Guideline to Determine Minimum Environmental Flow Regulations for Dewatered Reaches of Hydropower Projects in Bhutan

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Glossary

BBM	Building block method
CASiMiR	Computer Aided Simulation Model for Instream Flow Regulations
DRIFT	Downstream Response to Imposed Flow Transformations
ELOHA	Ecological Limits of Hydrologic Alteration
ESS	Ecosystem services
HEP	Hydroelectric Power plant (=HPP)
HHS	Hydraulic habitat suitability
HPP	Hydropower plant (=HEP)
HSI	Habitat suitability index (=SI)
MAF	Mean annual flow
PHABSIM	Physical habitat simulation system
SfM	Structure from motion
SI	Suitability Index (=HSI)
TEEB	The economics of ecosystems and biodiversity
UAV	Unmanned aerial vehicle
WUA	Weighted Usable Area

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1 INTRODUCTION

Bhutan has highly favorable conditions for hydropower and an enormous potential as outlined in the master plan for hydropower development. The development of these natural resources is a key to supply energy for Bhutan's economic development and to generate income from selling electricity to neighboring countries as well. To conserve the ecological integrity of the aquatic ecosystems and river corridors, environmental flows (E-flows) and fish migration are of major importance. While Bhutan's ecological standards are generally high, the past practice regarding environmental flows in Bhutan was not in agreement with the high priority given to the protection of natural ecosystems, mostly due to the lack of proper technical guidelines. While other habitats, for example natural forests, are highly protected, plans for hydropower development are leading towards fragmenting – by dams and reservoirs - and severely impacting 100 % of Bhutan's main stem river corridors which connect the Himalayan Mountains with the Brahmaputra. The National Environmental Commission Secretariat of the Royal Government of Bhutan has therefore launched an initiative to establish a national guideline for the determination of E-flow regulations throughout the country for existing and future hydropower developments. These standards are based on those applied in other mountainous countries with more than hundred years of hydropower experience on one side and a high level of environmental concern regarding river ecosystems on the other side. This guideline describes in detail the procedures and methods to be applied to all diversion-type run-of-river hydropower projects to determine E-flows regulations appropriate for the protection of fluvial aquatic ecosystems and river corridors in the country.

1.1 Experiences from other countries and regions

Countries with more than a century of industrial hydropower experience for electricity generation such as Switzerland, Austria and Germany in the European Alps, Scandinavian countries, as well as Canada and the USA are now in the process of restoring the ecological status of their rivers while still making use of their hydropower potentials. The European Water Framework Directive calls for bringing all rivers to a "good ecological status" which is defined not only by water quality and morphological criteria but by doing everything to bring fish and other aquatic species back to where they were historically. Hydropower development is not the only cause for the decline and loss of species, but legislation in all countries calls for ecological improvements of hydropower plants. This includes several components such as E-flows, fish migration upstream and downstream, routing sediments through reservoirs and re-balancing the sediment budget and mitigating hydropeaking impacts. The final evidence that measures taken are successful is based on a comparison of potentially occurring fish populations and actual findings. This is a challenging and costly effort but there is a general consensus that it must be attempted.

Countries and regions take different steps towards accomplishing these goals. Special difficulties arise from the fact that land which was historically part of the river floodplain is now disconnected from channelized and regulated rivers and used for agriculture, urban and industrial development. This makes the restoration attempts difficult and costly and partially impossible in the case of so-called "heavily modified rivers".

The application of hydrodynamic modeling in combination with aquatic habitat models to develop and study different restoration scenarios, including E-flows, is state-of-the-art in such projects.

Bhutan is in a somewhat lucky situation because the hydropower development is at an early stage. The decision makers can study the development in other countries and try to avoid the most serious damages which have occurred, including the loss of more than 40% of fish species in large European rivers, migratory species mostly.

It would go far beyond the scope of this report to describe all the different rules and regulations which apply to E-flows in the above mentioned countries because they differ not only from country to country but even within the countries provinces or states have their own rules. What is being proposed for Bhutan is in agreement with the regulations and methodologies applied in the countries listed above for large hydropower plants and in agreement with the World Bank's good practice handbook on environmental flows.

Hydropower in Europe is generally under pressure from very low electricity prices at the open market. Operators are therefore generally not supportive of increased E-flows as it compromises economic success and in alpine countries energy generation in winter when it is most needed. They are asking for some sort of compensation or other incentives. In Switzerland, for example, electricity consumers are paying an extra charge on electricity that is reserved for ecological improvements of hydropower operation. Very small HPP receive a special feed-in-tariff in various countries. However, the situation in Europe is dominated by cheap electricity from coal power plants and a very strong influx from unregulated renewables (wind and solar) which are heavily subsidized. It is easier for older HPP which are paid off to adopt measures for ecological improvements whereas for new hydropower plants, which come only at very high specific investments (per installed MW), it is a critical component of the financial viability.

A comparison with Bhutan's neighboring countries and other Himalayan regions is beyond the scope of this report. However, based on existing EIA reports for hydropower projects in Bhutan prepared by consultants from the region, it became obvious that in some cases "methods" have been applied in the past that lack scientific background and are ecologically questionable.

