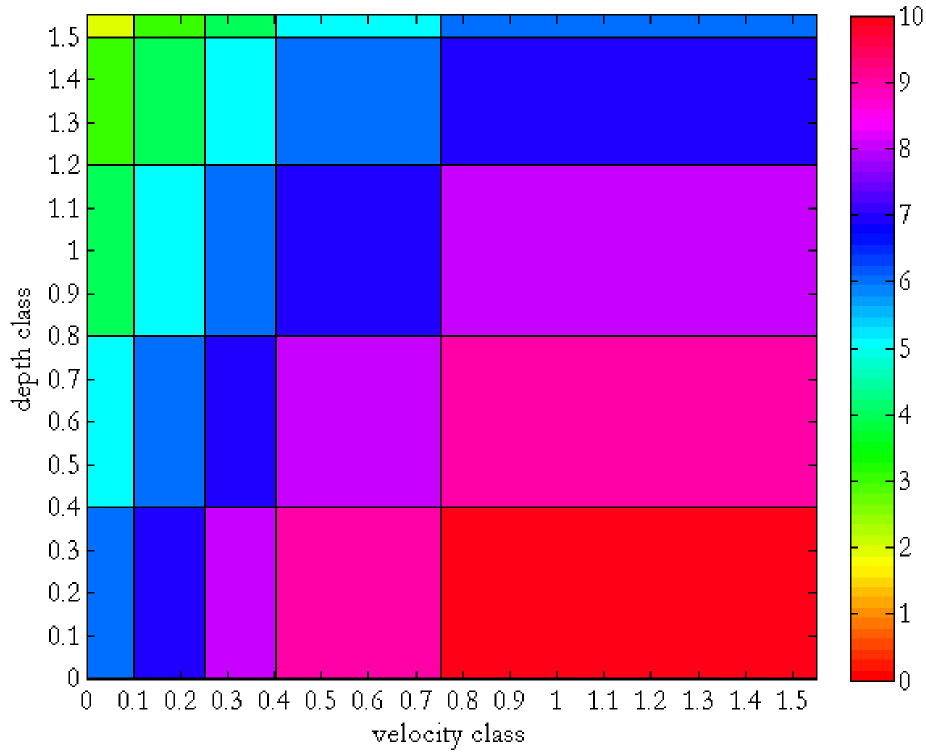


Figure 51: Resulting MHC values for shear stress class fixed to 1; depth classes are decreasing (e.g. 0-0.4: Nc(d) = 5), velocity class are increasing (e.g. 0-0.1: Nc(v) = 1); to yield to fast run, the highest velocity and the lowest depth is needed

Table 10: Meshabitattyp classification according to MHC values

Mesohabitat class range	Mesohabitat type
0	shallow water / backwater
1 - 4	pool
5 - 9	run
10 - 18	fast run
20	riffle

If MHC is equal to zero, a further step is required to distinguish between backwater and shallow water regions. This is done by evaluating the water depth: if the water depth is within class f(5), the mesohabitat is considered a shallow water region otherwise a backwater area. For the determination of areas, always a third of each triangle is added to the mesohabitat type of a mesh node in the case of different mesohabitat types for every node. (Mesohabitat Evaluation Model (MEM) Manual, 2010)

To sum up, the model is reliant on four velocity parameters (a,b,c and d), four depth parameters (f,g,h and i) and two shear stress parameters (k and l). HAUER, C. et al. (2009) outlines a calibration through sampling. Therefore, various Austrian river sections (n = 13), featuring clear variation in slope (0.0004–0.0132) and low flow discharge (0.05–915 m^3/s) in different river types (straight to meandering), where sampled. A comparative analysis of hydromorphological parameters (width, depth, velocity, froud number, thalweg and water surface elevation) formed the calibration basis. Two logarithmic correlations between minimum pool depth and mean daily low flow (D_{min}) and maximum pool depth and low flow (D_{max}) serve for calibration (tune pool related parameters with help of table 10 and table 14)

$$D_{min} = 0886 * \ln(Q) + 0.3412 \ \rightarrow R^2 = 0.95 \ \rightarrow (n = 13)$$

$$D_{max} = 0.1519 * \ln(Q) + 0.7497 \ \rightarrow R^2 = 0.91 \ \rightarrow (n = 13)$$

Calibration using a representative site

The shortest portion of a section encompassing HMU distribution is called a representative site. Mesohabitat units and therefore HMUs are easily visible in nature. Having done a site inspection at the representative site enables a mathematical optimization of the MEM classification parameters to adapt to the visual site estimation. At first, we have to prepare the input data for the optimization model. For each mesh point, velocity, depth, bed shear stress values and the visual estimated mesohabitat are needed. All information, except a value we call "MHC should be", which represents the optimization goal of the mesh nodes, can be exported in MEM or River2D. Table 11, shows the coordinates of the meshes, their depth, velocity and bed shear stress values, than the mesohabitat label of the last MEM classification run (not needed for optimization), the visual mesohabitat estimation and the "MHC should be" value. The "MHC should be" value reflects the arithmetic middle of the mesohabitat class range. To classify a pool, the MHC value has to be between one and four, hence the "MHC should be" is three. The optimization goal function can be expressed as:

$$Minimize\left(\sum_{i\ in\ Patches}(MHC_i - \text{"MHC should be"}_i)^2\right)$$

Equation 3: Mean squarred error optimization

Table 11: Calibration data needed for site calibration

			depth	vel	shear		visual estimation		MHC should be
X,N,19,11	Y,N,19,11	Z,N,19,11	H,N,19,11	U,N,19,11	T,N,19,11	Type,C,254	name,C,50	meso_desc,(	
612576	4422735	98.747	0.044	0.005	0	shallow_water	Pool	section 001;	3
612577	4422736	98.228	0.564	0.102	0.12	backwater	Pool	section 001;	3
612576	4422736	98.647	0.145	0.001	0	shallow_water	Pool	section 001;	3
612575	4422736	98.621	0.171	0.011	0	shallow_water	Pool	section 001;	3
612577	4422736	98.138	0.654	0.119	0.53	backwater	Pool	section 001;	3
612577	4422735	98.703	0.087	0.003	0	shallow_water	Pool	section 001;	3
612578	4422734	98.532	0.26	0.047	0.04	shallow_water	Pool	section 001;	3
612577	4422736	98.037	0.754	0.161	1.05	backwater	Pool	section 001;	3
612576	4422737	98.063	0.729	0.108	0.49	backwater	Pool	section 001;	3
612576	4422737	98.072	0.72	0.077	0.2	backwater	Pool	section 001;	3
612579	4422734	98.194	0.599	0.12	0.16	backwater	Pool	section 001;	3

The implementation of the optimization was done using the Microsoft's Solver Foundation, which consists of different solvers (linear programming problems, constraint satisfaction problems, mixed integer programming), an equation based modeling language called OML (Optimization Modeling Language), an API (Application Programming Interfaces) allowing programmers to talk to Solver Foundation services and a MS Excel based framework to develop and solve OML models (ERWIN, 2009). The MS Excel based framework was used in this master thesis.

One challenge of expressing the goal function was the transition of the class value step function to a continuous function usable for optimization. Therefore, trapezoidal class membership functions where employed

$$trapmf(x; a, b, c, d) = \max\left(min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right), 0\right)$$

Equation 4: Trapezoidal class membership function

where parameters are $a = b - q$ and $d = c + q$ and q is a small value to shape the trapezoid rectangularly. For the MEM default parameters, the following Matlab code forms the basis for figure 52, which visualizes depth and velocity class membership functions suitable for optimization.

```
q=0.05;

MHCdepth1 = 5.01*trapmf(dep, [0-q 0 f f+q]);
MHCdepth2 = 4.01*trapmf(dep, [f-q f g g+q]);
MHCdepth3 = 3.01*trapmf(dep, [g-q g h h+q]);
MHCdepth4 = 2.01*trapmf(dep, [h-q h i i+q]);
MHCdepth5 = 1.01*trapmf(dep, [i-q i 100 100+q]);

MHCvel1 = 1*trapmf(vel, [0-q 0 a a+q]);
MHCvel2 = 2*trapmf(vel, [a-q a b b+q]);
MHCvel3 = 3*trapmf(vel, [b-q b c c+q]);
MHCvel4 = 4*trapmf(vel, [c-q c d d+q]);
MHCvel5 = 5*trapmf(vel, [d-q d 100 100+q]);
```

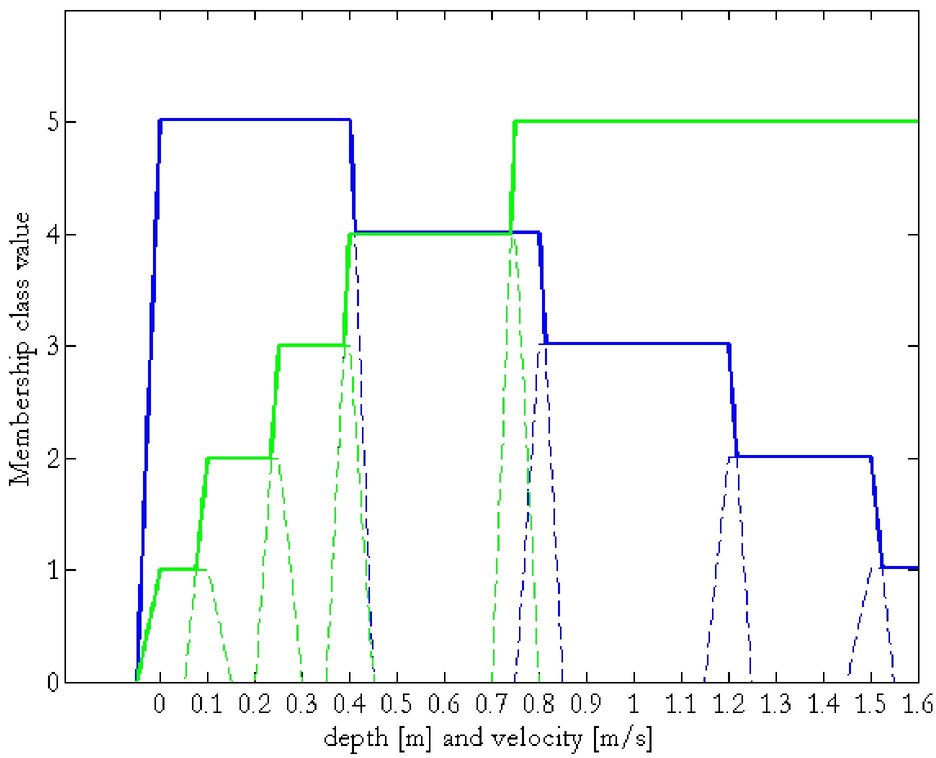


Figure 52: Continuous class value functions for depth (green) and velocity (blue) [default parameters see figure 49]

The whole MHC equation (equation 2) can be translated and incorporated into the goal function (equation 3), leading to the whole OML optimization model listened in Appendix code listening 17: Minimize mean squared error optimization.

The model for the representative site at River Cabriel consisting of ~3500 patches was solved in 7.5 min on a Core™ i5-2530 M CPU @ 2.50 GHZ dual core with 4 GB Ram running Win 7 64-Bit and revealed two local minimums:

First Run:

```
Model Name: DefaultModel
Capabilities Applied: NLP
Solve Time (ms): 445209
Total Time (ms): 447161
Solve Completion Status: LocalOptimal
Solver Selected: Microsoft.SolverFoundation.Solvers.HybridLocalSearchSolver
Directives:
Microsoft.SolverFoundation.Services.Directive
Step count: 29204.
Violation: 0
===Solution Details===
Goals:
Goal1: 116990.895903681

Decisions:
a: 0.00393805167049766
b: 0.00393805183082793
c: 0.0259818271518152
d: 4.00999999862483
f: 0.00999999979950026
g: 0.506000001295304
h: 0.633406492127514
i: 3.40905994638317
k: 0.00362337369003803
l: 32.3097520359207

[11.01.2014 12:32:51] Solve Complete
```

Successive runs:

```
===Solution Details===
Goals:
Goal1: 106938.075284369

Decisions:
a: 0.00400000047762091
b: 1.10721176864045
c: 3.71146652848438
d: 4.0099999997296
f: 0.00899999929421744
g: 0.487643161895109
h: 0.618712469884804
i: 0.619684733290785
k: 0.00161044462172724
l: 6.00
```

One drawback of this approach is that the goal function does not treat each mesohabitat type equally. If, for example the calculated MHC value is nine for a patch with type run ("MHC should be" = 7) and a second patch with a MHC value of 10 and type "fast run" ("MHC should be" = 14), the mean squared error of the patch "fast run" is greater than those of type "run", which leads to favor "fast run" habitats during optimization. One possible way to overcome this drawback could be the establishment of different goal functions for each habitat type; as an example for "fast run":

$$Minimize\left(\sum_{i\ in\ "Fast\ run"\ patches}\left(trapmf\big((MHC_i);0,10,18,28\big)*-1+10\right)^2\right)$$

Equation 5: Absolut difference optimization

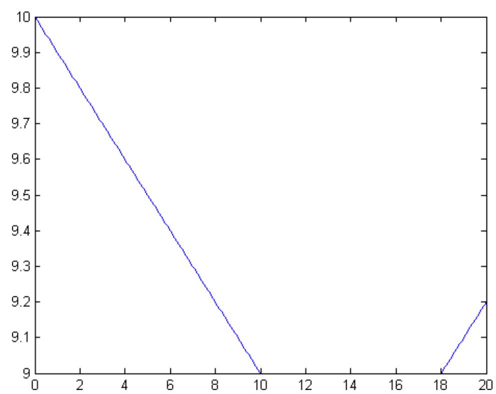


Figure 53: Function plot for equation 5

Another approach is to use generalized bell-shaped function to formulate the goal function:

$$Maximzie\left(\sum_{i\ in\ "Fast\ run"\ patches}\Big(gbellmf\big((MHC_i),5,14,15\big)\Big)\right)$$

$$for\ each\ mesohabitat\ typ$$

$$where\ gbellmf(x,a,b,c)=\frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}}$$

Equation 6 Goal definition using the generalize bell-shaped function as error estimator

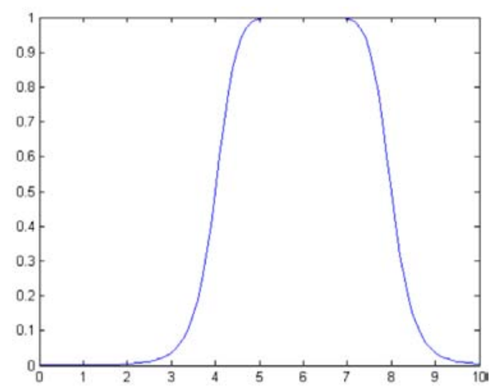


Figure 54:Generalized bell-shaped membership function; gbellmf(x,2,4,6)

This approach gives the advantages that the function argument of the bell function x, the MHC value only appears ones in the formula. Therefore, it is easy to substitute x for the MHC expression.

THALWEG DELINEATION

The deepest and fastest streamline down in a river is called thalweg, which helps to identify the type of mesohabitat. For example, a run-mesohabitat has a well-determined thalweg. Furthermore, in this thesis the thalweg is used as center of the streambed to derive a longitudinal altitude profile of the river reach. Because the thalweg was not surveyed in the fieldwork, the delineation of the thalweg was done like proposed in PASTERNACK, G. B. (2011). At first, a 20 cm grid export of the field velocity and depth in River2D was done. Next, these two raster datasets where multiplied and then a color scheme to clearly visualize the contiguous streamline segments that represent the thalweg was set. Last, a thalweg polyline was visually estimated. Therefore, the thalweg raster was displayed as color ramp (see figure 55) and shown as top layer above the terrain TIN. Furthermore, the thalweg polyline is used as linear reference system (ArcGIS: Create Route) which starts at the most upstream point. The longitudinal profile was derived by interpolating the altitude values from the streambed TIN on the thalweg polyline. For the water depths in the thalweg, a terrain irregular network (TIN) of the River2D export was created, and like before, used to interpolate values on the thalweg polyline. The section borders where stationed with the tool "Locate Features along Route".

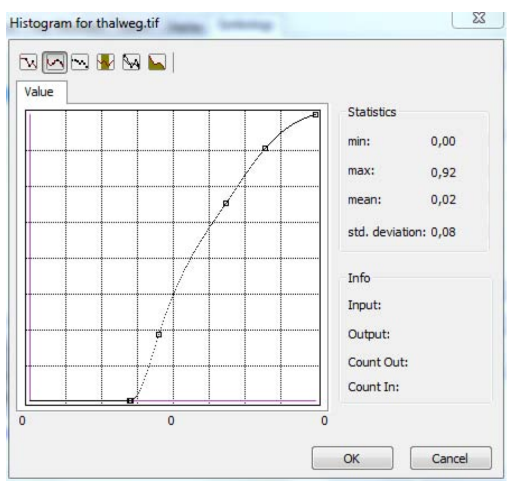


Figure 55: Thalweg raster visualization: a blue to violet color ramp was chosen; low values are visualized blue while higher ones are fast tending towards violet (the Y-axis identifies the position on the color ramp)

THE HYDRODYNAMIC 2D MODEL OF THE YBBS

Although a hydrodynamic 2D model of the river Ybbs is available, for reasons of comparison, it is advisable to use hydrodynamic 2D models of the same simulation software as MEM inputs. Especially, the bed shear stress value calculation could have an influence on the classification performance. The available hydrodynamic model for the Ybbs was created in HydroAS, a program that is calculating bed shear stress values explicitly. River2D, the simulation software used for the river Cabriel reach, does not calculate bed shear stress values; instead, MEM is calculating those using the flow velocity. For this reason, a River2D model was set up for the Ybbs too.

The digital terrain model was created out of sampled transects and afterwards condensed with interpolated profiles between the sampled ones. The final DTM used as input consists of regular scattered elevation data. The water surface elevation from the HydroAS model was used for calibration. The calibration procedure was as follows: First, the simulation was run with an estimated k-value (hydraulic resistance) for the total reach. The initial k-value was estimated by using the formula d_{90}/water height. Then, the result was assessed by calculating the water surfaces differences between the River2D model and the HydroAS model. In the next iteration, the k-value was adjusted accordingly. Finally, a k-value of 0.125 was elected as most suitable.

The quality of the result is plotted in figure 56. It shows a section with relatively high deviations especially behind boulders. The cause could be that the HydroAS mesh contains manually declared breaklines. However, these relatively small areas should not make any differences for the mesohabitat classification.

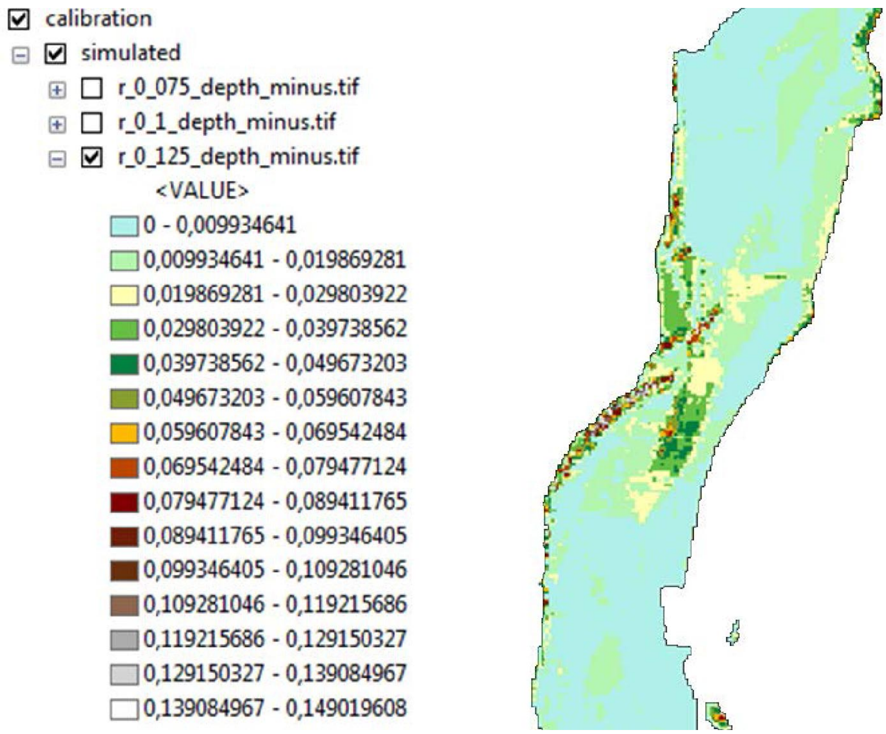


Figure 56: Water surface differences between the River2D model and the HydroAS model (reference).

RESULTS

RIVER CABRIEL: MESOHABITAT CLASSIFICATION AT MEAN FLOW

The visual mesohabitat classification in the river Cabriel was done at discharge 2.58 m^3/s (exceedance time 63 %), whereas the flows 2.78 m^3/s and 2.33 m^3/s were used for the MEM classification. The visual site inspection revealed pools, runs and fast runs. Shallow water and backwater habitats are categorically left over and no riffles are available at the survey site. Because of the absence of riffles, technically, this reach cannot serve as representative site.