1.2 Purpose and limitations of this guideline

This guideline focuses on run-of-river operations with dewatered reaches. It is not directly applicable to storage reservoirs large enough to change the intra-annual flow regime and it is neither directly applicable to river reaches affected by intermittent hydropower operation or so-called hydro peaking. However, the tools and some of the methodological approaches described in this guideline are based on general principles and also applicable to any other hydrological or fluviomorphological alteration of river systems including regime changes caused by large reservoirs or intermittent hydropower generation.

The dewatered reach is the reach of river between a dam or intake structure from where water is diverted into a conveyance system (such as headrace canals or tunnels) and the tailrace tunnel outlet where the water is released back into the natural riverbed.

The guideline has a focus on fish and their habitats but also touches methods to address the needs of other aquatic and semiaquatic species such as benthic invertebrates, floodplain vegetation, mammals, birds and other inhabitants of river corridors. Not only ecological aspects are considered, socioeconomic and sociocultural effects of reduced flow in rivers as well as the impact of E-flow releases on power generation and financial revenue for the power plant are treated as well.

Parallel to the work on this guideline, the World Bank Group has published a "Good practice handbook" on "Environmental Flows for Hydropower Projects" and it is recommended to also read this highly valuable document as supplemental background information.

1.3 Definition of the term environmental flows (E-flows)

Environmental flow describes the quantity, quality and timing of water flows required to sustain freshwater ecosystems and the human livelihoods and well-being that depend on these ecosystems (after the Brisbane Declaration 2007).

Environmental flows (E-flows) is therefore the minimum flow of water which must be flowing in a certain cross-section of a river bed at a certain time of the year. E-flow is not a single number but can be any combination of constant flows to be released during certain times of the year (e.g. seasons, specific months or in between certain dates) or which must be released or exceeded within certain temporal intervals (e.g. once in every three year interval), or randomly (e.g. during natural spill periods). Environmental flows can change along the course of the dewatered reach and they can differ from the actual releases at the foot of the dam because they are sometimes supplemented by natural inflows from tributaries or groundwater exfiltration but also reduced by evaporation losses or losses to permeable undergrounds such as karstic conditions.

1.4 Impact of reduced flows in river ecosystems

River ecosystems are influenced in multiple and complex ways by the reduction of flow and often also sediment. Dewatered reaches have specific properties which differ from pristine reaches. For a systematic understanding of what chain of impacts is caused and also where mitigation can be successfully applied it is helpful to structure the impact of reduced flows into four hierarchical orders. First order impacts directly describe the change of the hydrological regime caused by the diversion of water and, depending on the size of the upstream reservoir, a change in water quality and a reduction of the supply of sediments to the downstream river reaches. These are direct impacts caused by the abstraction and they can be influenced directly by the operation of the dam, reservoir and hydropower plant based on E-flows and sediment management.

Second order impacts are caused by the reduction of flow and sediment supply and mainly describe the change in hydraulic parameters, such as local water depths, flow velocities, turbulences, water volumes, water surface elevations, but also a change in water temperatures, typically warmer in summer and colder in winter. Sediments are often trapped in reservoirs, particularly in large ones with a large storage volume near or above the annual runoff volume, thus causing a reduction of the sediment supply from the upstream catchment. At the same time the sediment transport capacity can be reduced because of the reduction of flow, but it is often maintained to a large extent if the reservoirs are small and spill is occurring during the wet season. In such a situation it can be expected that fine sediments are flushed out from the dewatered reach and an armor layer is developing at the surface of the riverbed. Depending on the relationship and the changes to supply of sediments and transport capacity the riverbed bathymetry and floodplain morphology will change over the first years or decades and eventually reach a new equilibrium. Some of the most common impacts are depth erosion of the riverbed or the formation of an armor layer at the bed surface. Riverbed depth erosion is resulting in the formation of single thread channels versus braided channels and the disconnection of side channels in the floodplains or access into tributaries.

Second order impacts are purely physical but they have an impact on riverine species and species communities since they are forming the habitats.

> E-flows must be evaluated in a catchment wide approach, not only based on individual sites. This leads to the consideration of cumulative impacts, e.g. several HPPs, also including other consumptive or non-consumptive water uses such as irrigation water supply or wastewater dilution. The sediment handling at the dam and reservoir and E-flows are interlinked and must be considered conjunctively.

Third order impacts are biological alterations of the species and their communities because of the change of their habitats. In general, a change in species communities is observed, mostly for fish and benthic species but also for floodplain vegetation or fish feeding birds and mammals. Changes in fish communities refer to biomass, age class distribution, size and weight of individuals, spawning success, health status and other parameters describing the species. If the flow reduction is too severe, a loss of some or all fish species in the dewatered reach will occur. Some of these changes are driven continuously by physical alterations, others can be instantaneously and terminal once a certain threshold is reached or exceeded. What is most obvious for fish is also happening to benthic species where the composition of the benthic community will change due to the alteration of the riverbed (armor layer or siltation with fine materials) and the reduction of flow forces at the river bottom. In general reophilous species, those preferring stronger currents, are reduced and replaced by limnophilous species. A change in inundation dynamics and reduction of sediment supply especially in braided or meandering river reaches with adjacent floodplains will also change the vegetation communities of the floodplains over time. Where large reservoirs are storing even flood flows, the downstream river corridors channels will be covered by vegetation otherwise removed by annual floods. This results in a loss of open gravel and sandy areas which is important habitat to ground breeding birds and many insects such as spiders and beetles.

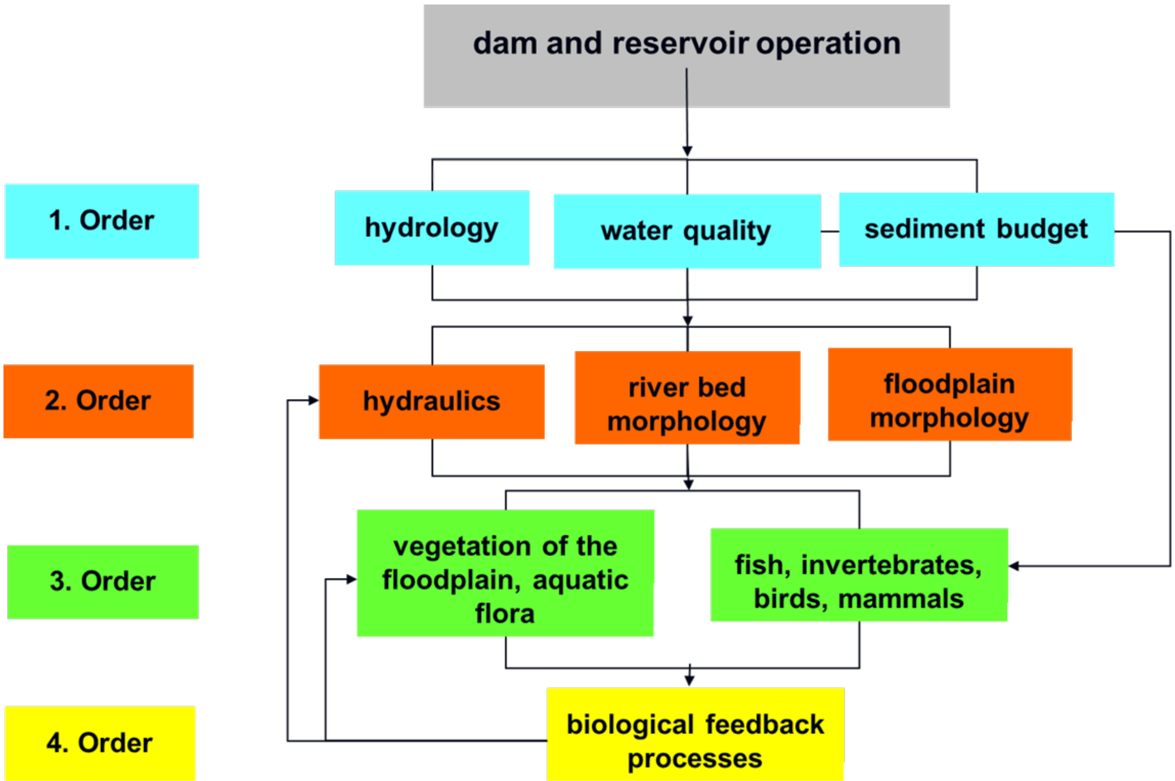


Fig. 1: A hierarchical view of river ecosystem alterations caused by reservoir operations and flow reduction.

Finally fourth order impacts are caused by biological alterations that have an effect on the higher order impacts. A very common consequence of flow reduction is the encroachment of permanent vegetation towards the river channel which then has an effect on the hydraulic roughness of the channel and thus causes higher water levels during floods.

The removal of regular (e.g. annual) flood flows is usually followed by construction of homes along the river, now somewhat protected by the dam but still in the floodplain. Larger floods (e.g. 50 or 100 year events), exceeding the storage capacity of the reservoir, can destroy these buildings and cause major economic damage. This is not yet the case in Bhutan but definitely in neighboring countries and a general trend all over the world.

Fig. 1 is showing an overview of physical and biological changes common to dewatered reaches.

Depending on the degree of dewatering a river reach because of hydropower use, the changes can be highly dramatic including complete loss of species. The losses can go way beyond aquatic ecosystems and, if the dewatered reach is part of the migration path of long-distance migrating fish species, the changes can reach far upstream and downstream from the actual hydropower development. For this reason, it is mandatory that environmental flows and the conservation targets linked with them must be evaluated in a watershed context.

Ecosystems are adaptive over time and a loss of some species or the replacement by others does not mean that the ecosystem no longer exists. However, pristine river ecosystem with their spatial and temporal dynamics are limited and there is no replacement anywhere.

Species lost in a system like that will not find replacement habitats. The species which remain are mostly less specialized ubiquists which can be found everywhere in the region.