Default parameter classification results and parameter deduction

Appendix map 2 states the result of the classification done by MEM. The dark polygons mark the visually estimated mesohabitat borders. The sections are numbered upstream beginning with section 001. Three mesohabitat classifications were conducted. One with default calibration parameters, a second one with calibration parameters derived from the results of the first run (called run 01, appendix map 6) and a third one with calibration parameters calculated using the described representative site calibration approach (called run 02, appendix map 7).The overall impression of the results is two folded. While shallow and backwater water mesohabitats are reasonable located at the banks, mesohabitats classified as pools are absent and areas classified as runs or rapids show now clear affinity to one class.

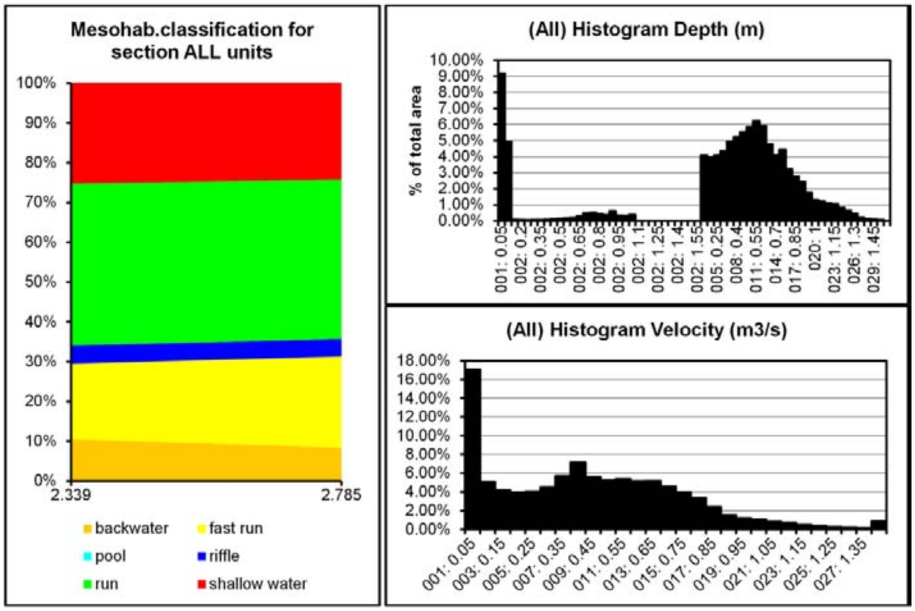


Figure 57: Mesohabitat classification results with default parameters and histograms for velocity and depth for the whole investigation reach.

The confusion matrix for the default classification run yields:

Table 12: Confusion matrix for default run

		Predicted			
		riffle	fast run	run	pool
Actual	riffle	0	0	0	0
	fast run	0	1	2	0
	run	0	1	1	0
	pool	0	0	2	0

Table 13: Confusion table for Fast Run

1 true positives (actual fast runs that were correctly classified as fast runs)	2 false negatives (fast runs that were incorrectly marked as other habitats)
1 false positives (other habitat classes incorrectly marked as fast run)	4 true negatives (all the remaining habitat classes correctly classified as non-fast runs)

To derive new calibration parameters it is necessary to investigate each section to find the reason for the bad prediction quality.

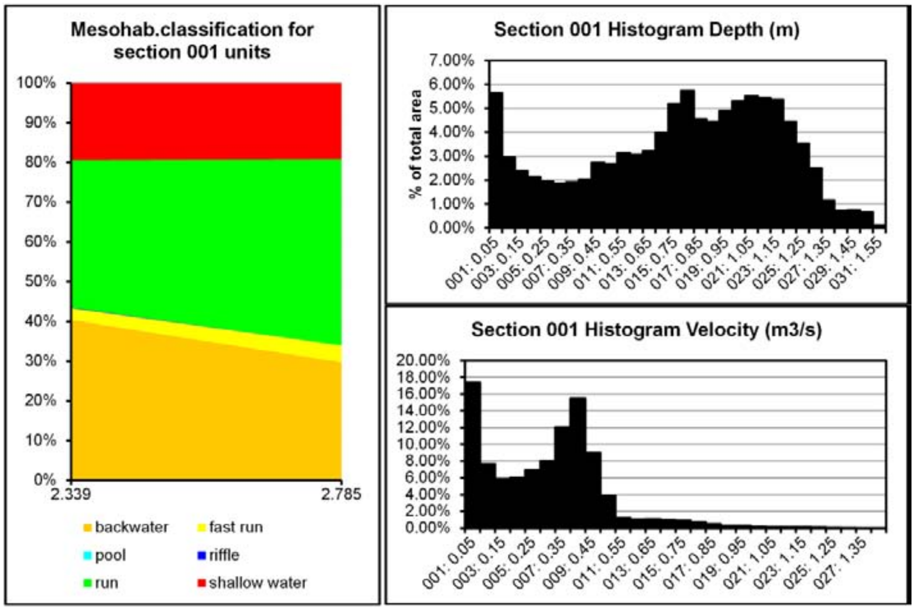


Figure 58: Mesohabitat classification results with default parameters and histograms for velocity and depth Section 001.

Table 14: MEM classification table expanded for bed shear stress classes l and m; default parameters

shear stress class l (1)			Depth	0 - 0.4	0.4 - 0.8	0.8 - 1.2	1.2 - 1.5	> 1.5
Shear stress	*l*	2-20 N/m2		*f*	*g*	*h*	*i*	*j*
	Velocity			**5**	**4**	**3**	**2**	**1**
	0-0.10	*a*	**1**	run	pool	pool	pool	pool
	0.10-0.25	*b*	**2**	run	run	run	pool	pool
	0.25-0.40	*c*	**3**	run	run	run	pool	pool
	0.4-0.75	*d*	**4**	run	run	run	run	pool
	>0.75	*e*	**5**	fast	run	run	run	run

shear stress class m (2)			Depth	0 - 0.4	0.4 - 0.8	0.8 - 1.2	1.2 - 1.5	> 1.5
Shear stress	m	> 20		*f*	*g*	*h*	*i*	*j*
	Velocity			**5**	**4**	**3**	**2**	**1**
	0 - 0.10	*a*	**1**	fast	run	run	pool	pool
	0.10 - 0.25	*b*	**2**	fast	fast	fast	run	pool
	0.25 - 0.40	*c*	**3**	fast	fast	fast	fast	run
	0.4 - 0.75	*d*	**4**	fast	fast	fast	fast	run
	> 0.75	*e*	**5**	riffle	fast	fast	fast	fast

The visual estimation classifies section 001 as pool. Unfortunately, the pool mesohabitat extends further downstream and the investigation area does not cover the whole mesohabitat. In pool-riffle reaches pools transit from run or fast run. In this case, a fast run is situated before the pool. So one can argue that the section 001 pool can be seen as a run transiting outside of the investigation area to pool, but due to flow velocity above the mean and water depths more than one meter, this section should be classified as pool. Moreover, the profile of the thalweg and of the surface water level displayed in appendix map 9 show impounded water and signs of a concave streambed shape. The misclassification happens due to shear stress values centered between 0-4 N/m^2 and wide areas with values lower than two, which in turn is explaining the high amount of backwater/shallow water in the results. In combination with velocities centered around 0.45 m^2/s and the high depth values, the classification results in a run or fast run habitat instead of a pool habitat. To classify this section as pool, velocity class borders are shifted until the class c starts at 0.4 m/s. (See Appendix map 3: Cabriel: Depth distribution for flow 2.78m^3/s, appendix map 4: cabriel: velocity distribution for flow 2.78m^3/s and appendix map 5: cabriel: bed shear stress distribution for flow 2.78 m^3/s)

Section 002 was classified by MEM primarily as run, fast run mesohabitat with some small riffle patches. The classification quality can be seen as good. The abiotic histograms state high shear stress values, depth values centered around 0.45 m and uniform velocity values between 0.35 – 0.75. For this section the threshold values seem adequate; maybe shifting the bed shear stress threshold to 25 N/m^2 would lead to more fast run patches. Especially in the downstream part of the section (see appendix map 9), the thalweg is not that distinctive visible, whereas the high velocity HMU can also be seen in the steepness of the water level.

The visual estimation of section 003 has yielded a run habitat, which fits to the MEM classification. The thalweg is well defined and continuous. The velocity and depth values are centered on 0.5. Overall, default MEM class alignment should be sufficient to recognize this mesohabitat type.

Section 004 also shows a positive correlation between the predicted and expected mesohabitat type. The rapid or fast run habitat features a well-defined convex shaped thalweg profile and, similar to section 002, a poor expressed thalweg downstream. The abiotic histogram presents depth values around 0.45 m and velocity values from 0.1 to 1.15 m/s; uniform until 1.15 m/s with a peak at 1 m/s.

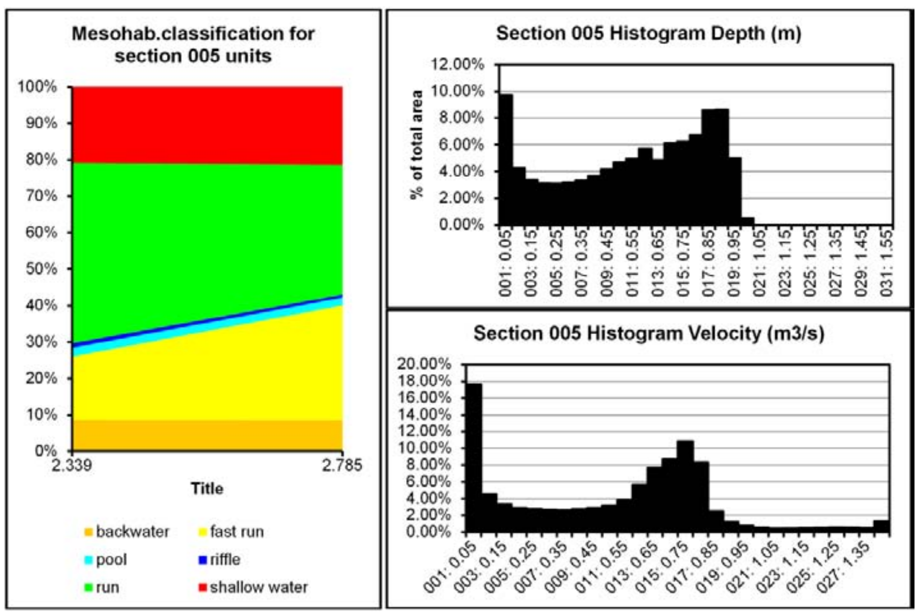


Figure 59: Section 005 mesohabitat classification results with default parameters and histograms for velocity and depth.

Section 005 was visually defined as run mesohabitat. The MEM yields similar, but as seen in figure 59, the amount of HMUs classified as fast run habitats strongly increases at higher discharge values. The MEM accommodates due to depth values higher than in section 004; centered around 0.8 m, which leads to fast run HMUs for high shear stress values. In general, this section has lower shear stress values than in section 0004 but still higher than 20 N/mm² (threshold between shear stress class l and m). It is recommendable to increase the shear stress threshold and reduce every depth class by 0.2 m to sharpen the classification quality. Moreover, the thalweg is well defined and shows a concave shape in the profile.

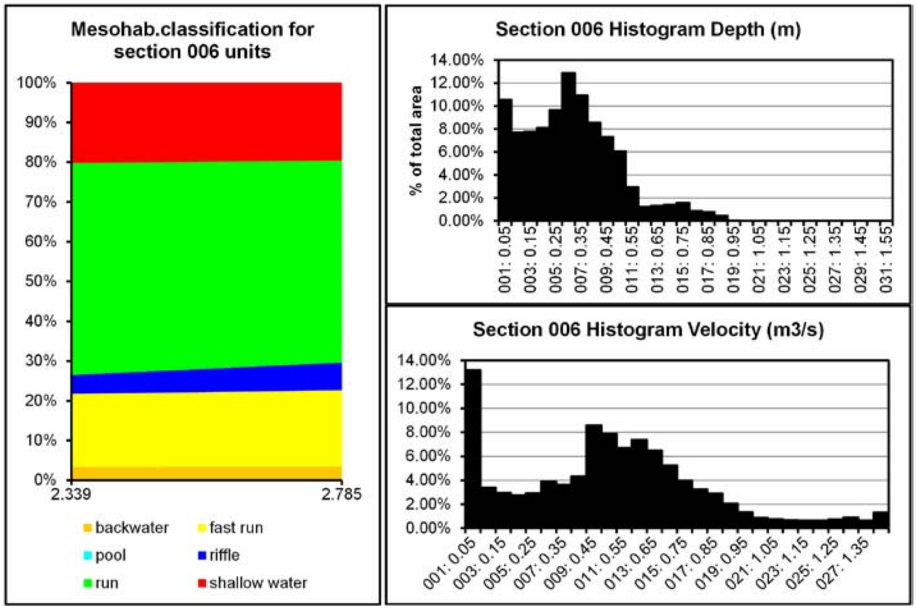


Figure 60: Mesohabitat classification results with default parameters and histograms for velocity and depth in section 006.

Section 006 was visually classified as fast run mesohabitat. The water surface is decreasing fast, indicating a high-energy mesohabitat class, whereas the thalweg profile shows a concave shaped form. In the MEM classification the run type dominates. The high velocity values do not lead to fast run, because of the low bed shear stress values; velocity values are centered at 0.8 m/s. A decrease of the shear stress thresholds between class l and m is not a feasible way because an increase was suggested before (section 002).

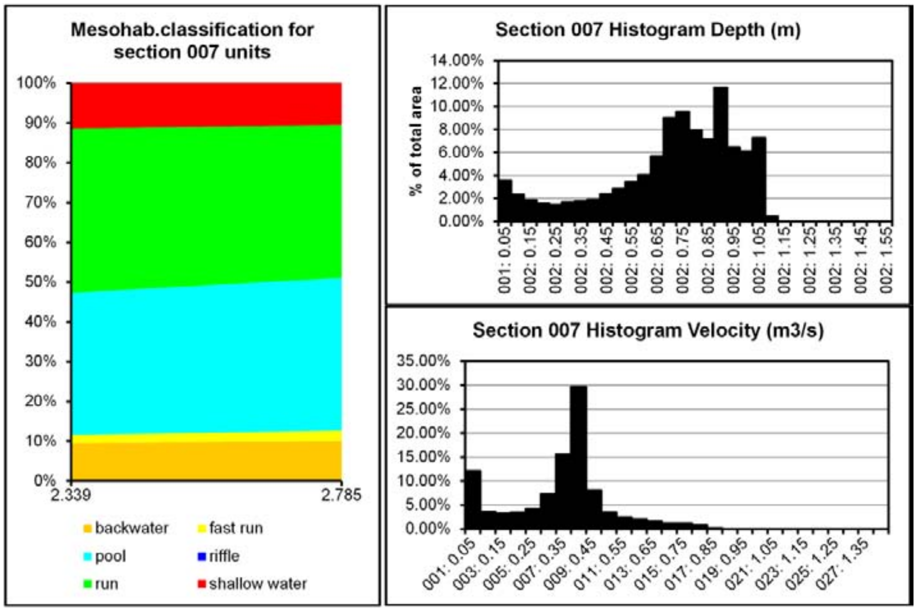


Figure 61: Mesohabitat classification results with default parameters and histograms for velocity and depth Section 007.

Section 007, the most upstream section, was visually classified as pool. Looking at the thalweg and water surface profile gives a similar impression (longitudinal concave shaped streambed and a nearly horizontal water surface level). The MEM classify this section as run, due to a peak at velocity 0.4 m/s and depth values around 0.9 m. Reducing the depth thresholds in that way that class i catches the center of the depth values (0.9 m) should give better classification results.

Derived parameters classification results

Table 15 states the new MEM calibration parameters for this reach as a conclusion from the MEM run with the default parameters. Further, in this thesis we will call the MEM classification run with derived parameters "run 01" to keep things clear.

Table 15: MEM calibration parameters derived from the abiotic classification; expanded for shear stress classes l and m (changed values marked bold); run 01

shear stress class l (1)			Depth	**0 - 0.2**	**0.2 - 0.6**	**0.6 - 0.8**	**0.9 - 1.1**	**> 1.1**
Shear stress	*l*	2-25 N/m²		*f*	*g*	*h*	*i*	*j*
	Velocity			**5**	**4**	**3**	**2**	**1**
	0-0.20	*a*	**1**	run	pool	pool	pool	pool
	0.20-0.40	*b*	**2**	run	run	run	pool	pool
	0.4-0.6	*c*	**3**	run	run	run	pool	pool
	0.6-0.75	*d*	**4**	run	run	run	run	pool
	>0.75	*e*	**5**	fast	run	run	run	run

shear stress class m (2)			Depth	**0 - 0.2**	**0.2 - 0.6**	**0.6 - 0.8**	**0.9 - 1.1**	**> 1.1**
Shear stress	*m*	> 25		*f*	*g*	*h*	*i*	*j*
	Velocity			**5**	**4**	**3**	**2**	**1**
	0-0.20	*a*	**1**	fast	run	run	pool	pool
	0.20-0.40	*b*	**2**	fast	fast	fast	run	pool
	0.4-0.6	*c*	**3**	fast	fast	fast	fast	run
	0.6-0.75	*d*	**4**	fast	fast	fast	fast	run
	>0.75	*e*	**5**	riffle	fast	fast	fast	fast

Table 16: Confusion matrix for run with derived calibration parameters (run 01)

		Predicted			
		riffle	fast run	run	pool
Actual	riffle	0	0	0	0
	fast run	0	2	1	0
	run	0	0	2	0
	pool	0	0	0	2

Table 17: Confusion table for pool mesohabitats (derived parameters; run 01)

1 true positives (actual pools that were correctly classified as pools)	1 false negatives (Pools that were incorrectly marked as other habitats)
0 false positives (other habitat classes incorrectly marked as pool)	5 true negatives (all the remaining habitat classes correctly classified as non-pools)

The pool mesohabitat class was the most problematic one in the MEM classification with zero true positives. Run 01 shows an improvement in the recognition of pool habitats (Appendix map 6: Cabriel: MEM Mesohabitat classification run 01 with derived parameters for flow 2.758 m^3/s). Table 17 states one true positive and, if the backwater mesohabitat is not taken into account, two true positive hits could be stated (see figure 62). Next, the differentiation between fast fun and run fails clearly in section 06 because of the absent of sufficient zones with high bed shear stress values, which are necessary for high-energy mesohabitats. According to the MEM approach, a classification as fast run in low shear stress areas (class l) is only possible with the combination of the highest velocity class and the lowest depth class.

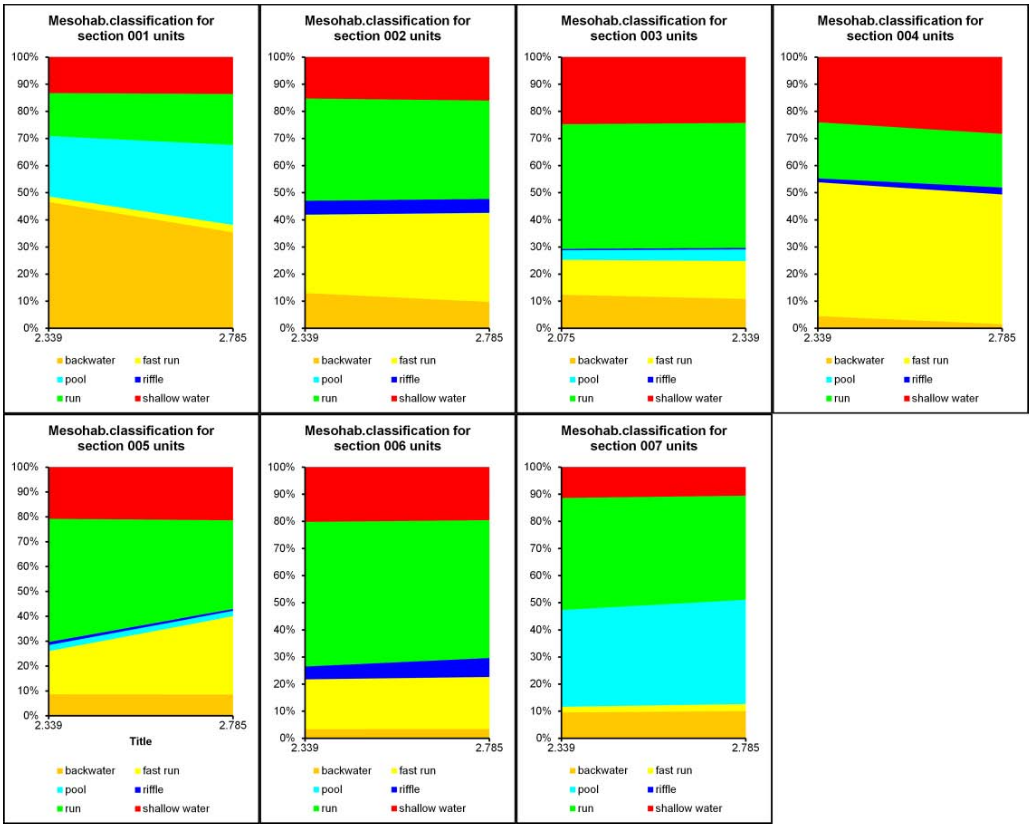


Figure 62: Run 01 mesohabitat distribution (visual estimations beginning with section 001: pool, rapid, run, rapid, run, rapid and pool)

Representative site calibration classification results

The first result of the optimization was given up in favor of the successive one:

```
Decisions:
a: 0.00  b: 1.11  c: 3.71  d: 4.01
f: 0.01  g: 0.49  h: 0.62  i: 0.62
k: 0.00  l: 6.00
```

Table 18: Confusion matrix for run using site calibration (optimization) (run 01)

		Predicted			
		riffle	fast run	run	pool
Actual	riffle	0	0	0	0
	fast run	0	3	0	0
	run	0	0	2	0
	pool	0	0	0	2

As can be seen in appendix map 7, figure 63 and table 18 the results encourage to invest more research in this calibration approach. All mesohabitat types are predicted according to the visual estimation and the difference between pools and runs (fast runs) are clearly visible in sections 001 and 007.