1.5 Other impacts

Environmental flows are causing a significant reduction in revenue for the hydropower plant generated by selling energy to the market. The reduction of the total flow volume which has to be released into the dewatered reach instead of running through the turbines is approximately linearly linked with the loss of financial revenue. In extreme cases and depending on the type and number of turbines it is even possible that the HPP cannot be operated any more because the minimum flow necessary to operate even one turbine is no more available resulting in a complete shutdown. Early consideration of E-flows would help to avoid such situations.

River flows are not only fundamental for riverine ecosystems but often they are also highly significant for the livelihoods of people dwelling along the river valleys. River corridors have been traditional habitats for humans. Rivers provide water for drinking and irrigation, they provide opportunities for fishing and hunting, they enable transportation, navigation, remove wastewater etc. In regions where tourism plays an important role, river valleys are essential components of the natural inventory which attracts tourists. Rafting and kayaking, sport fishing as well as hiking and trekking along rivers is considered highly attractive. Often important cultural sites are located close to rivers and their floodplains. All these human aspects are affected by a significant reduction of the flow of water in a river bed. Some are highly significant and may completely disrupt the livelihoods of people living along the river, others are more a reduction of the general amenities people living along the river can enjoy. In some cases where rivers pose a threat through flooding and destruction to the people living along them it is seen as a positive development when the rivers are dammed and dewatered for hydropower generation.

1.6 Objectives of establishing environmental flows

The general objective of establishing environmental flows is to maintain the integrity of aquatic environments affected by hydropower operation by maintaining the physical processes, such as the flow of water and sediments, which are driving the biological functions. While fish populations are a key component of most aquatic environments, other aspects such as other aquatic species but also birds and mammals, as well as sociocultural and social economic aspects must also be considered. The conservation of biodiversity and the conservation of the ecosystem services provided to humans is the general objective of establishing environmental flows. Since environmental flows are significantly affecting hydropower generation and production and therefore the direct economic benefit resulting from hydropower use, this aspect must be considered as well.

In this regard setting environmental flow regulations is imposing a dilemma on the decision-makers since nearly every drop of water left in the river for biodiversity conservation is at the same time reducing the direct economic benefit from the hydropower plant.

Providing environmental flows should always be considered in conjunction with enabling fish migration upstream and downstream across dams and reservoirs.

2 METHODS TO DETERMINE ENVIRONMENTAL FLOWS

Environmental flows, predominantly for the protection of fish populations, have been used in some countries for more than 100 years. A percentage of some hydrologically determined discharge was used in most cases. The methods are simply to apply but they have no ecological relevance unless they are based on regional empirical studies. For this reason transferability is very questionable. Hydrological methods are still utilized for a large share of the environmental flows established worldwide. However, countries with more than 100 years of hydropower experience and a high concern for environmental sustainability began adopting more advanced methods, such as hydraulic rating methods and habitat modeling, over the past decades. They are now the internationally recognized state of the art in many countries and regions. So called holistic methods have been developed on the southern hemisphere where large reservoirs which are changing the annual flow regime are affecting the livelihoods of people living sometimes hundreds of kilometers downstream of the reservoirs along the river corridor and whose livelihood is dependent on the hydrologic cycles of the river.

2.1 General overview of methods applied

A brief overview is showing some of the most commonly applied approaches to determine environmental flows.

- Hydrological methods (Tennant Method, Methods based on Mean Annual Flows, Q_{347}, ELOHA[1])
- Hydraulic rating methods (hydraulic perimeter, water depths, flow velocities etc.)
- Methods based on aquatic habitat modelling (PHABSIM, CASiMiR…)
- Holistic Methods (DRIFT, BBM)
- Advanced methods and models for specific situations, usually a combination of physical processes and ecological functions to be analysed, e.g. fish-population dynamics modelling based on hydraulic parameters, hydraulic parameters plus temperature for fish hatching, floodplain-vegetation dynamics modelling, fish stranding due to rapid flow changes caused by peaking operations etc.

Table 1 summarizes a comparison including advantages and disadvantages of different methods.

[1] ELOHA cannot be counted to the “simple” methods because it integrates much more than simple hydrological data and is based on empirical knowledge from many advanced studies.

Table 1: Comparison of methods to determine environmental flows

Category	Duration of assessment (months)	Major advantages	Major disadvantages
Hydrological Index	1/2	Low cost, rapid to use	Not site specific, purely empirical, not transferable ecological links only assumed
Hydraulic rating	2-4	Low cost, site specific, relevant habitat parameters considered	Ecological links assumed but not quantitative
Habitat simulation	3-18	Relevant habitat parameters, quantitative ecological links included	Extensive data collection and use of experts, high cost
Holistic approach	12-36	Covers most aspects	Requires very large scientific expertise, very high cost, not operational

Today the state-of-the-art in countries with long hydropower experience and high ecological standards is mostly based on site-specific studies that have to prove that certain habitat requirements for fish and other species are maintained.

More complex methods like habitat simulation and holistic approaches have the advantage of allowing the development of scenarios, which can then be given to the decision makers. The scenarios are based on best scientific understanding and not influenced by a tendency to favor one or the other direction, hydropower development or river ecosystem protection.

The advantage of using habitat simulation models is based on the integration of quantitative ecological links which allow to determine with a fairly good precision how much water must remain in the river to achieve certain protection levels for habitats. At the same time these methods allow for avoidance of the release of more water than necessary into the dewatered reach which would otherwise be lost for power generation.

2.2 Objectives of setting environmental flows

The objectives of setting environmental flows are:

- to maintain the hydrological character
- to protect the longitudinal, lateral, vertical and temporal connectivity of the water bodies in the river system
- to maintain the sediment transport regime
- to support the riverine landscapes and biotopes
- to provide sufficient habitat for species communities in terms of quality and quantity

In addition socioeconomic and sociocultural aspects must be considered.

Finally the effect of E-flow regulations on power generation and annual revenue of the HPP must be considered.

Maintaining the hydrological character means that the natural flow regime should not be reversed (e.g. wet season, dry season) and no sudden and rapid flow changes should occur in the dewatered reach. It also means that natural flood cycles should be maintained to a certain level. In the case of run-of-river operation this is usually automatically the case.

Connectivity refers to the connection between different water bodies. In the longitudinal direction it means that no upstream and downstream migration barriers due to low flows should be created. In lateral direction it refers to the connection between the mainstem river and site channels in the floodplain but most of all to the access into smaller tributaries which may be necessary for spawning or to take refuge during harsh conditions such as flooding. Vertical connectivity refers to the connection between the water body and the interstitial aquifer. In a natural river bed several meters of the gravel bed are used as habitat for benthic species and also for fish eggs and freshly hatched fish. If the riverbed is clogged by fine sediment depositions, the access to the interstitial space is blocked. Temporal connectivity refers to the interruption of access or connectivity due to unnatural flow changes throughout the year or shorter timescales.

The maintenance of the sediment transport regime is important for several reasons. Under natural conditions sediment is transported from upstream to downstream with most of the transport taking place during the flooding season. This transport regime is based on a dynamic equilibrium between sediment supply and transport capacity. For example, it brings suitable spawning gravel into river reaches and it cleans the gravel from fine deposits during floods where sediment motion is taking place. This dynamic equilibrium is therefore of utmost importance for the ecological function of the riverbed bottom.

The support of the riverine landscape and biotopes is a fairly general term but it becomes highly significant in conjunction with tourism. Riverine landscapes without water are not attractive for tourism including lodging along riverbeds, hiking and trekking along the river valleys, kayaking and rafting etc. Riverine landscape can also include case specific aspects such as a river acting as a divide between habitats and animal populations, e.g. between predator and prey. Where such functions are known they can be analyzed and protected.

Finally, the conservation of aquatic and semiaquatic habitats is at the core of the conservation goals for riverine ecosystems.

A full conservation of aquatic and semiaquatic habitats would actually include all the other aspects because they are components of sustainable habitats. It is still meaningful to include the other specific aspects since they are addressing conservation goals at a level that may go beyond specific habitat requirements of individual species.

3 Methodology recommended in Bhutan

The methods recommended in Bhutan are based on methods applied nowadays in countries with more than a century of hydropower experience and a high level of commitment towards the conservation of river ecosystems. A systematic approach is suggested which is applicable to all hydropower projects, including types of hydropower plants yet to be introduced in Bhutan. Since there is no one method which is appropriate in all situations, a decision tree approach has been developed. The decision tree is applicable to all types of hydropower projects and leads, depending on the specific features of the project, along a specific path through the decision tree, covering a suite of methodological components to be applied. The individual components and methods are described in the flowing chapters and the project specific path along the decision tree identifies which of the components are to be applied.

Thus, for each specific project, a clearly defined methodological approach is identified.

3.1 Introduction

Environmental flow regulations are applied to three different types of river reaches affected by hydropower operation. Most commonly, environmental flows are applied in dewatered reaches of diversion-type hydropower plants where the water is taken from the river system at the intake and returned back into the river system at the tailrace outlet of the power plant. In such a situation most of the water is conveyed through artificial canals, shafts and tunnels and only a small residual flow is left in the natural river bed. The length of the dewatered reach usually is between some tens of meters up to tens of kilometers.

The second situation is downstream of large reservoirs, either directly below the dam, if the HEP is at the foot of the dam, or downstream of the TRT outlet, where all the water is back in the river bed. These river reaches are affected by regime changes only, not by flow reduction, unless some of the water from the reservoir is taken for consumptive uses, such as irrigation purposes.

The third situation are river reaches affected by intermittent hydropower operation, so called hydropeaking, where regime changes and rapid instantaneous flow changes occur in combination. These reaches are starting immediately downstream of the TRT outlet or the power house located at the foot of the dam and they reach as far downstream as the regime change is relevant, possibly as far as the river delta stretching into the ocean.

While many components of the methodologies described here are applicable to all situation this guideline is focusing on the first situation, the dewatered reach of diversion type HEPs.