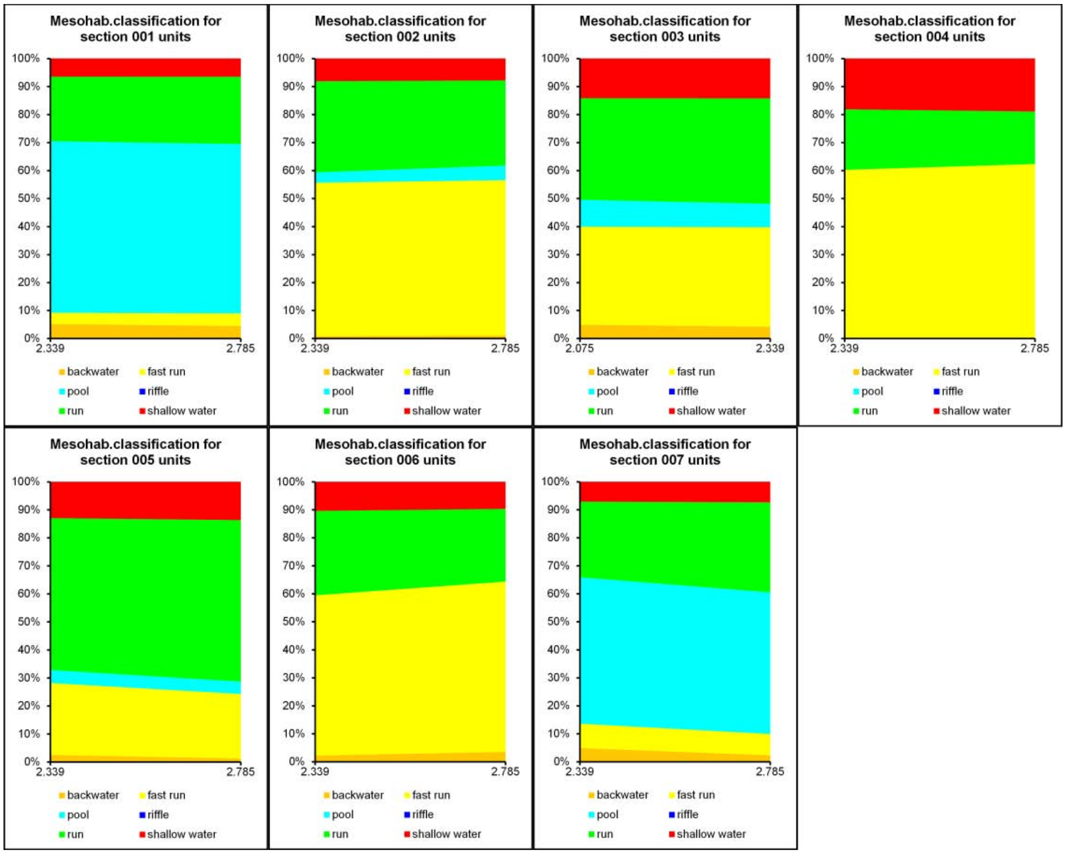


Figure 63: Run 02 mesohabitat distribution (visual estimations beginning with section 001: pool, rapid, run, rapid, run, rapid, pool)

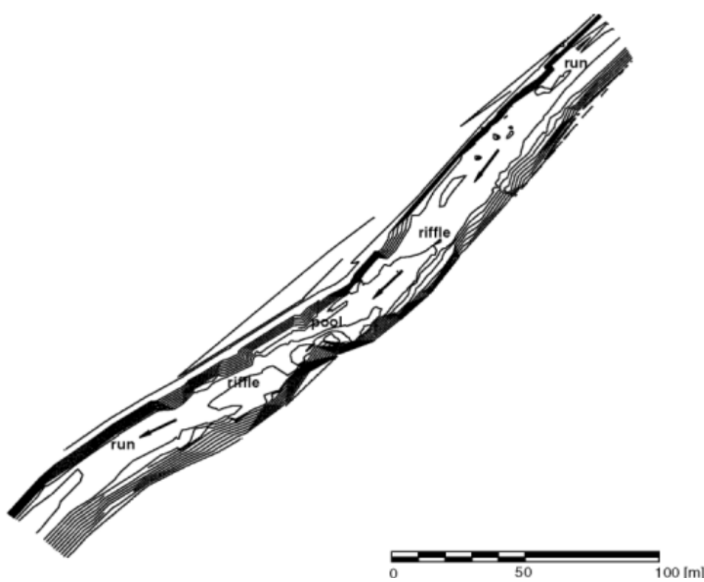


Figure 64: Sampled mesohabitats at river Ybbs; no borders were sampled

The visual mesohabitat classification in the Ybbs was done at a discharge of 1.64 m^3/s (exceedance time 75%). The visual site inspection only considered pools, runs and riffles. Shallow water and backwater habitat were categorically left over and no fast runs were available at the survey site. In contrast to Cabriel, mesohabitat borders were not sampled (figure 64).

Deduction of mesohabitats from abiotic data

Another aim of the master thesis is to evaluate if it is possible to recognize the predominant mesohabitat type by using only abiotic data. The approach undertaken was quite simple: First, the reach was visually classified into zones of different velocity and depth classes (high, med and low). Bed shear stress was categorized into two classes (high and low) only (Appendix map 15: Ybbs: Deduction of mesohabitats). In the most cases the intersections of those zones form the mesohabitat extent. Next, all available abiotic information was taken into account to deduct the mesohabitat type.

Available abiotic information:

Element	Deductible information for mesohabitat classification
water surface, thalweg elevation profile	thalweg steepness, water depth along thalweg, impoundments, irregularities in the water surface, convex or concave thalweg (~channel) shape
velocity times depth plot (raster operation)	intensity of discharge, thalweg
terrain contour lines	channel shape, channel or cross section homogeneity
velocity plot	velocity distribution and uniformity, velocity kernels
depth plots	~ 2D channel geometry, wetted with, bars
bed shear stress plot	possible instable areas

Deducted mesohabitat units:

Starting upstream at section 06 (lowest red polygon in the plot on the right side) to section 01:

Section 06: avg. depth values, slow moving waters and low bed shear stresses; thalweg indicates a slightly concave shape →**estimated run**

Section 05: shallow waters, fast moving, non-uniform velocity distribution, steepness visible in water surface - thalweg diagram, terrain contour lines do not indicate a symmetric channel, irregular water surface and thalweg →**estimated riffle**

Section 04: deep, slow moving, impounding clearly visible in water surface - thalweg diagram. →**estimated pool**

Section 03: shallow and fast flowing, steepness not visible in thalweg diagram; irregular thalweg and water surface, no channel visible in terrain contours →**estimated riffle**

Section 02: avg. velocity values, depth distribution and terrain contour lines indicate channel, smooth thalweg and water surface →**estimated run**

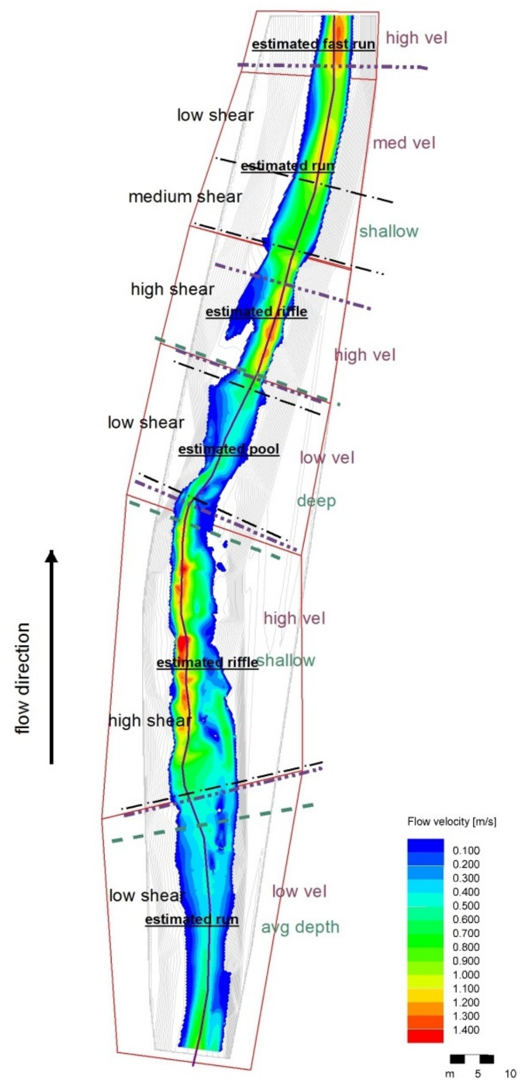


Figure 65: Excerpt of Appendix Map 7: Ybbs: Deduction of mesohabitats

Section 01: fast moving, deep, depth distribution and terrain contour lines indicate channel, flat streambed, borderline to preceding HMU ambiguous →**estimated fast run**

Table 19: Mesohabitat deduction: comparison of target and actual

Section	Deducted as	Target	Comments
section 06	run	run	
section 05	riffle	riffle	
section 04	pool	pool	
section 03	riffle	riffle	
section 02	run	run	
section 01	fast run	part of prev. run	split in run and fast run because of buckle in the thalweg profile

Mesohabitat classification results with sampled parameters

Appendix map 2 states the result of the classification done by MEM. The expectation was that MEM performs well at this river reach, due to the use of sampled calibration parameters and because MEM was developed for the application at that river type. Contrary to the expectation, the confusion matrix (table 20) shows only one true positive hit. Even, if the downstream fast run habitat would be valued as run, the two riffles classified as run and the pool classified as run, leaves an unsatisfied impression of the results.

Table 20: Confusion matrix for classification run with sampled parameters

		Predicted			
		riffle	fast run	run	pool
Actual	riffle	0	0	2	0
	fast run[6]	0	0	1[6]	0
	run	1	0	1	0
	pool	0	0	1	0

There are several possible explanations for this result. One is that the river morphology is laterally more distinctive than longitudinal (e.g. appendix map 13, section 5; D9 to D11: riffle run coexistence). Another possible explanation is that the different mesohabitat sections, especially sections classified as riffle or fast run habitats, lack of a significant distinct abiotic profile:

[6] Section 06

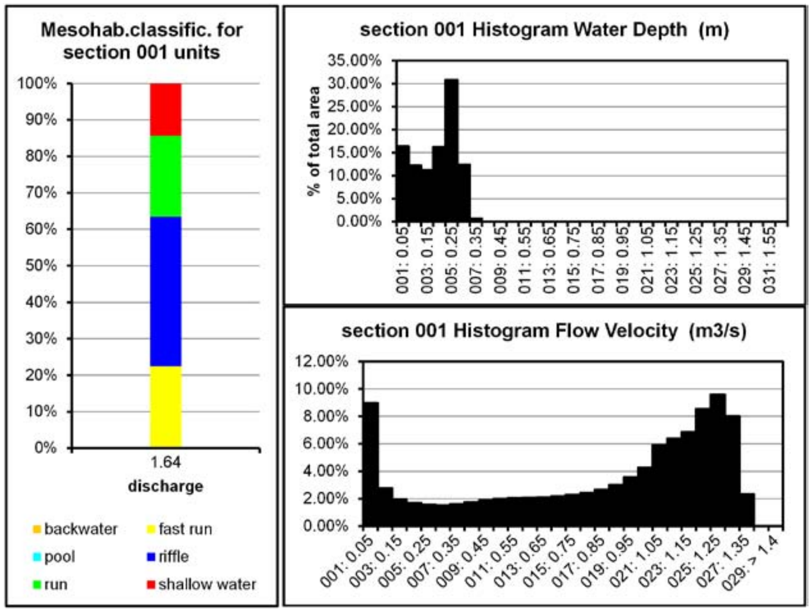


Figure 66: Section 01: Mesohabitat classification results and histograms for velocity and depth; section deducted as fast run but visual classified as run.

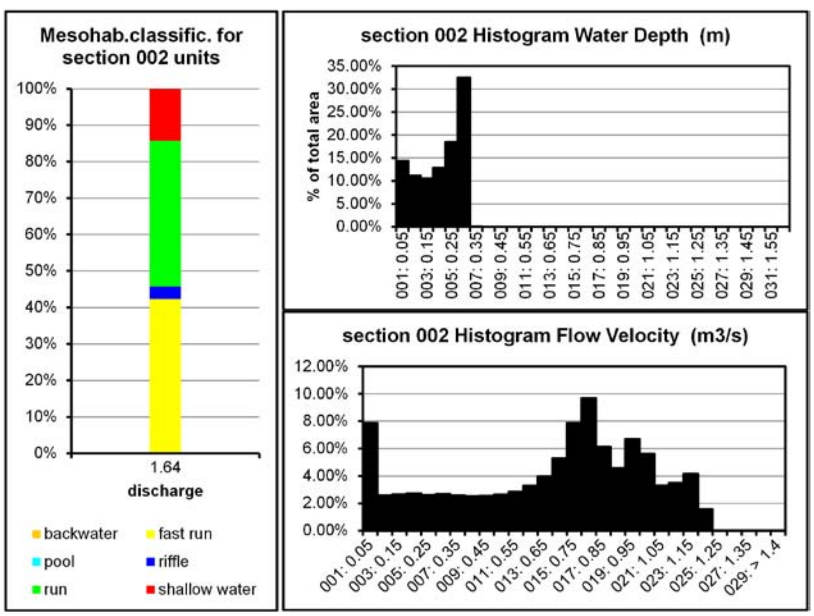


Figure 67: Section 02: Mesohabitat classification results and histograms for velocity and depth; visual classified as run

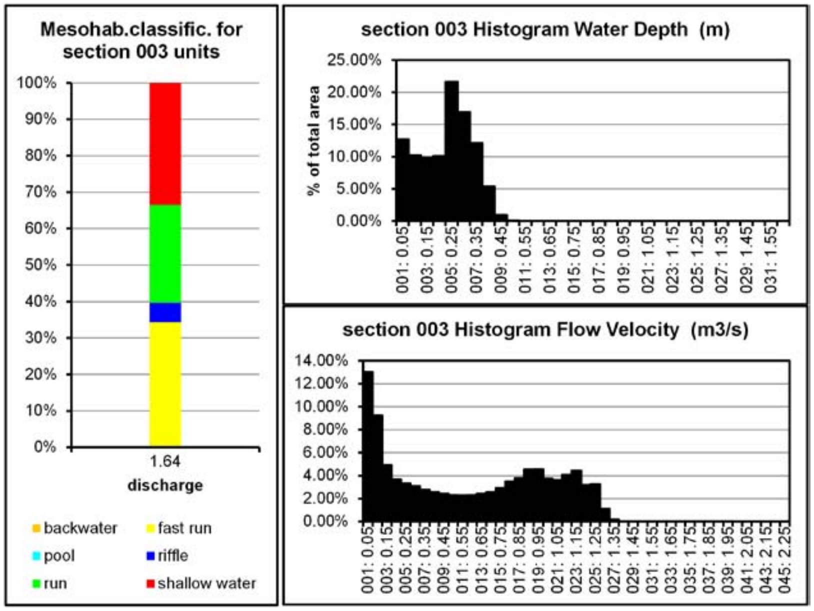


Figure 68: Section 03: Mesohabitat classification results and histograms for velocity and depth but visual classified as riffle

Figure 66 and figure 67 show two visual classified run habitats. It can be clearly seen that, despite it was classified as run habitat during fieldwork, they features two velocity kernels, which underline the separation into a run and fast run habitat during mesohabitat deduction. This is not a problem if two deducted sections would have been delineated as one large run mesohabitat, because the areas classified as run would clearly outweigh the complete different riffle habitat type. Nevertheless, if combined, fast run would be the dominant mesohabitat type (summed mesohabitat area dominates; cannot be seen in figures). There are many contradictions in the abiotic histograms that it is impossible for MEM to show the predominant mesohabitat type. One is that the section 06 and 05 have overall shallower areas than the riffle in section 05. Moreover, the water is moving faster than in the riffle area. This is contradicting the definition. MEM needs high bed shear stress values (for River2D models, bed shear stress is a function of the velocity) and low water depths to classify areas as riffle.

The above explanation should also justify why the representing site calibration method developed is not working in this case. Both, the calibration method using the mean squared error goal and the generalized bell-shaped function goal do not yielded meaningful results. Moreover, to overcome the influence of larger mesohabitat areas distorting the goal function, area weighted approaches were investigated, too.

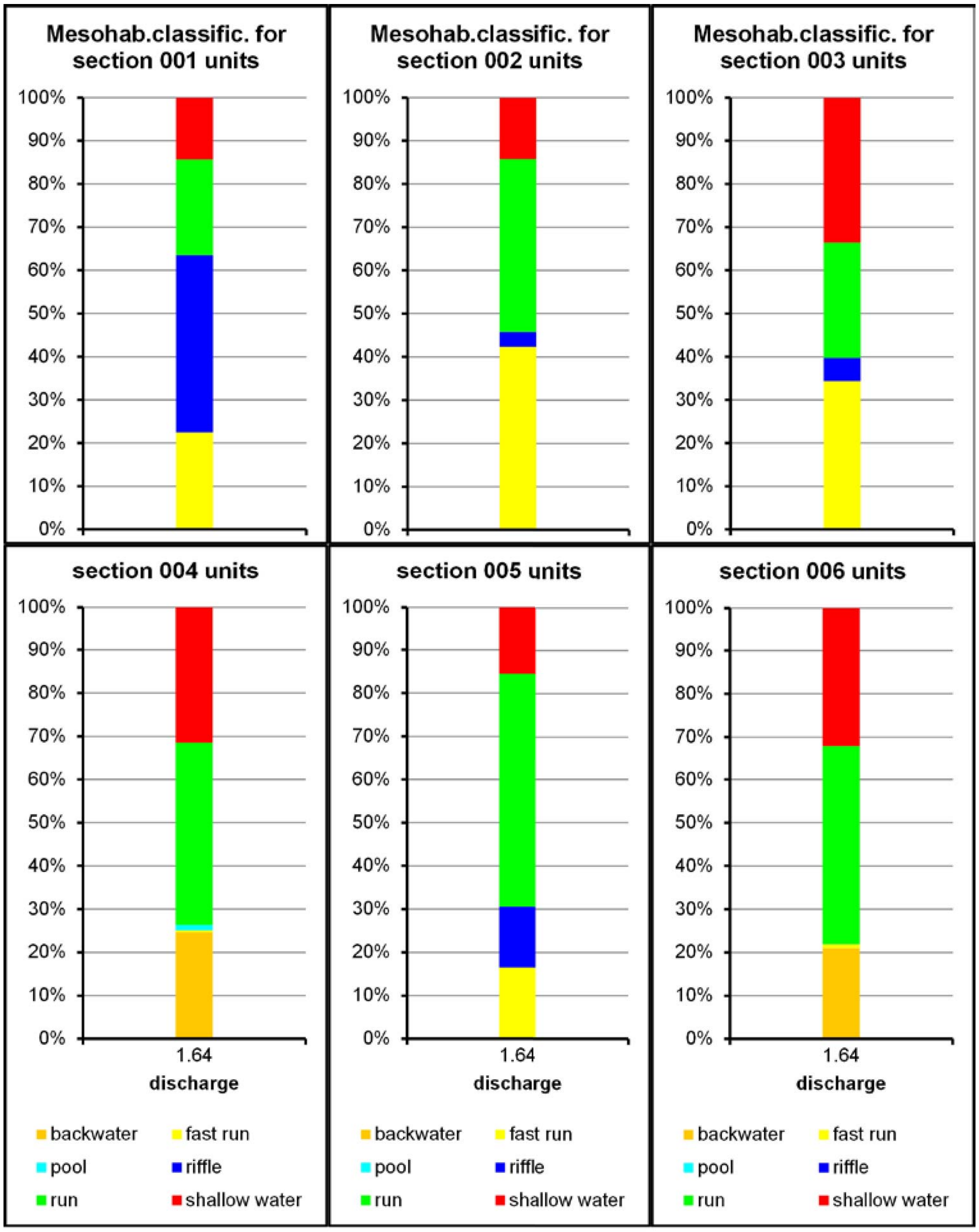


Figure 69: Mesohabitat distribution: visually sampled section 03 to 06: riffle, pool, riffle, run and section 01-02 is run [abiotic information showed run and fast run]

DISCUSSION

In recent years, there has been an increasing interest in mesohabitat modeling over microhabitat modeling. The scientific critique of microhabitat modeling (p. 37ff) is mainly concerning the difficulties in describing the rivers (representation in the model), the habitat suitability curves and the biological meaning of the weighted usable area (WUA) value. This encouraged the development and application of mesohabitat modeling methodologies. While they do not solve all of the weaknesses of microhabitat modeling, for example the biological meaning of indices like usable mesohabitat area (UMA) and mesohabitat suitability index (MSI), they do provide solutions in the problem field of river representation and in the linkage to biological models. Representing the river in mesohabitats enables biological models to use a variety of different input parameters like the mesohabitat typ. The mesohabitat type itself may include more valuable information about a habitat than a bunch of velocity and depth values. The type provides a description about the habitat structure and an integrative or averaged view on a habitat on a higher spatial scale. Leveraging this averaging effect of working on a higher spatial scale may overcome problems of microhabitat modeling, such as the transferability of HSC or coping with the nature's inaccuracy in general. Turning to the linkage to biological models, the MEM approach is quite similar to common microhabitat methodologies. As a kind of estimator for fish abundance, the UMA value is the product of available mesohabitat area times a suitability curve for the target fish species. It links an expert driven or evidence based preference value to available type specific habitat area, but, in contrast to microhabitat modeling, this approach can incorporate the average effect in the preference value. Whereas MEM only takes the area and habitat type as input for its biological model, more sophisticated ones exists. The one described in MOUTON, A.M. et al. (2011) takes biotic and abiotic parameters like habitat coverage (flora dependent) and habitat width (abiotic) into account. It represents the river through mesohabitat units that have at least the length of the average width (see p. 70). On the contrary, MEM uses smaller patches. The question remains, which representation is more appropriate. Is a strict sequential alignment of mesohabitats justifiable in braided river systems? Which properties are needed to describe mesohabitats? Are abiotic properties reliable indicators for mesohabitat classification? The last question is one investigated in this master thesis and brings us to the master thesis's aims. Is it possible to use the MEM mesohabitat classification approach to deduce a sequential mesohabitat unit representation?

The results of the master thesis project show that it is possible, nevertheless, success is river type dependent. Especially, the river Cabriel shows a well-pronounced straight character, where in each visually sampled section the MEM-classified target HMUs overweigh all others (table 18 and appendix map 7). Taken all the results together, one can identify two key elements for a successfully automatic detection of the predominant mesohabitat type: First, river representation: In the beginning of the discussion, the question was raised which representation (patches or units) is the best for biological models. That would be interesting to compare, but at first sight, I would favor a unit representation (mesohabitat type plus additional properties) over a patch representation (mesohabitat type and area) for biological models. On the other hand, a patch representation shows its strengths in meandering or breaded river types with side-by-side mesohabitat (see morphology of riffle-pool sequences on p. 71ff). For example in river inventory studies, to record the hydromorphological change after a flood, the change in area of specific mesohabitat types may be sufficient. The second key element is calibration: The default MEM parameters did not work out. A manual calibration, like deducted in this master thesis, is not as trivial as it may look at first sight. Abiotic histograms for each visually sampled sections help in adjusting the parameters and reveal if the MEM mesohabitat classification approach works. Different abiotic profiles for each mesohabitat type (seen in the abiotic histograms) have to be present. Otherwise, no predominant habitat can be stated for the visually classified section. That is also the reason why the classification at the river Ybbs fails. The deducted mesohabitat sections do not show sufficient distinctive abiotic characteristics. The premise to have only one non-overlapping habitat type along the thalweg does not work out at the river Ybbs and therefore the automatic calibration approach presented is not applicable. In general, the automatic calibration approach undertaken encourages for further testing. A true visually sampled representative site is needed as calibration input to test if, for example, the calculated parameter set is working in not sampled areas too. Addressing now another project aim: the manual deduction of mesohabitat type and borders: The methodology used states how abiotic information available in the terrain model or thalweg vs water surface profile plots help in finding the right mesohabitat type (see section deduction of mesohabitats from abiotic data, p. 99).

At this point, I would like to propose new features for the MEM classification approach to improve quality: the inclusion of abiotic information beyond water depth, velocity and bed shear stress, which is already available. Taking into account some sort of impoundment indicator could enhance classification quality. Maybe some kind of GIS "Fill Sink" operation can reveal impoundments in the streambed. For example, in section 04 at river Ybbs (see appendix map 13 and appendix map 15) the clear impoundment visible in the thalweg water surface plot could solve the problem that only a small area is recognized as pool habitat in this section. Furthermore, incorporating some kind of channel form indicator could be valuable for classifying larger homogenous areas of the same mesohabitat type. This may lead to less scattered patches of different mesohabitats in definite sections and may allow the inclusion of habitat area that normally would not be included due to their improper hydraulic conditions. Another nice to have feature could be the presented automatic calibration approach.

The nowadays-limiting factor for applying MEM or 2D mesohabitat modeling in general to a whole river is that a digital terrain model and a 2D hydraulic simulation are needed. Advances in hydrography could be a remedy. Traditionally, digital terrain models of the riverbed are created cost effective by manual surveying transects or by using echo sounding, a type of SONAR. The application of high resolution terrestrial-aquatic LIDAR could make a broader application of mesohabitat modeling for monitoring possible (MCKEAN, J., 2010). Sediment mass budgets and habitat availability could be brought together on catchment scale. An intensification of the use of mesohabitat models is likely due to soon available economic high quality terrain data, due to the raising pressures on rivers caused by the energy transition towards renewable energy sources and the higher variability of water availability provoked by climate change.

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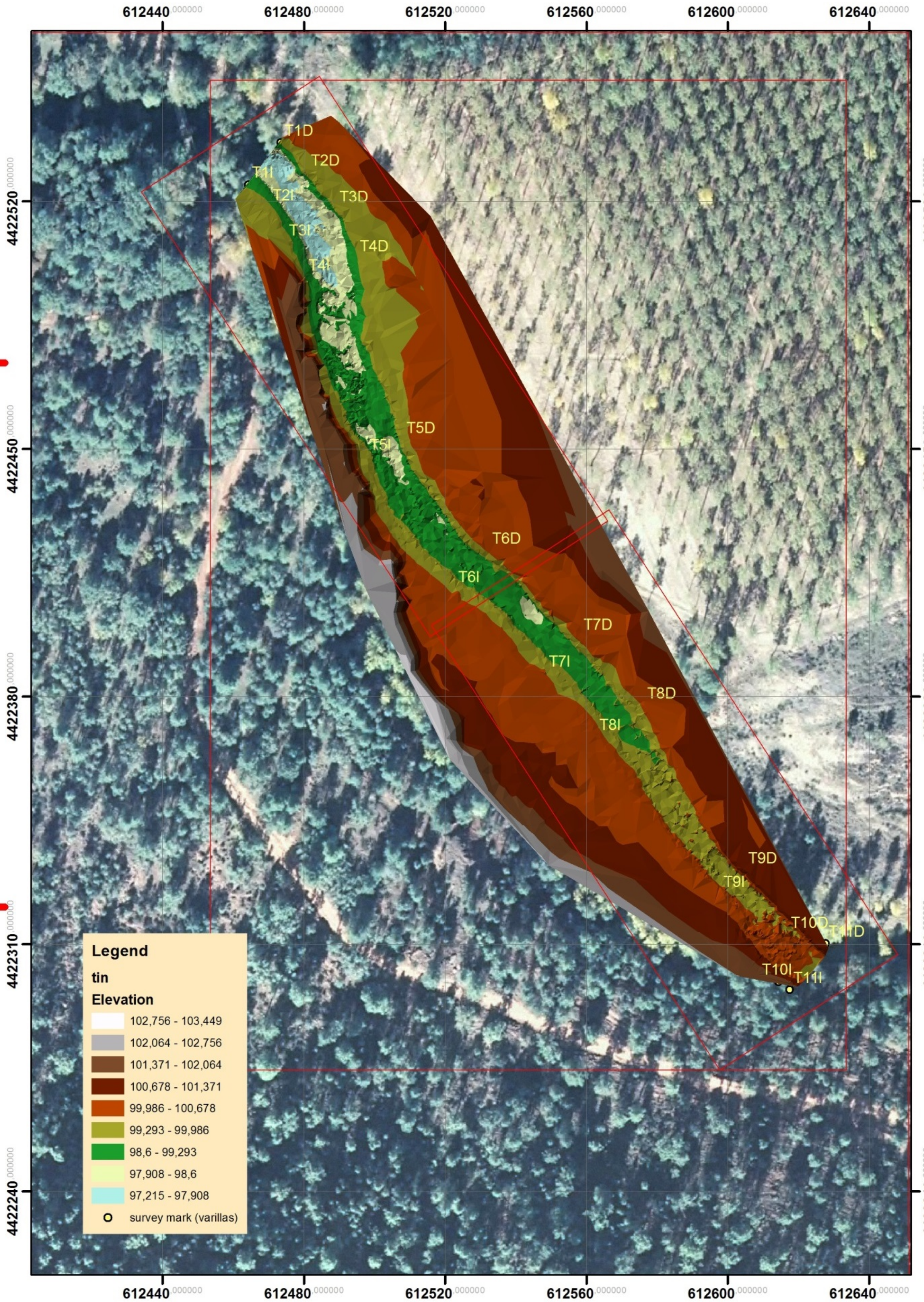
APENDIX

Remarks to the maps shown in the appendix:

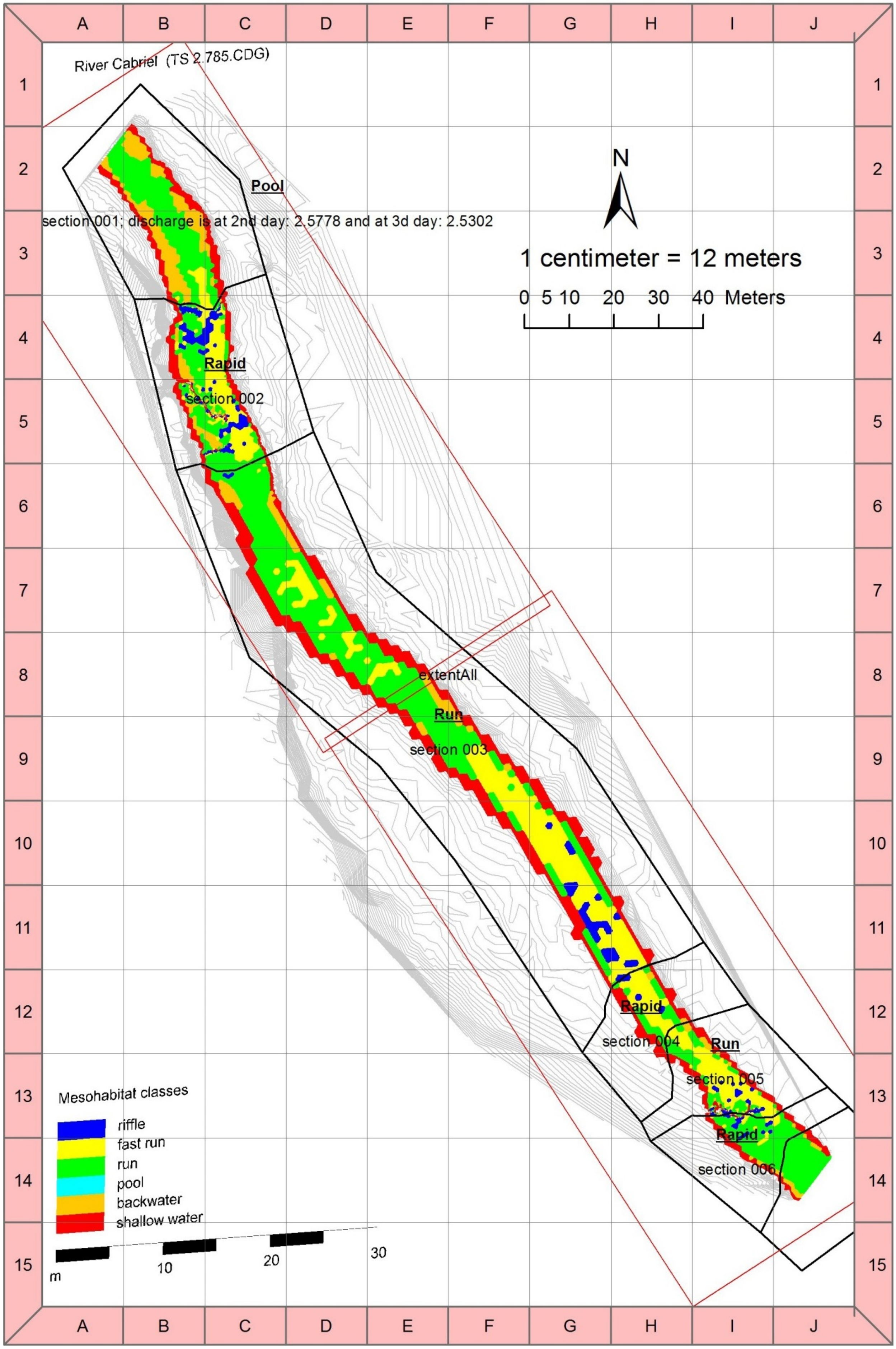
Initially, the A4 sized maps in the appendix were part of A0 sized maps; three for the Cabriel (one for each mesohabitat classification run) and two for the Ybbs. The layout of the A4 parts in the A0 map was as follows:

<table>
<tr><td>general location</td><td>location</td><td>location</td><td>Result report; calibration details</td></tr>
<tr><td>meso.hab. classific. of the whole reach</td><td>velocity distribution in detail</td><td>velocity distribution in the entire reach</td><td rowspan="3">abiotic profiles of the sections</td></tr>
<tr><td>water depths in detail</td><td>meso. hab classific. in detail</td><td>bed shear stress detail</td></tr>
<tr><td>water depth of the whole reach</td><td>thalweg and water surface diagram</td><td>bed shear stress of the whole reach</td></tr>
</table>

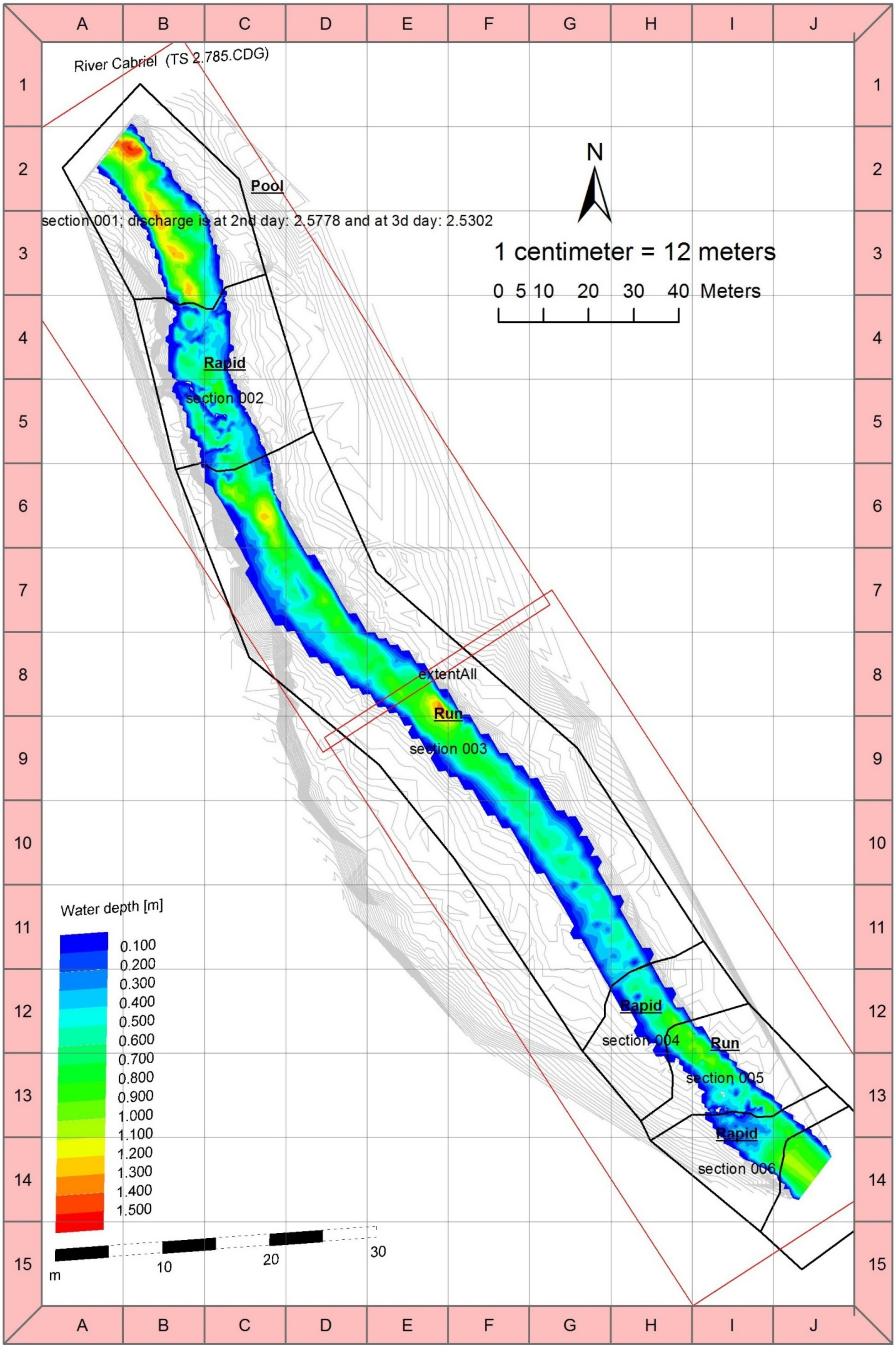
The parts with white background are not included in the document, but are available upon request (bernhard.wipplinger@gmail.com).