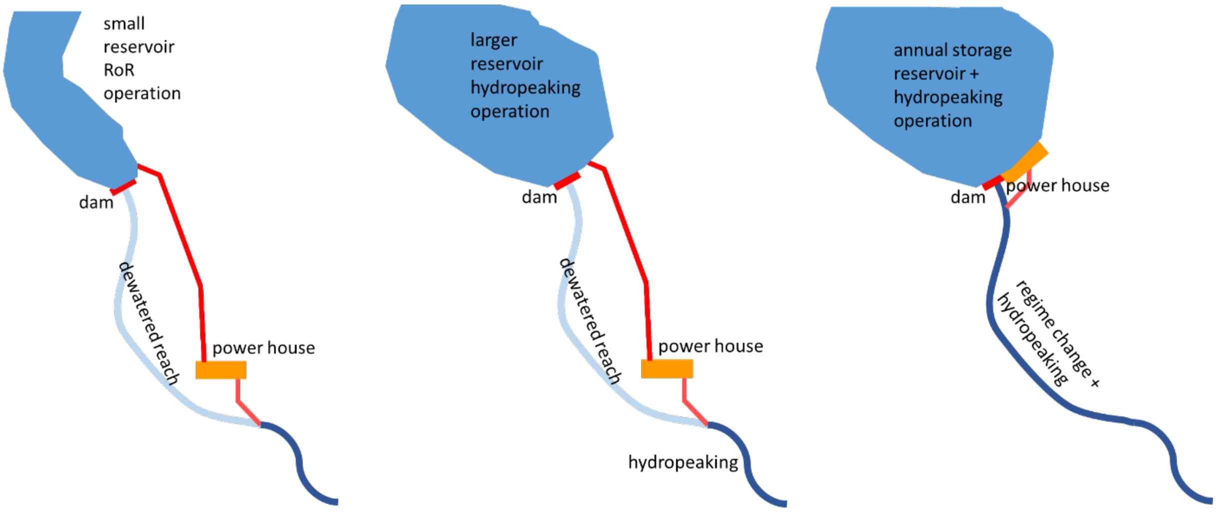


Fig. 2: Types of hydropower plants and river reaches where E-flows are relevant, dewatered reach only (left), dewatered reach and downstream of TRT outlet (middle), downstream of dam (right)

3.2 Decision tree

The decision tree provides the structured path towards a tiered approach to finding the general procedure and detailed methodologies to determine river and site-specific E-flow regulations. A tiered approach is necessary because of differences in the natural condition of river ecosystems in dewatered reaches of different HEPs. In particular, existing or potential fish communities abundant in the dewatered reaches and the level of protection required in a watershed context will have a strong influence on the methods to be applied. For this reason a decision tree has been developed which will guide through different types of E-flow evaluation strategies and result in a clear recommendation which methods are to be applied.

> A run-of-river hydropower plant is characterized as follows: The inflow rate into the reservoir or intake pond equals at any point in time the flow rate downstream of the power house or tailrace tunnel outlet. No regime change takes place, independently of the time period considered.

The decision tree is split into components: the first component (Fig. 3) is used for the distinction of different types of hydropower plants regarding the construction and operation and particularly between run-of-river and intermittently operated or regime changing HEPs.