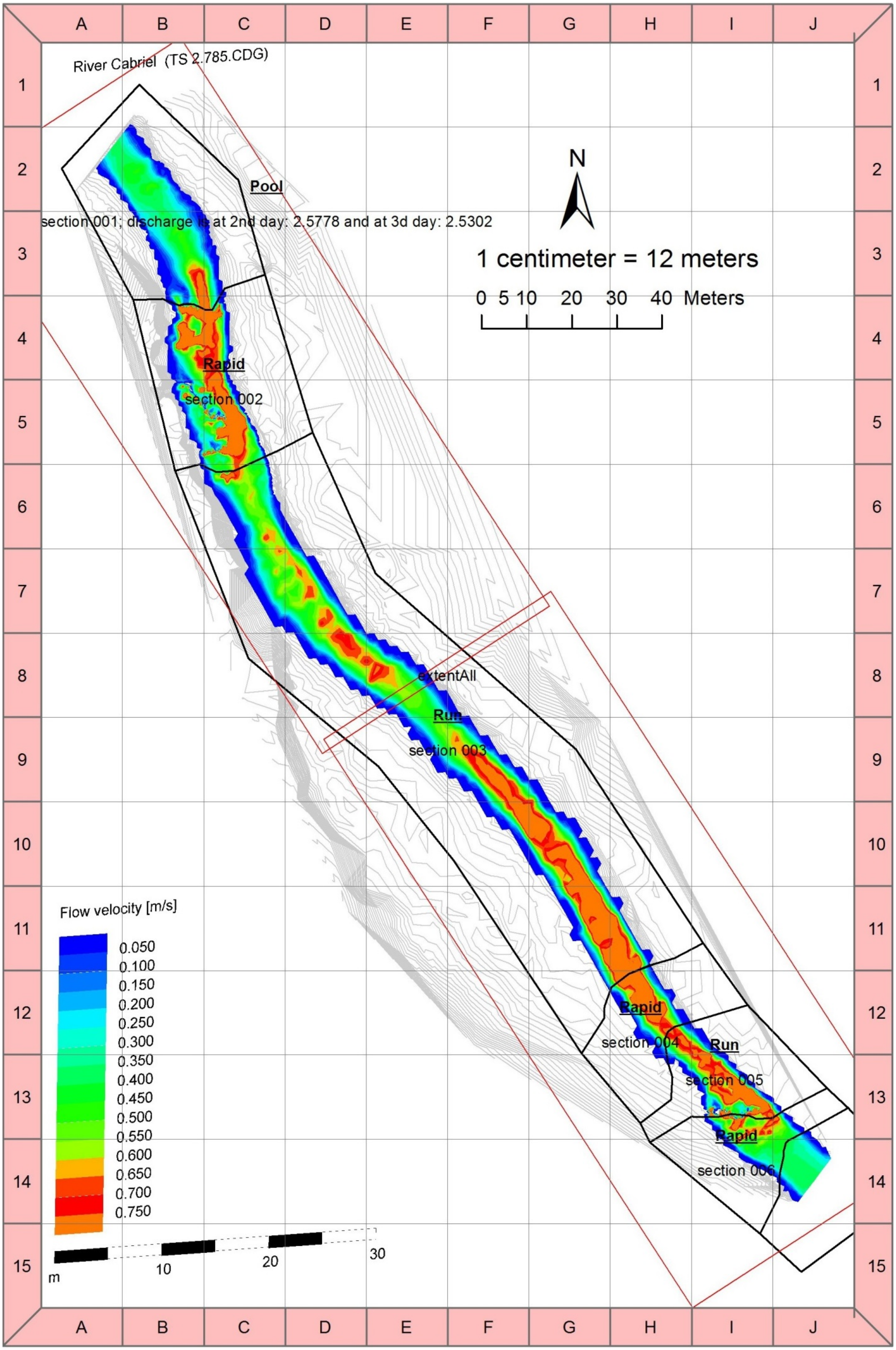
Appendix map 1: Cabriel: Detailed location of testing site



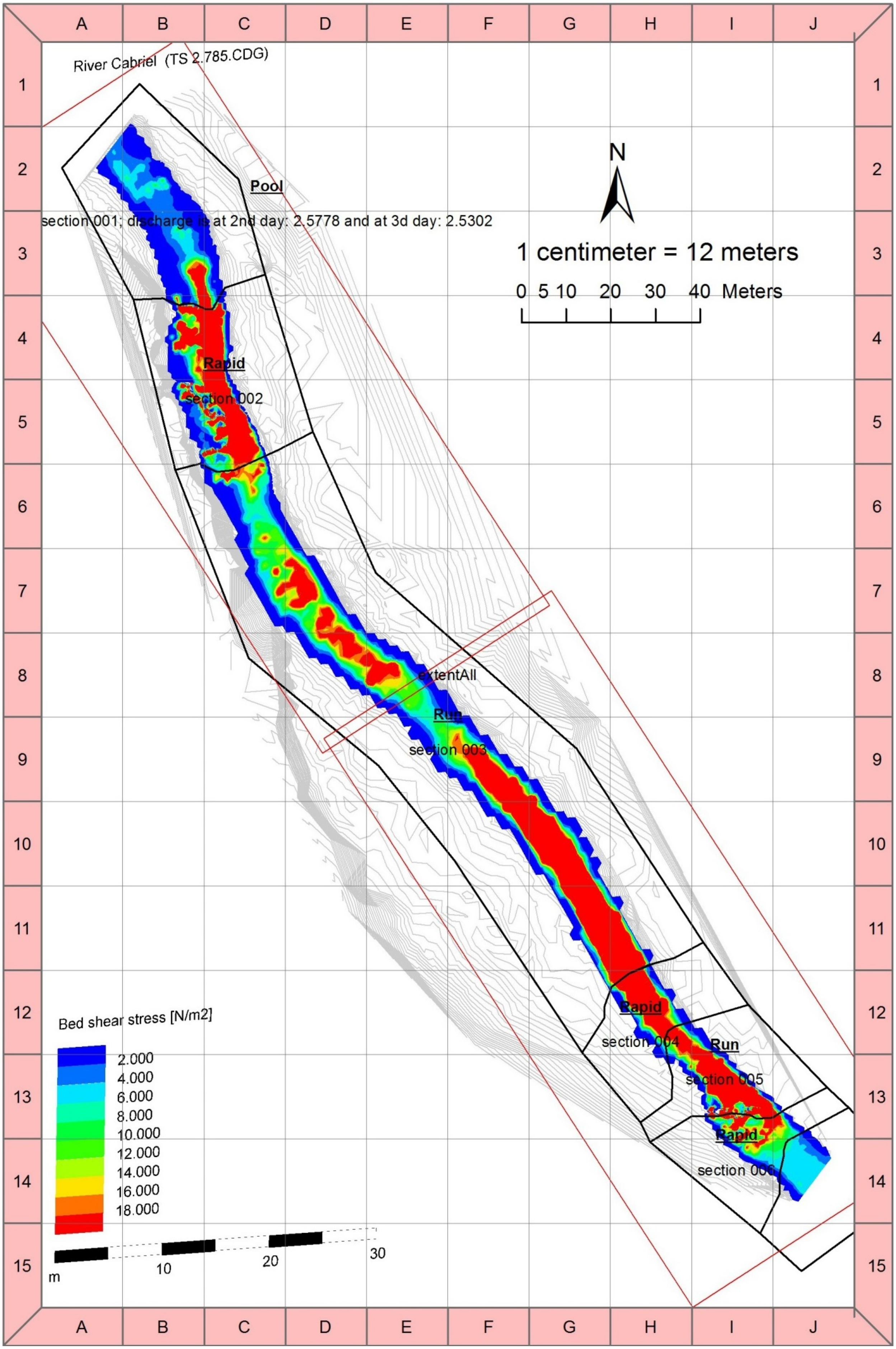
Appendix map 2: Cabriel: MEM Mesohabitat classification with default parameters for flow 2.758 m³/s



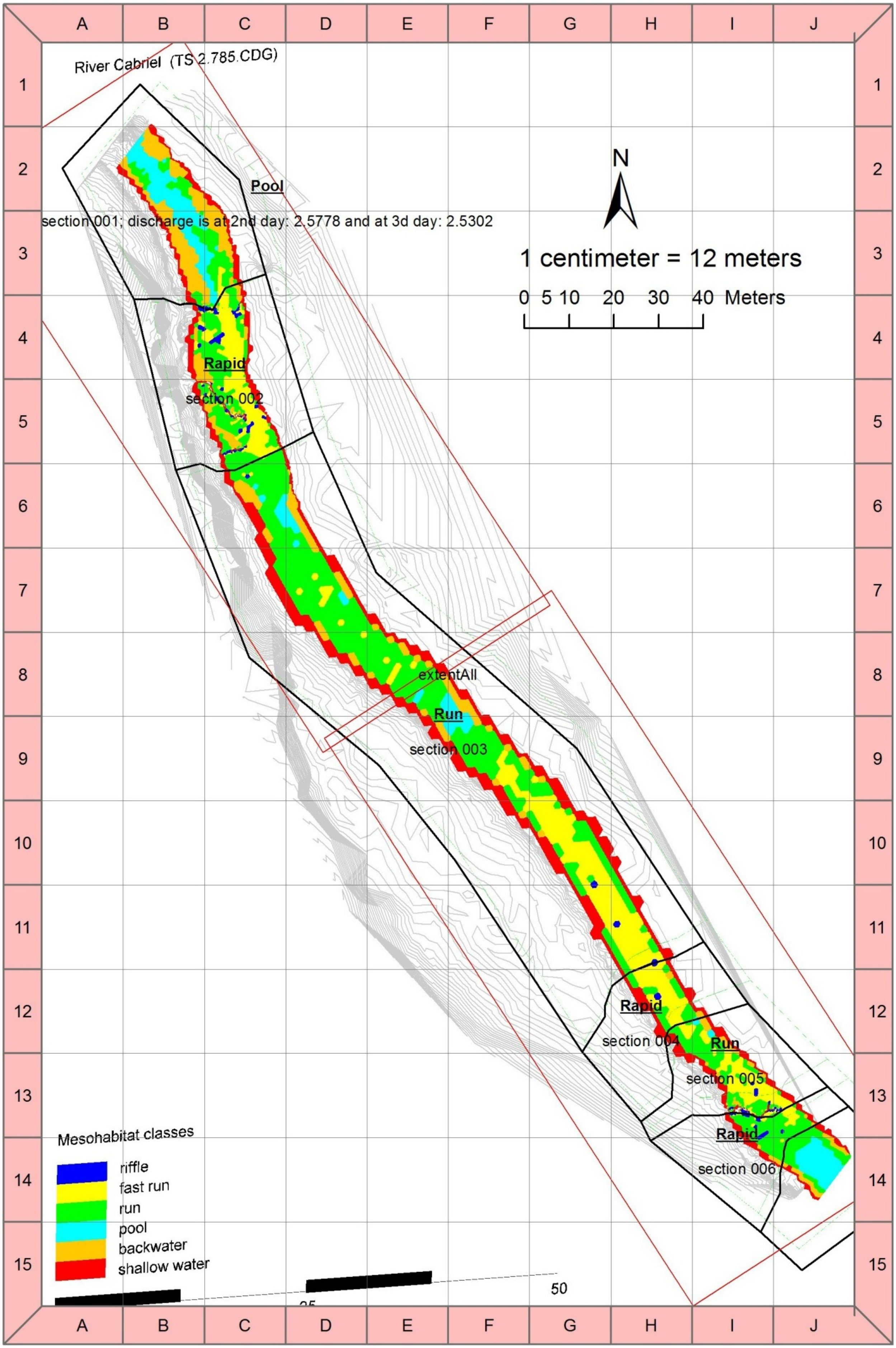
Appendix map 3: Cabriel: Depth distribution for flow 2.78m³/s



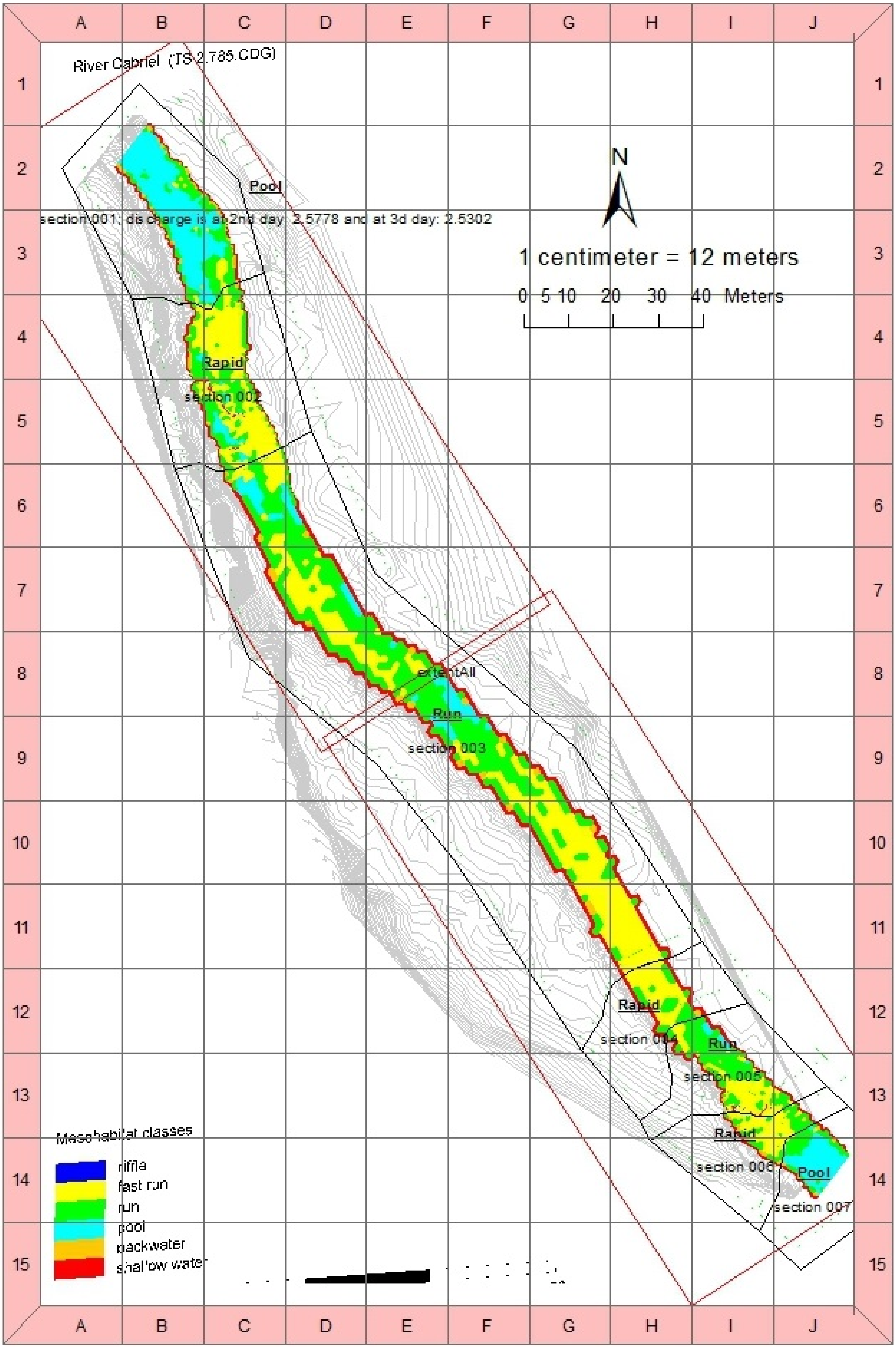
Appendix map 4: Cabriel: Velocity distribution for flow 2.78m³/s



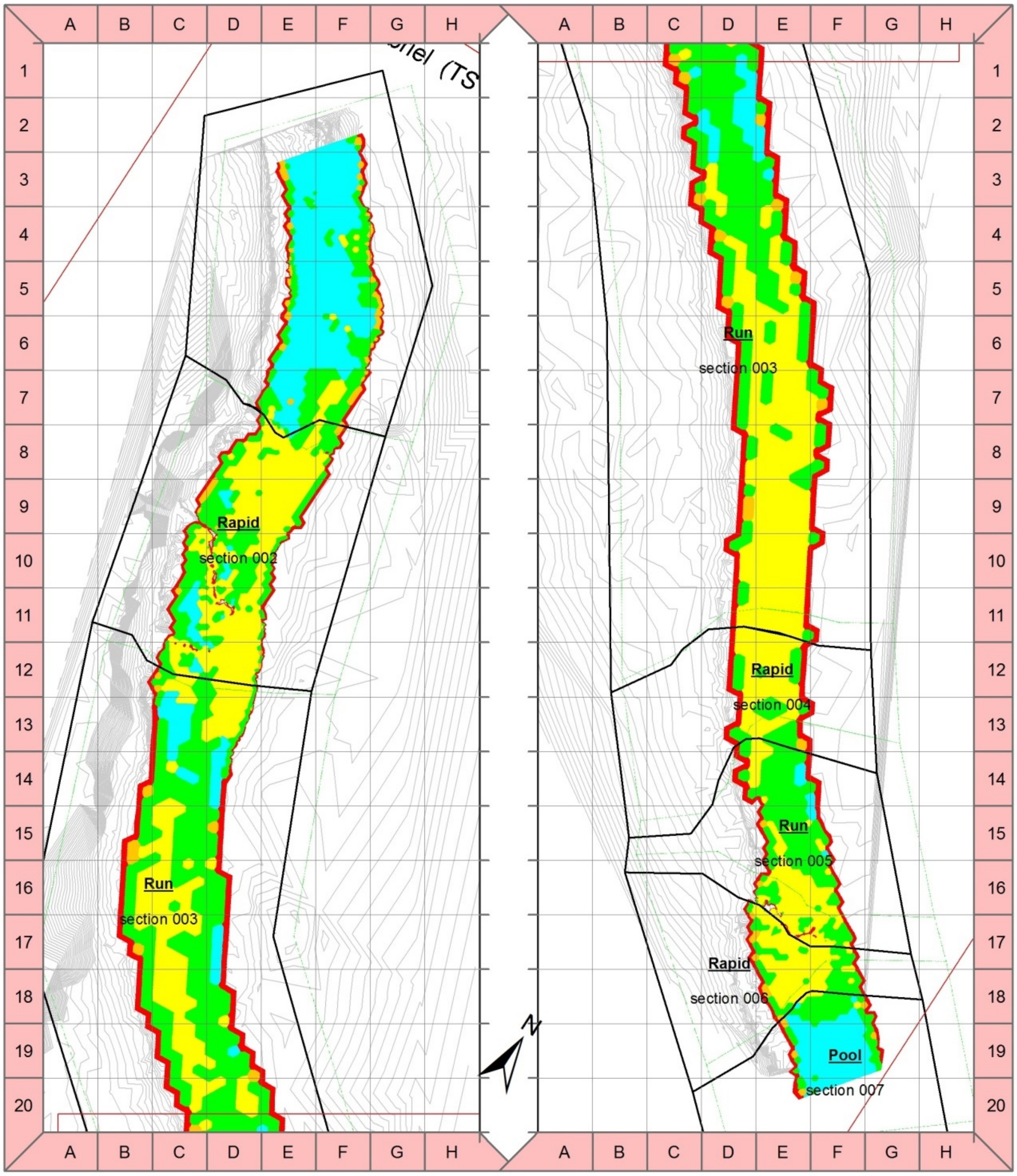
Appendix map 5: Cabriel: Bed shear stress distribution for flow 2.78 m³/s



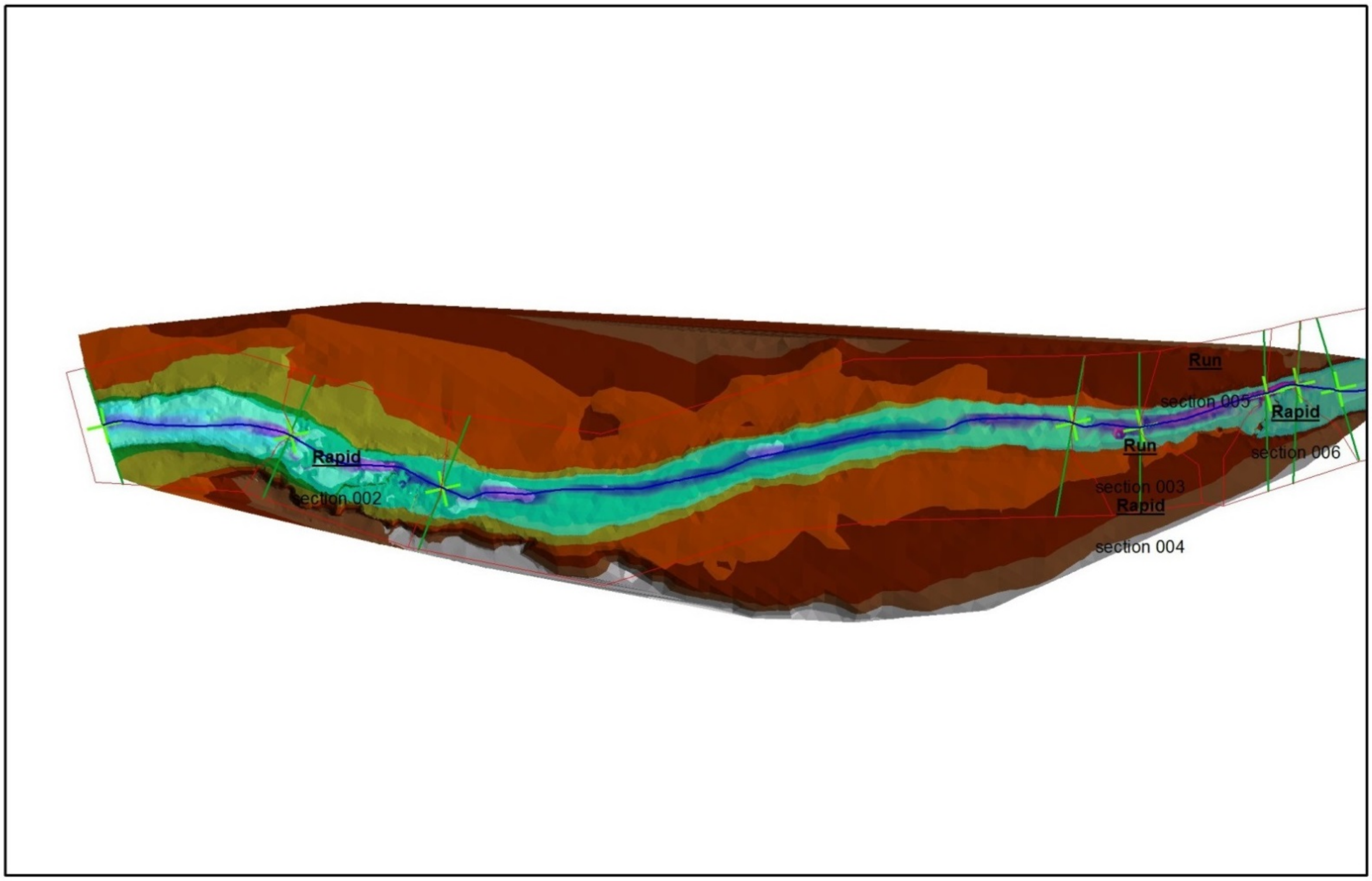
Appendix map 6: Cabriel: MEM Mesohabitat classification run 01 with derived parameters for flow 2.758 m³/s

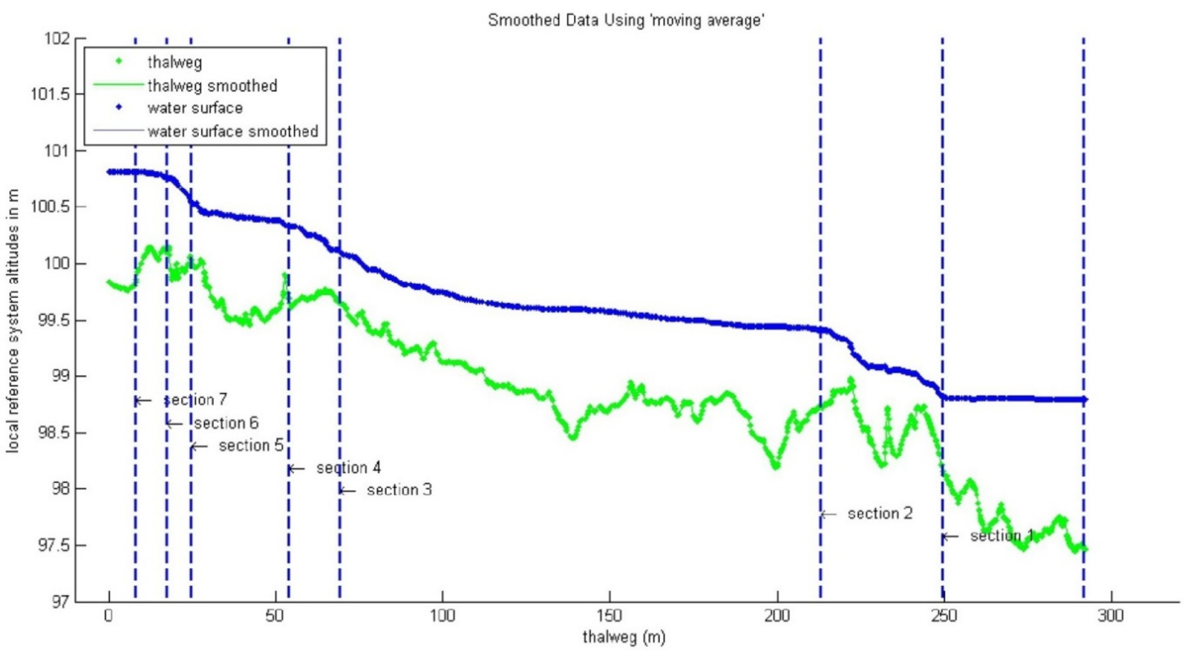


Appendix map 7: Cabriel: MEM Mesohabitat classification run 02 with calculated parameters for flow 2.758 m³/s

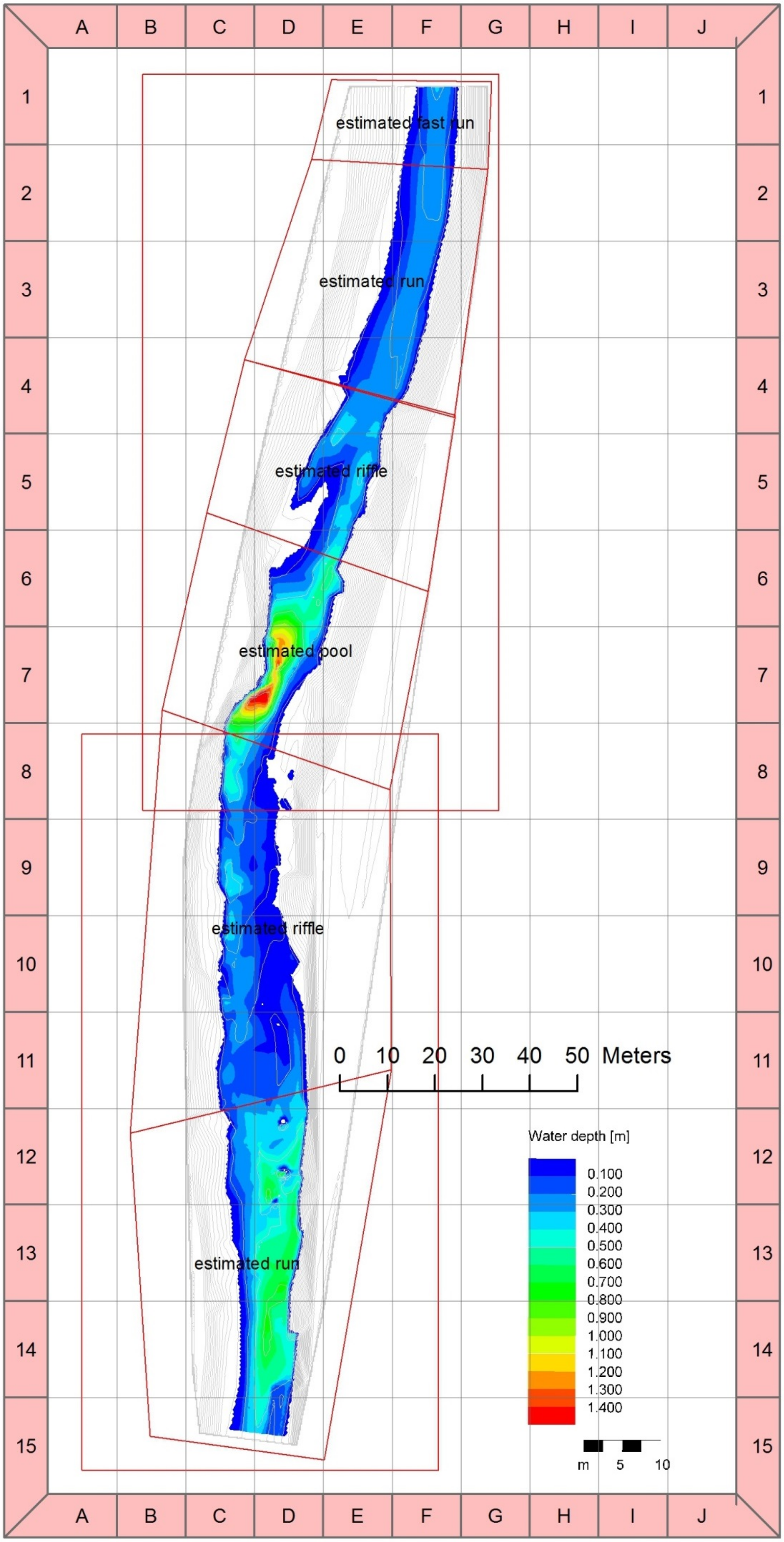


Appendix map 8: Cabriel: MEM Mesohabitat classification run 02 with calculated parameters for flow 2.758 m³/s (left the northern, right the southern part)

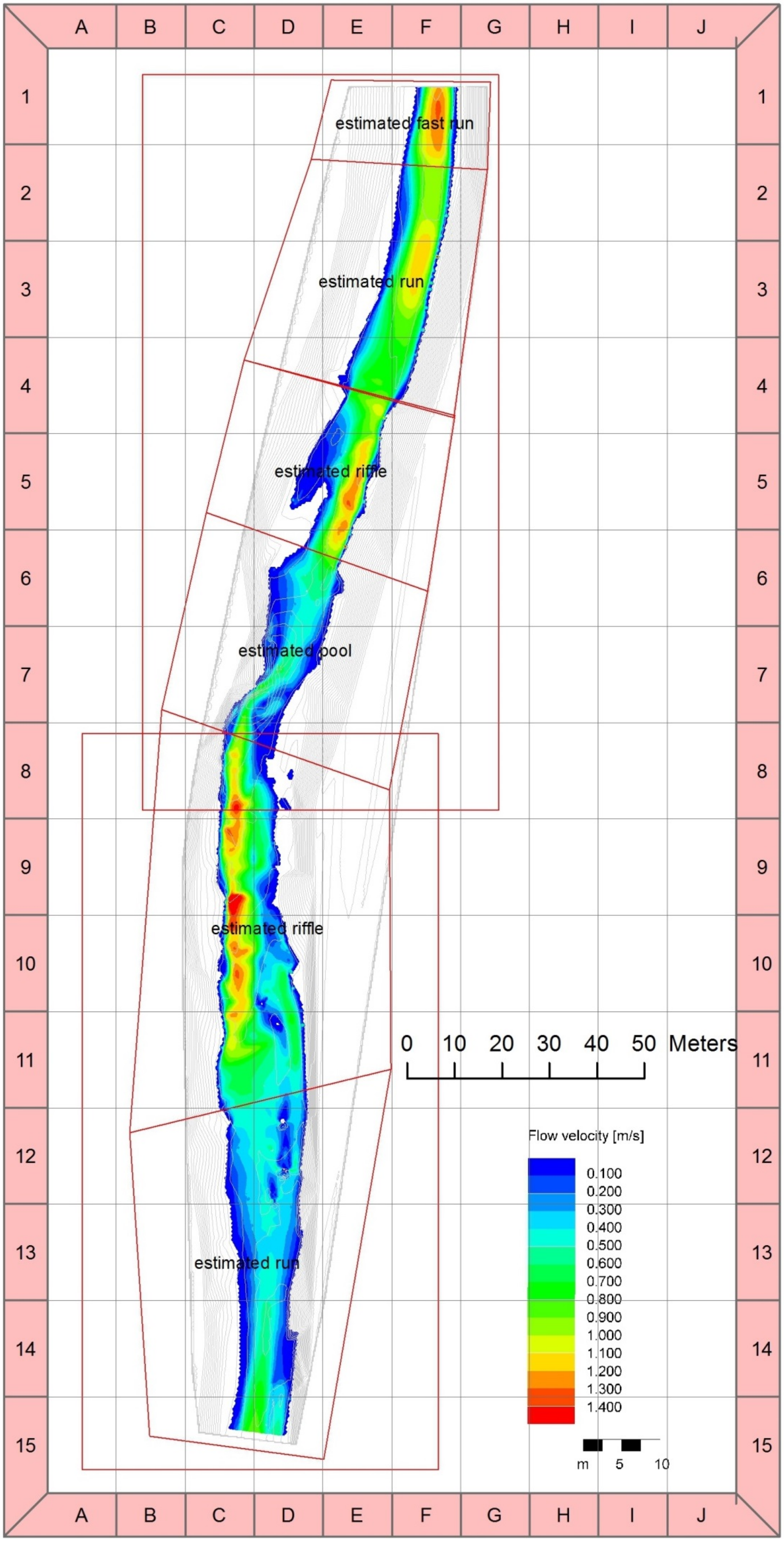




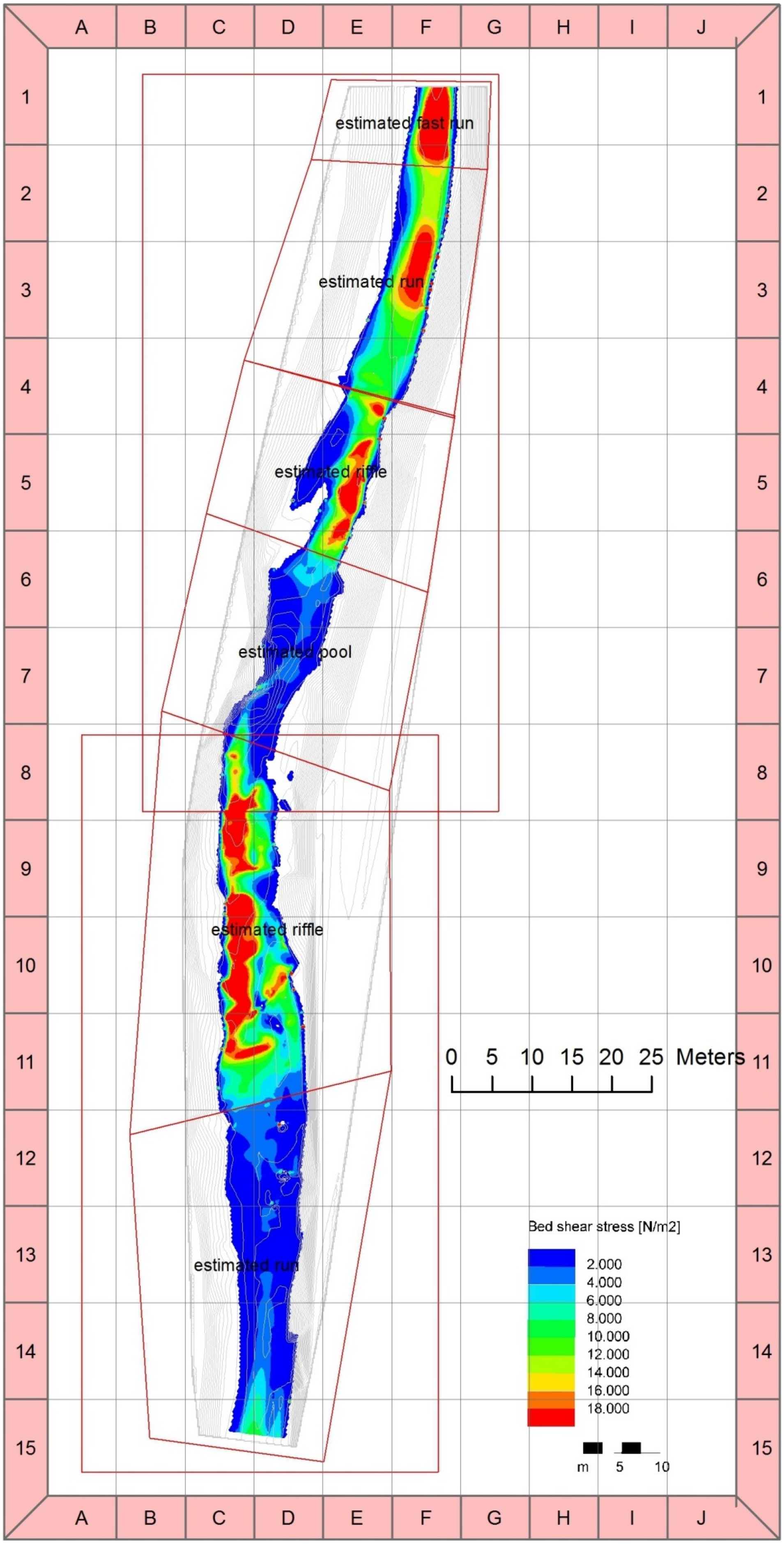
Appendix map 9: Cabriel: Thalweg and water surface for flow 2.578 m³/s



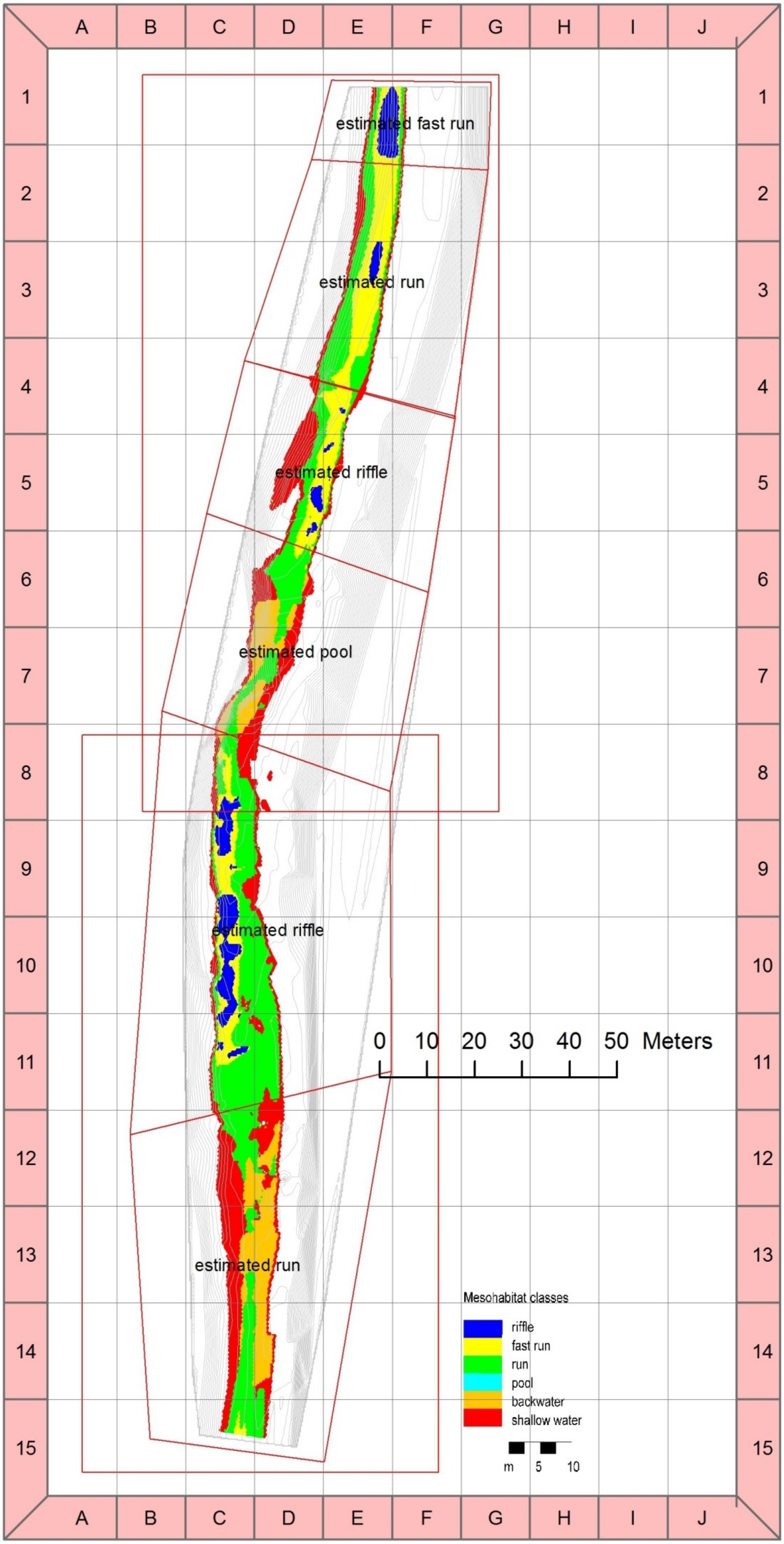
Appendix map 10: Ybbs: Depth distribution for flow 1.64 m³/s



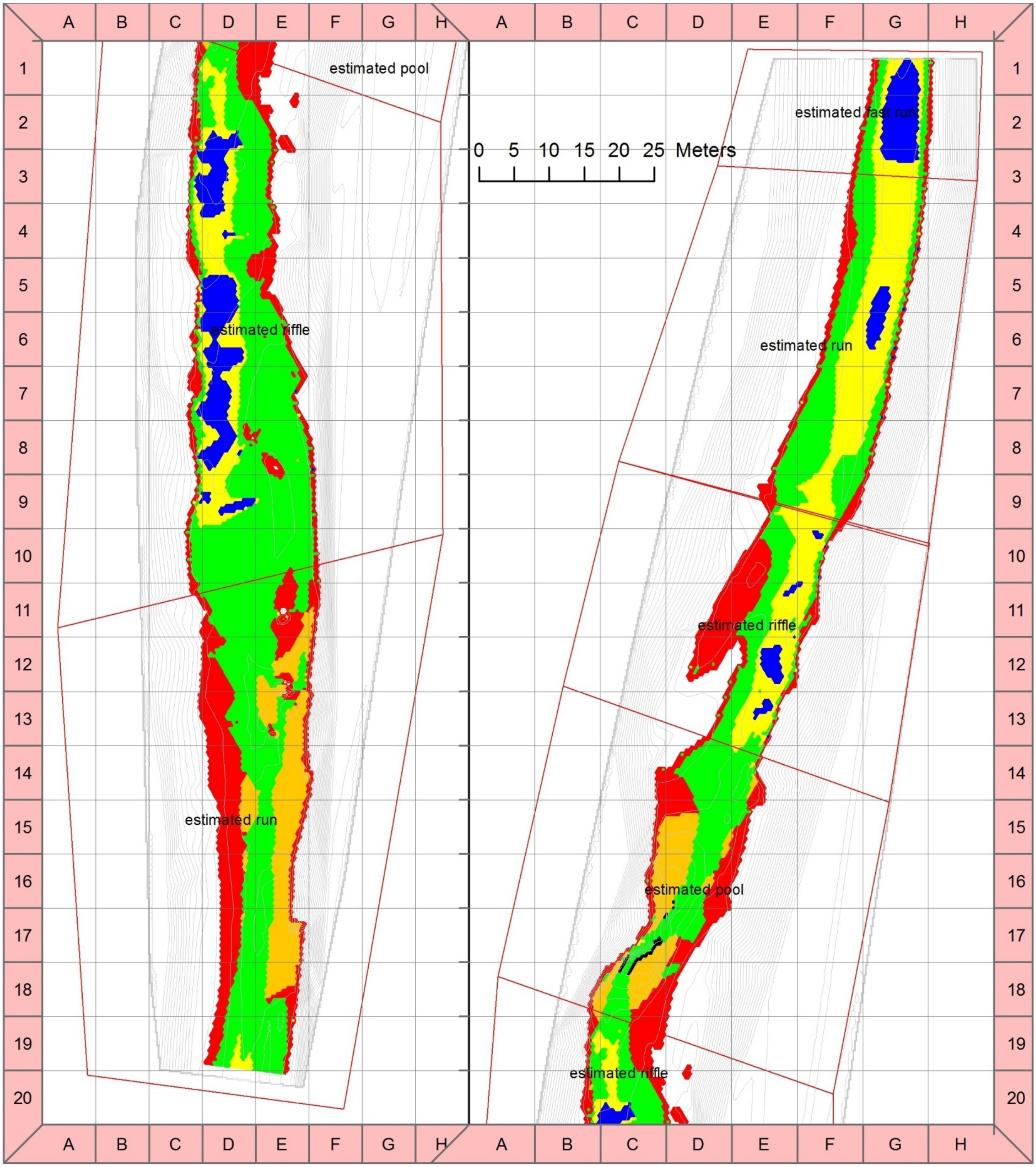
Appendix map 11: Ybbs: Velocity distribution for flow 1.64 m³/s