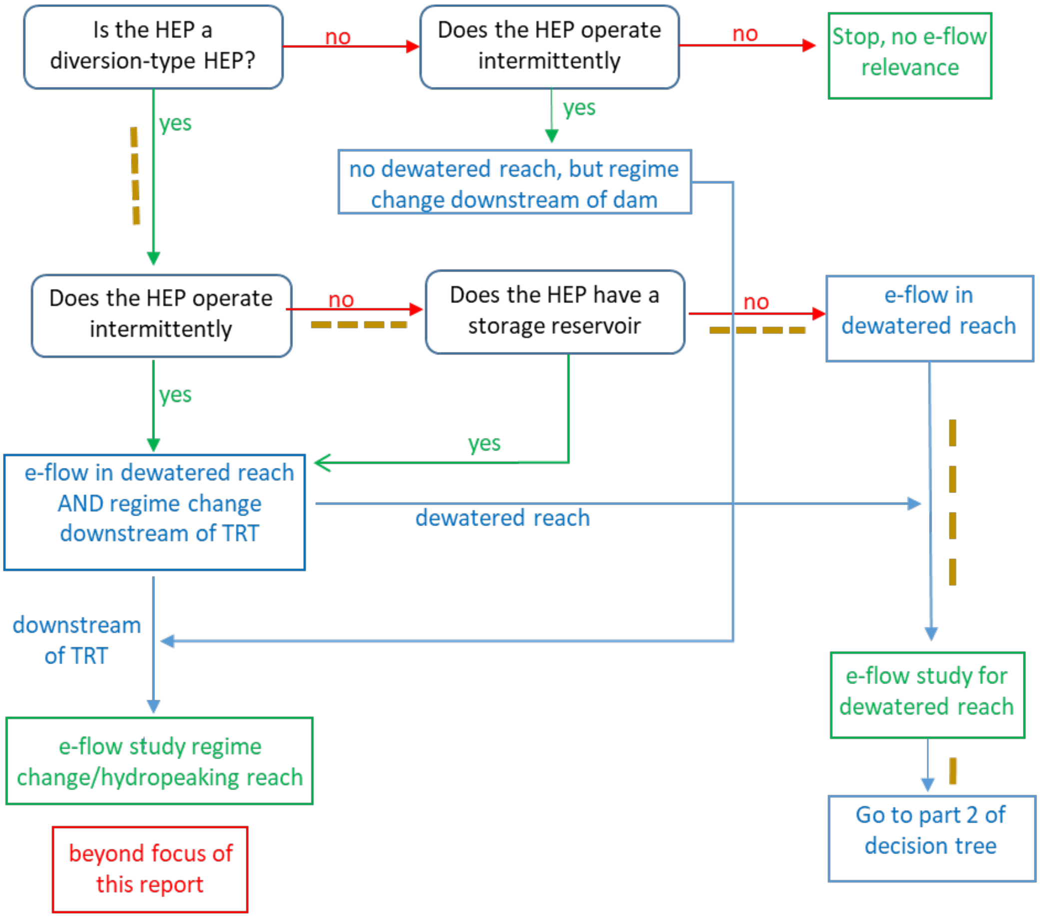


Fig. 3: Decision tree part 1, the dashed golden lines represent the pathway for the pilot reaches for this study

The second part of the decision tree (Fig. 4) is leading to the specific methodology to be applied depending on the presence or absence of different fish species or communities, the conservation goals and other relevant biota. The dashed box in Fig. 4 contains the core methodological components described in detail in chapter 3.

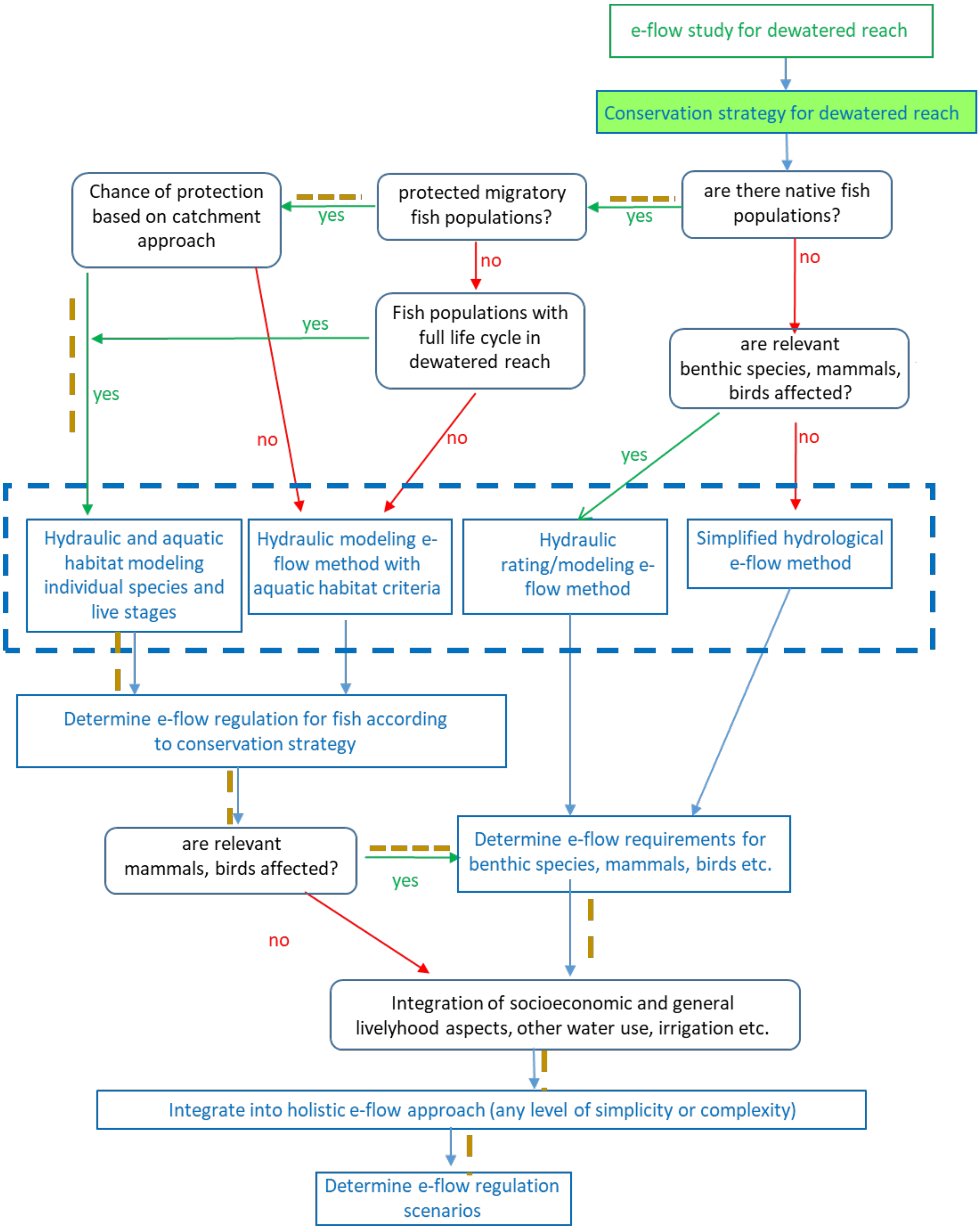


Fig. 4: Decision tree part 2, the dashed golden lines represent the pathway for the pilot reaches for this study

For any existing or planned HEP a clear path through both parts of the decision tree will lead to a final distinction of the methods to be applied.