Appendix map 12: Ybbs: Bed shear stress distribution for flow 1.64 m³/s



Appendix map 13: Ybbs: MEM Mesohabitat classification run 01 for flow 1.64 m³/s with sampled parameters

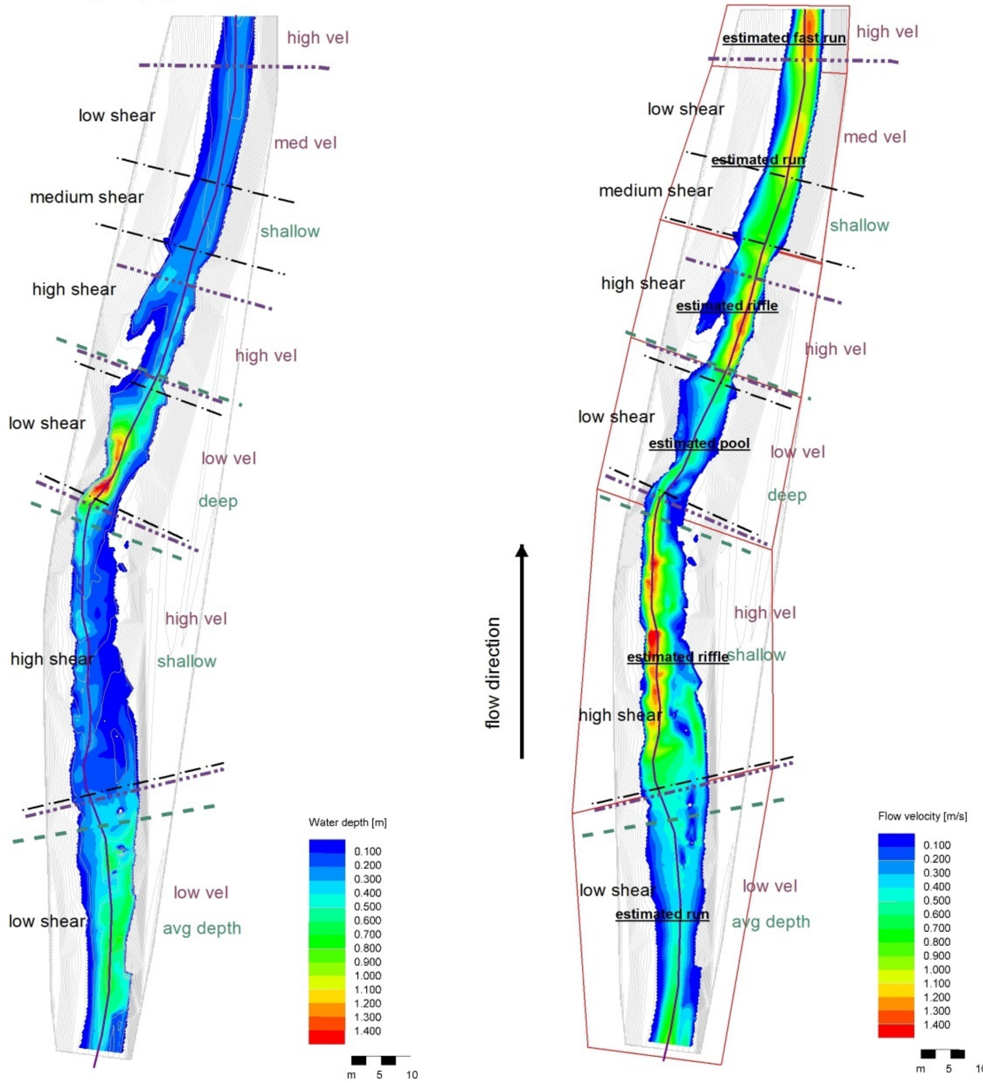


Appendix map 14: Ybbs: MEM Mesohabitat classification run 01 for flow 1.64 m³/s with sampled parameters; left the upstream part, right the downstream part

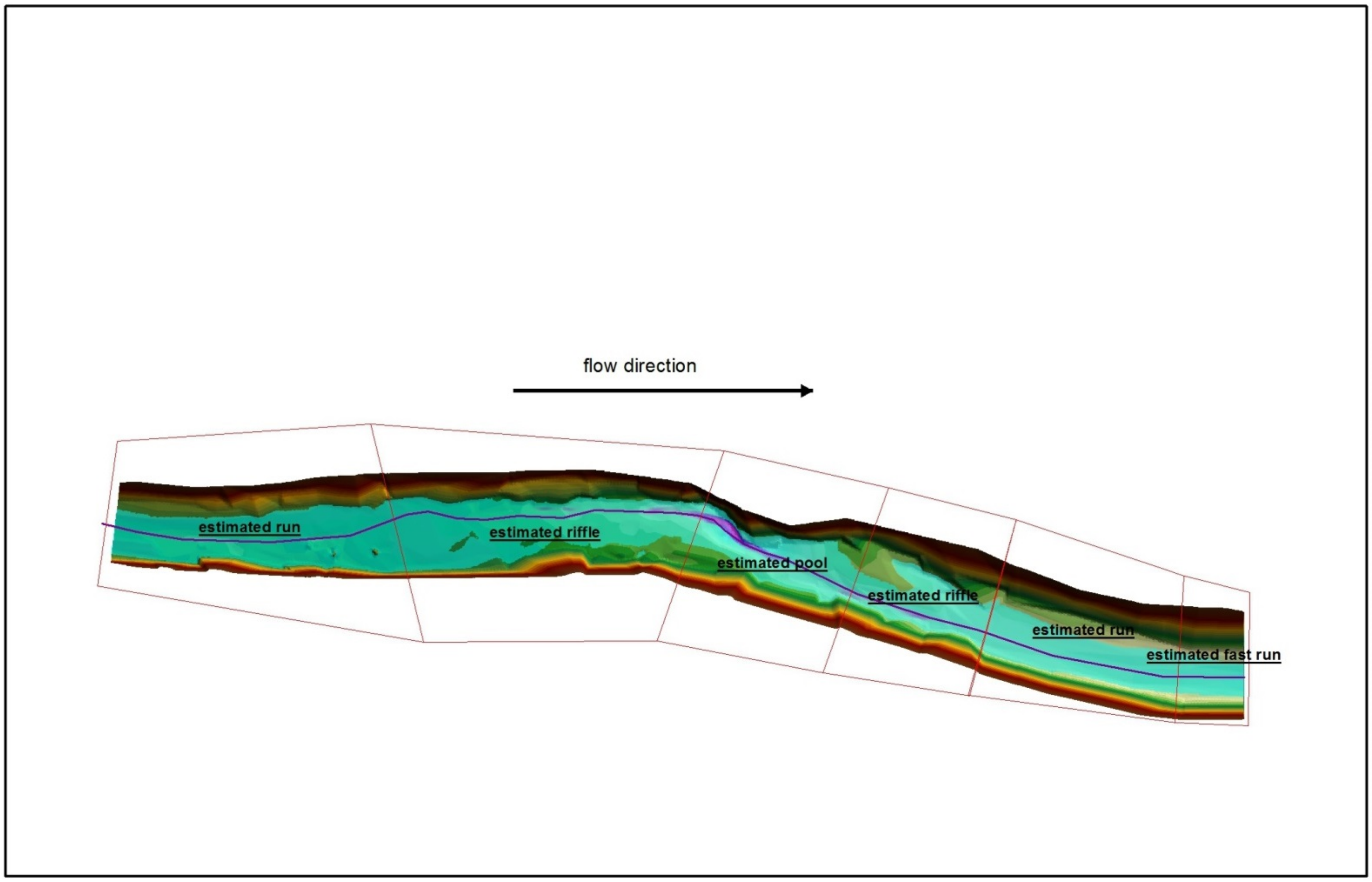
Q = 1.64

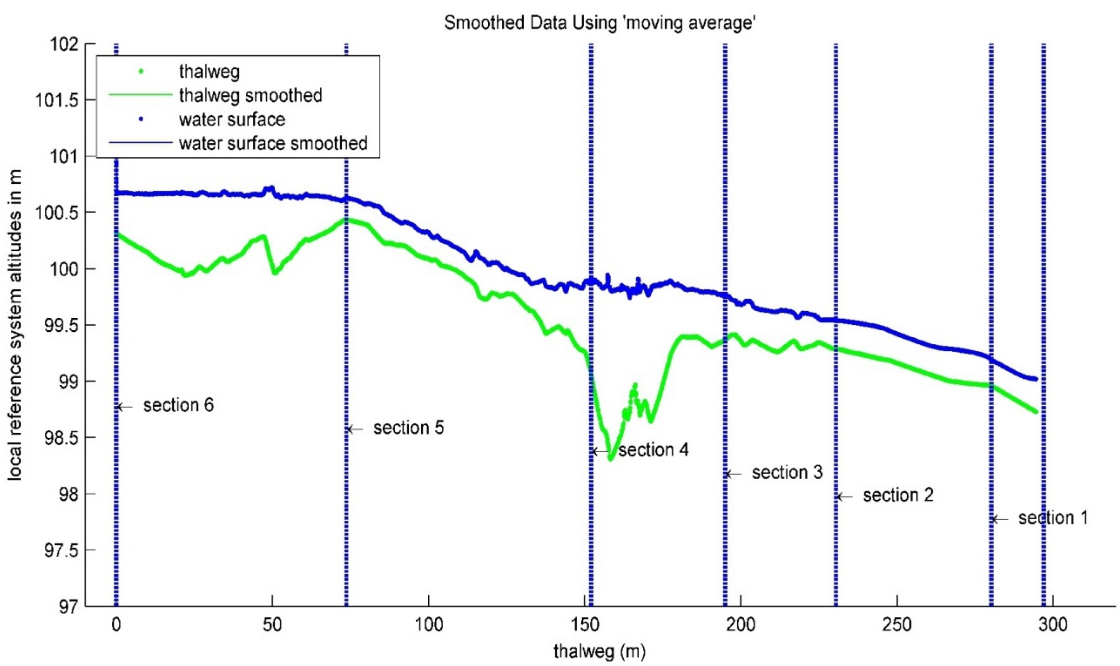
Left:
- Manually classified reach into zones of different velocity (high, medium, low) and depth, as well as zones of different bed shear stress classes (high, low)

Right:
- Red polygons show the deducted mesohabitats



Appendix map 15: Ybbs: Deduction of mesohabitats





Appendix map 16: Ybbs: Thalweg and water surface for flow 1.64 m³/s

Appendix code listening 17: Minimize mean squared error optimization.

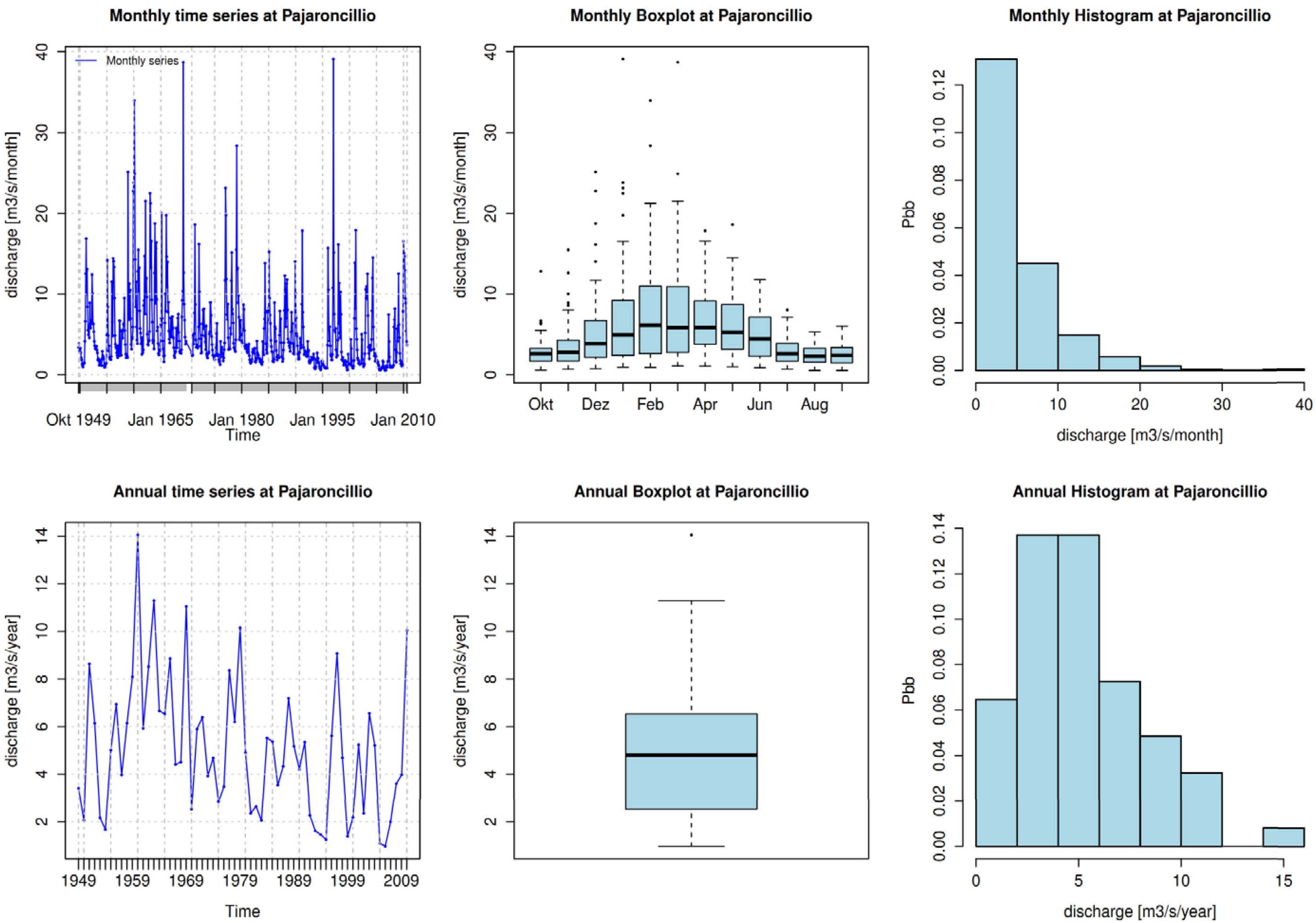
Code

```
1  Model[
2    Parameters[
3      Sets[Integers[-Infinity, Infinity]],
4      parcels
5    ],
6    Parameters[
7      Reals[0, Infinity],
8      vel[parcels],
9      should[parcels],
10     dep[parcels],
11     shear[parcels]
12   ],
13   Decisions[
14     Reals[0, Infinity],
15     a, b, c, d,
16     f, g, h, i,
17     k, l
18   ],
19   Constraints[
20     Constraint1 -> 5 > d > c > b > a > 0,
21     Constraint2 -> 5 > i > h > g > f > 0,
22     Constraint3 -> 40 > l > k > 0
23   ],
24   Goals[
25     Minimize[
26       Goal1 -> Annotation[Sum[{i, parcels},
27 (
28   (Max[Min[(vel[i]-0.01)/(0-0.01),1,
29   ((a+0.01)-vel[i])/((a+0.01)-a)],0]
30   +
31   2*Max[Min[(vel[i]-(a-0.01))/(a-(a-0.01)),1,
32   ((b+0.01)-vel[i])/((b+0.01)-b)],0]
33   +
34   3*Max[Min[(vel[i]-(b-0.01))/(b-(b-0.01)),1,
35   ((c+0.01)-vel[i])/((c+0.01)-c)],0]
36   +
37   4*Max[Min[(vel[i]-(c-0.01))/(c-(c-0.01)),1,
38   ((d+0.01)-vel[i])/((d+0.01)-d)],0]
39   +
40   5*Max[Min[(vel[i]-(d-0.01))/(d-(d-0.01)),1,
41   ((99+0.01)-vel[i])/((99+0.01)-99)],0]
42   +
43   5*Max[Min[(dep[i]-0.01)/(0-0.01),1,
44   ((f+0.01)-dep[i])/((f+0.01)-f)],0]
45   +
46   4*Max[Min[(dep[i]-(f-0.01))/(f-(f-0.01)),1,
47   ((g+0.01)-dep[i])/((g+0.01)-g)],0]
48   +
49   3*Max[Min[(dep[i]-(g-0.01))/(g-(g-0.01)),1,
50   ((h+0.01)-dep[i])/((h+0.01)-h)],0]
51   +
52   2*Max[Min[(dep[i]-(h-0.01))/(h-(h-0.01)),1,
53   ((i+0.01)-dep[i])/((i+0.01)-i)],0]
54   +
55   1*Max[Min[(dep[i]-(i-0.01))/(i-(d-0.01)),1,
56   ((99+0.01)-dep[i])/((99+0.01)-99)],0]
57 )*(
58   Max[Min[(shear[i]-(k-0.01))/(k-(k-0.01)),1,
59   ((l+0.01)-shear[i])/((l+0.01)-l)],0]
60   +
61   2*Max[Min[(shear[i]-(l-0.01))/(l-(l-0.01)),1,
62   ((99+0.01)-shear[i])/((99+0.01)-99)],0]
63 )
64 -should[i]
65 )^2
66 ], "order", 0]
67     ]
68   ]
69 ]
```

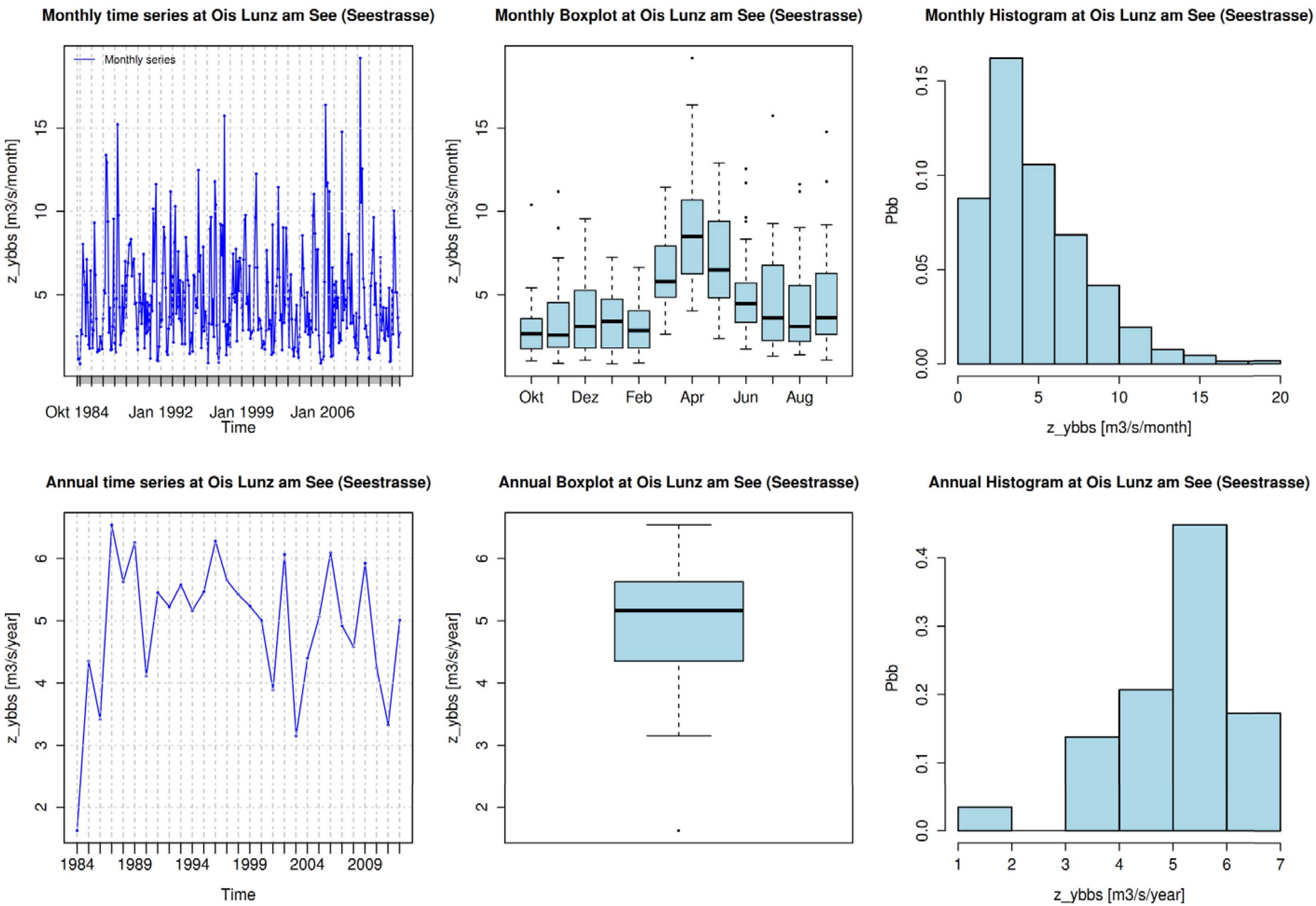
Comments

- (lines 3–5) A set call parcel is declared, which is used to index each table row of the calib. data.
- (lines 7–11) A vector of real values for velocity is defined. All thes values are bound the corresponding spreadheet column.
- (lines 14–17) Decision values to opti.
  … class borders for velocity
  … class borders for depth
  … class borders for stress
- (lines 20–22) defined ordered of parameters with limits of 5 m/s and 5 m shear stress limits
- (lines 24–28) goal function definition the square (line 65) sum of deviation over all parcels(all rows of the input data) should be minimized
- (lines 34–35) Trapozoidal class membership function for veleocity class 3
- (lines 57–59) multiplication by th shear stress class makes the model non linear
- (lines 64–65) “MHC should by” value = parcel visual estimation

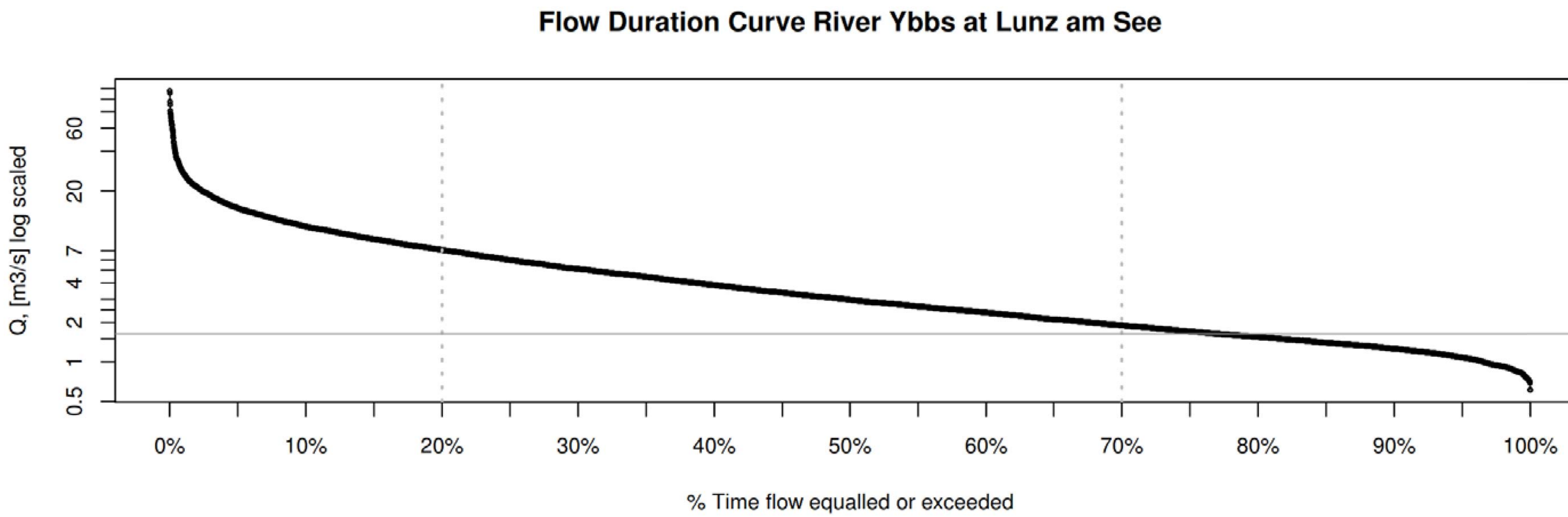
```
Code
Sum[{u, parcels_runs},
(
1/(1+(Abs[(
(
(Max[Min[(vel_run[u]-0.01)/(0-0.01),1,
((a+0.01)-vel_run[u])/((a+0.01)-a)],0]
+
2*Max[Min[(vel_run[u]-(a-0.01))/(a-(a-0.01)),1,
((b+0.01)-vel_run[u])/((b+0.01)-b)],0]
+
3*Max[Min[(vel_run[u]-(b-0.01))/(b-(b-0.01)),1,
((c+0.01)-vel_run[u])/((c+0.01)-c)],0]
+
4*Max[Min[(vel_run[u]-(c-0.01))/(c-(c-0.01)),1,
((d+0.01)-vel_run[u])/((d+0.01)-d)],0]
+
5*Max[Min[(vel_run[u]-(d-0.01))/(d-(d-0.01)),1,
((99+0.01)-vel_run[u])/((99+0.01)-99)],0]
+
5*Max[Min[(dep_run[u]-0.01)/(0-0.01),1,
((f+0.01)-dep_run[u])/((f+0.01)-f)],0]
+
4*Max[Min[(dep_run[u]-(f-0.01))/(f-(f-0.01)),1,
((g+0.01)-dep_run[u])/((g+0.01)-g)],0]
+
3*Max[Min[(dep_run[u]-(g-0.01))/(g-(g-0.01)),1,
((h+0.01)-dep_run[u])/((h+0.01)-h)],0]
+
2*Max[Min[(dep_run[u]-(h-0.01))/(h-(h-0.01)),1,
((i+0.01)-dep_run[u])/((i+0.01)-i)],0]
+
1*Max[Min[(dep_run[u]-(i-0.01))/(i-(d-0.01)),1,
((99+0.01)-dep_run[u])/((99+0.01)-99)],0]
)*(
Max[Min[(shear_run[u]-(k-0.01))/(k-(k-0.01)),1,
((l+0.01)-shear_run[u])/((l+0.01)-l)],0]
+
2*Max[Min[(shear_run[u]-(l-0.01))/(l-(l-0.01)),1,
((99+0.01)-shear_run[u])/((99+0.01)-99)],0]
)
)
-7)/3])^(2*11))
)
]
+
Sum[{u, parcels_fast},
(
1/(1+(Abs[(
(
(Max[Min[(vel_fast[u]-0.01)/(0-0.01),1,
((a+0.01)-vel_fast[u])/((a+0.01)-a)],0]
+
2*Max[Min[(vel_fast[u]-(a-0.01))/(a-(a-0.01)),1,
((b+0.01)-vel_fast[u])/((b+0.01)-b)],0]
+
3*Max[Min[(vel_fast[u]-(b-0.01))/(b-(b-0.01)),1,
((c+0.01)-vel_fast[u])/((c+0.01)-c)],0]
+
4*Max[Min[(vel_fast[u]-(c-0.01))/(c-(c-0.01)),1,
((d+0.01)-vel_fast[u])/((d+0.01)-d)],0]
+
5*Max[Min[(vel_fast[u]-(d-0.01))/(d-(d-0.01)),1,
((99+0.01)-vel_fast[u])/((99+0.01)-99)],0]
+
5*Max[Min[(dep_fast[u]-0.01)/(0-0.01),1,
((f+0.01)-dep_fast[u])/((f+0.01)-f)],0]
+
4*Max[Min[(dep_fast[u]-(f-0.01))/(f-(f-0.01)),1,
((g+0.01)-dep_fast[u])/((g+0.01)-g)],0]
+
3*Max[Min[(dep_fast[u]-(g-0.01))/(g-(g-0.01)),1,
((h+0.01)-dep_fast[u])/((h+0.01)-h)],0]
+
2*Max[Min[(dep_fast[u]-(h-0.01))/(h-(h-0.01)),1,
((i+0.01)-dep_fast[u])/((i+0.01)-i)],0]
+
1*Max[Min[(dep_fast[u]-(i-0.01))/(i-(d-0.01)),1,
((99+0.01)-dep_fast[u])/((99+0.01)-99)],0]
)*(
Max[Min[(shear_fast[u]-(k-0.01))/(k-(k-0.01)),1,
((l+0.01)-shear_fast[u])/((l+0.01)-l)],0]
+
2*Max[Min[(shear_fast[u]-(l-0.01))/(l-(l-0.01)),1,
((99+0.01)-shear_fast[u])/((99+0.01)-99)],0]
)
)
-14)/5])^(2*14))
)
]+
Sum[{u, parcels_riffle},
(
1/(1+(Abs[(
(
(Max[Min[(vel_riffle[u]-0.01)/(0-0.01),1,
((a+0.01)-vel_riffle[u])/((a+0.01)-a)],0]
+
2*Max[Min[(vel_riffle[u]-(a-0.01))/(a-(a-0.01)),1,
((b+0.01)-vel_riffle[u])/((b+0.01)-b)],0]
+
3*Max[Min[(vel_riffle[u]-(b-0.01))/(b-(b-0.01)),1,
((c+0.01)-vel_riffle[u])/((c+0.01)-c)],0]
+
4*Max[Min[(vel_riffle[u]-(c-0.01))/(c-(c-0.01)),1,
((d+0.01)-vel_riffle[u])/((d+0.01)-d)],0]
+
5*Max[Min[(vel_riffle[u]-(d-0.01))/(d-(d-0.01)),1,
((99+0.01)-vel_riffle[u])/((99+0.01)-99)],0]
+
5*Max[Min[(dep_riffle[u]-0.01)/(0-0.01),1,
((f+0.01)-dep_riffle[u])/((f+0.01)-f)],0]
+
4*Max[Min[(dep_riffle[u]-(f-0.01))/(f-(f-0.01)),1,
((g+0.01)-dep_riffle[u])/((g+0.01)-g)],0]
+
3*Max[Min[(dep_riffle[u]-(g-0.01))/(g-(g-0.01)),1,
((h+0.01)-dep_riffle[u])/((h+0.01)-h)],0]
+
2*Max[Min[(dep_riffle[u]-(h-0.01))/(h-(h-0.01)),1,
((i+0.01)-dep_riffle[u])/((i+0.01)-i)],0]
+
1*Max[Min[(dep_riffle[u]-(i-0.01))/(i-(d-0.01)),1,
((99+0.01)-dep_riffle[u])/((99+0.01)-99)],0]
)*(
Max[Min[(shear_riffle[u]-(k-0.01))/(k-(k-0.01)),1,
((l+0.01)-shear_riffle[u])/((l+0.01)-l)],0]
+
2*Max[Min[(shear_riffle[u]-(l-0.01))/(l-(l-0.01)),1,
((99+0.01)-shear_riffle[u])/((99+0.01)-99)],0]
)
)
-22)/3])^(2*27))
)
]
+
Sum[{u, parcels_pool},
(
1/(1+(Abs[(
(
(Max[Min[(vel_pool[u]-0.01)/(0-0.01),1,
((a+0.01)-vel_pool[u])/((a+0.01)-a)],0]
+
2*Max[Min[(vel_pool[u]-(a-0.01))/(a-(a-0.01)),1,
((b+0.01)-vel_pool[u])/((b+0.01)-b)],0]
+
3*Max[Min[(vel_pool[u]-(b-0.01))/(b-(b-0.01)),1,
((c+0.01)-vel_pool[u])/((c+0.01)-c)],0]
+
4*Max[Min[(vel_pool[u]-(c-0.01))/(c-(c-0.01)),1,
((d+0.01)-vel_pool[u])/((d+0.01)-d)],0]
+
5*Max[Min[(vel_pool[u]-(d-0.01))/(d-(d-0.01)),1,
((99+0.01)-vel_pool[u])/((99+0.01)-99)],0]
+
5*Max[Min[(dep_pool[u]-0.01)/(0-0.01),1,
((f+0.01)-dep_pool[u])/((f+0.01)-f)],0]
+
4*Max[Min[(dep_pool[u]-(f-0.01))/(f-(f-0.01)),1,
((g+0.01)-dep_pool[u])/((g+0.01)-g)],0]
+
3*Max[Min[(dep_pool[u]-(g-0.01))/(g-(g-0.01)),1,
((h+0.01)-dep_pool[u])/((h+0.01)-h)],0]
+
2*Max[Min[(dep_pool[u]-(h-0.01))/(h-(h-0.01)),1,
((i+0.01)-dep_pool[u])/((i+0.01)-i)],0]
+
1*Max[Min[(dep_pool[u]-(i-0.01))/(i-(d-0.01)),1,
((99+0.01)-dep_pool[u])/((99+0.01)-99)],0]
)*(
Max[Min[(shear_pool[u]-(k-0.01))/(k-(k-0.01)),1,
((l+0.01)-shear_pool[u])/((l+0.01)-l)],0]
+
2*Max[Min[(shear_pool[u]-(l-0.01))/(l-(l-0.01)),1,
((99+0.01)-shear_pool[u])/((99+0.01)-99)],0]
)
)
-2.5)/2])^(2*20))
)
]
```

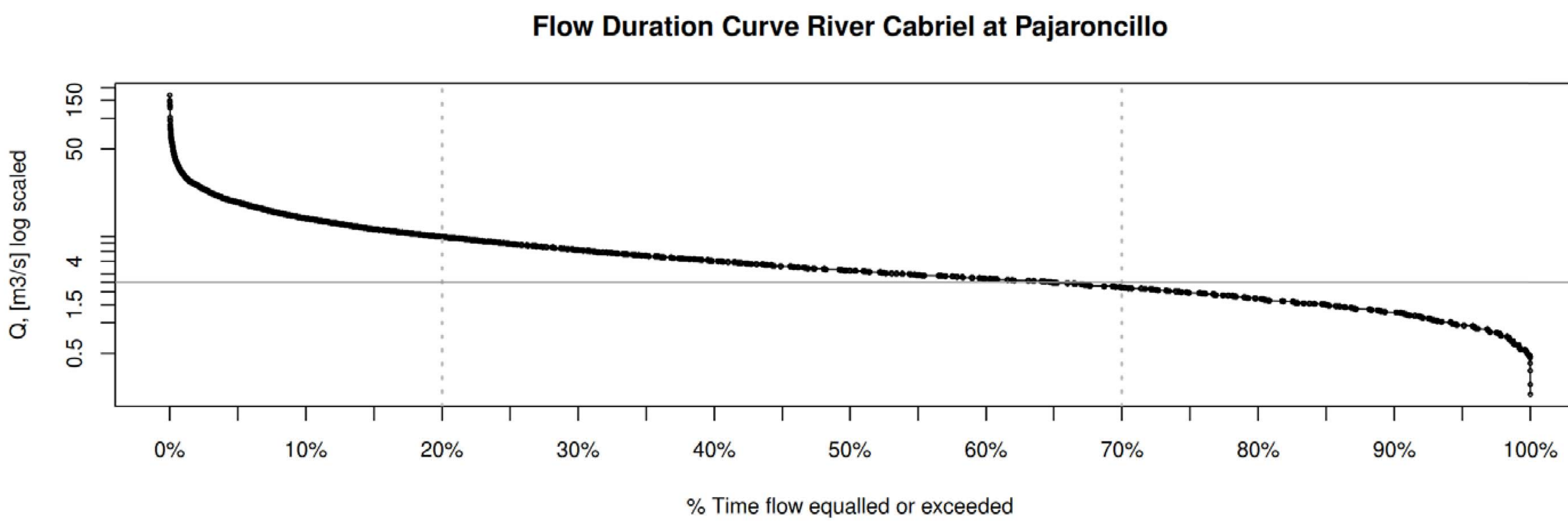


Appendix figure 19: R: Hydroplots river Cabriel

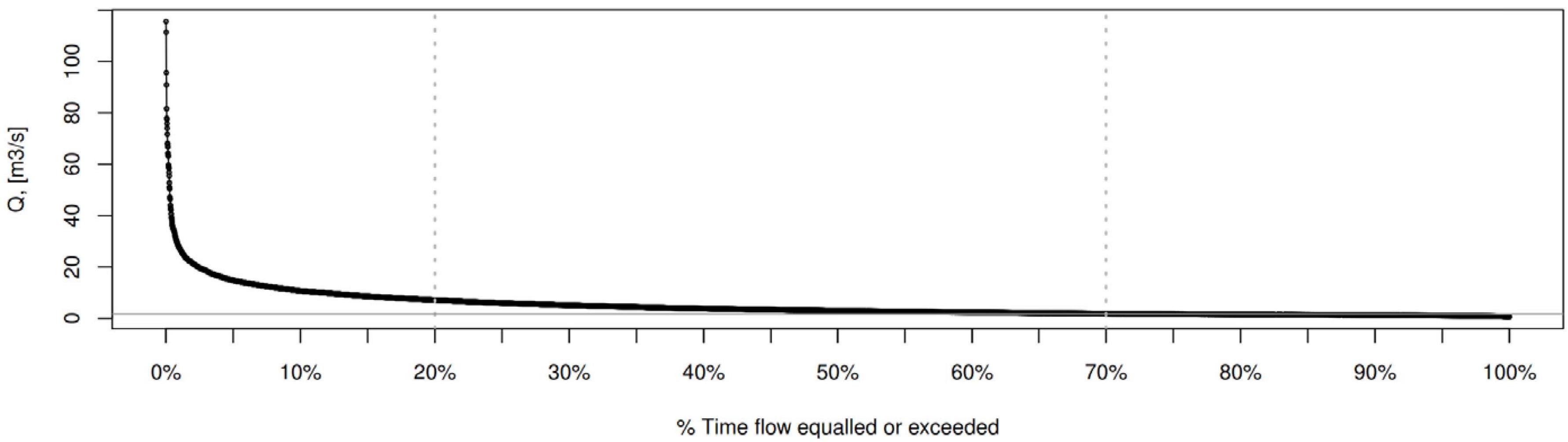


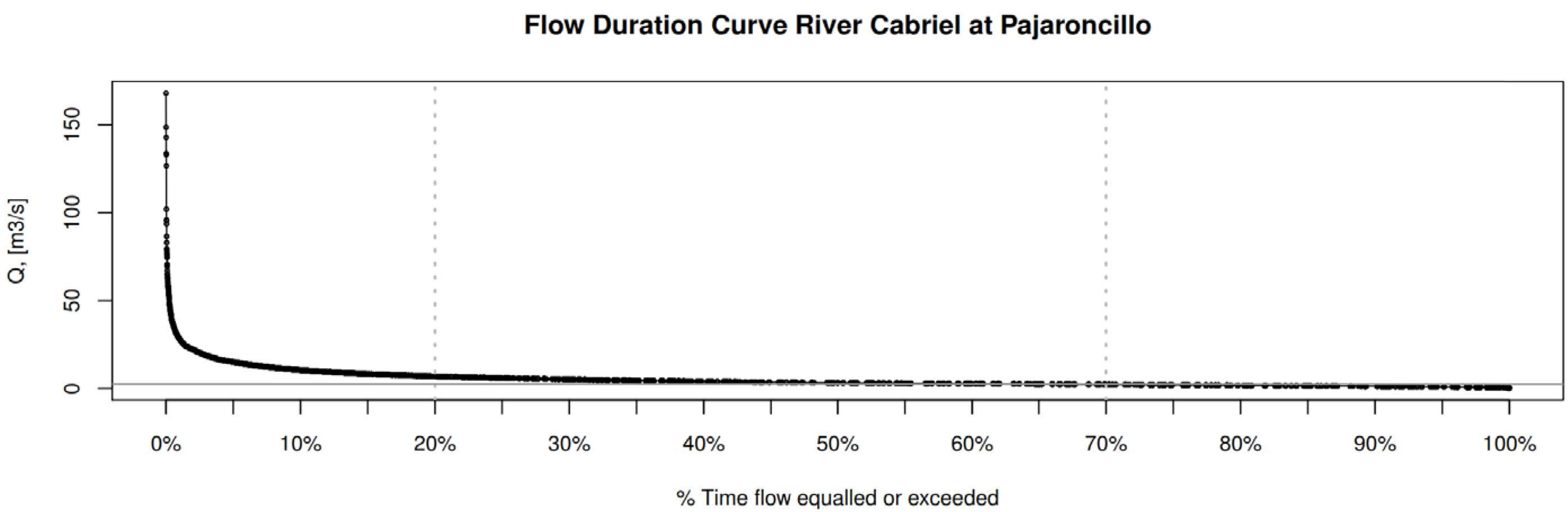
Appendix figure 20: R: Hydroplots river Ybbs (Ois)





Appendix figure 21: R: FDC compared in a logarithmic scale





Appendix figure 22: R: FDC compared

Eidesstattliche Erklärung

Hiermit erkläre ich eidesstattlich, dass ich die vorliegende Diplomarbeit selbstständig und ohne Benutzung andere als der angegebenen Hilfsmittel angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommen Stellen sind gemäß den Richtlinien wissenschaftlichen Arbeitens zitiert und mit genauen Quellenangaben kenntlich gemacht. Diese Diplomarbeit wurde bisher in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegt und auch nicht veröffentlicht.

September, 2014, Wien

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