3.3 Description of individual methods and components

In this chapter the methods in the decision tree are described in detail. Which of the methods should be applied in a specific situation is determined by the path through the decision tree.

3.3.1 Definitions

In this chapter some "terms" which are an essential part of the procedure described in this guideline are explained. Table 2 is also describing some of the essential characteristics of the terms which will be used to describe the procedure.

Table 2: Definitions of terms used in this guideline

Term	Spatial range	Target communities	Metric parameter	Based on, derived from	Examples
Conservation plan	Countrywide, catchment, cumulative assessment[2]	Species communities, individual species	Linguistic description	National conservation plan	Conservation of all naturally or potentially occurring species
Conservation goal	Specific river or river reach (e.g. entire tributary to next confluence)	Species communities, individual species	Linguistic description	Watershed conservation goal in agreement with national conservation plan	Maintain access to tributaries, protect migration corridor for large migratory species (Golden Mahseer) and habitat for other fish.
Protection category (PC)	River reach under investigation, e.g. dewatered reach	For each individual target species, may differ from specie to specie	5 Categories very high to very low, determined by most critical potentially occurring specie	Individual assessment based on (potential) fish inventory and conservation plan	Very high, high, moderate, low, very low, max. value for any specie determines PC for reach
Achievement goal (AG)	River reach under investigation	Specific species, life stages and season	WUA and HHS, translates into discharge	Based on protection category and results from habitat simulation models	0-20%, 20-40%, 40-60%, 60-80%, 80-100%
Achievement level (AL)	River reach under investigation	Specific species, life stages and season	WUA and HHS in comparison to achievement goal or WUA at reference flow	Achievement goal, scenario development, habitat simulation model	0 % - >100%

Conservation Plan: conservation plan refers to the national plan to protect and to preserve species communities or specific species in a river basin or in the country. It must be based on a national fish inventory which is currently under preparation through another project but was not yet available for this project as of May 2018. It should be in line with the constitution and national legislation as well as international standards for the protection of ecosystems. The conservation plan has nothing to do with a specific project such as a hydropower plant. It should not only be a political statement but it should be a nationally recognized document along which strategic and concrete project related decisions should be made. The conservation plan is a text document.

[2] cumulative assessment means that the conservation goal cannot be considered based on a single hydropower plant or other measure to be implemented but that previously existing HPP and HP development planned in the future must be included in an overall evaluation.

Conservation Goal: The conservation goal is in reality a set of individual conservation goals for species or communities. It should be set up for a specific basin or sub-basin and specify conservation goals for the main river including tributaries or individual river reaches. For main Bhutanese rivers the conservation goal should cover the rivers from the steep headwaters to the confluence with the Brahmaputra in India. The conservation goal has to be in full agreement with the national conservation plan but more specific by identifying conservation goals for certain species communities or individual species. The conservation goal clearly relates to the specific situation of the river or river reach within the catchment, including the existing or potentially existing fauna and flora and the existing and/or planned hydropower development and therefore also make assumptions regarding fish migration in the future. All decisions regarding the construction or operation of hydropower plants or other relevant activities must be in agreement with the conservation goal. The conservation goal is a text document and the same documented conservation goal is to be applied to all hydropower projects along a particular river.

Protection Category: The protection category is referring to individual fish species and the river reach under investigation. It is reflecting how important the river reach under investigation is for the achievement of the conservation goal for the species under consideration and how endangered and therefore how important the protection of the species is. The protection category is organized as a general scale with five categories which are to be applied to each individual target species. Along with the protection category a description of the seasonal and lifecycle related use of the reach by the species under consideration has to be provided. The protection category depends how threatened a fish species is and which critically important role the reach of river is representing for the life cycle of the species. Flow requirements for species and life stages with a high PC will be an overruling during the integration process. A protection category directly links to the preservation of a certain percentage of weighted usable area (WUA) (see Table 3).

> As an example, the national conservation plan could determine that Golden Mahseer must be protected. The conservation goal for Punatsangchhu could determine that for the protection of Golden Mahseer according to the national conservation plan the following aspects are of highest importance: 1) the spawning creeks upstream of the PHP II TRT outlet must remain accessible during rearing and spawning time and 2) migration corridors and rearing habitat before spawning must be fully maintained in the main river. A protection category of “very high” applies which means that 80% of the WUA under natural or “reference” conditions must be preserved. WUA ≥ 80% is therefore the achievement goal.

Achievement goal: The achievement goal is a percentage figure and results from dividing the WUA simulated for a certain E-flow by the WUA during the natural reference flow for a life stage of a fish species during a certain time of the year, the lean season for example. The level of percentage to be achieved depends on the protection category. For example if a fish species is falling under the protection category “high” and the adults are living in that reach of river all year round then at least 60% - 80 % of the WUA during natural flows (seasonal reference flows) must be reached by the E-flows during each respective month or season. These percentages can directly be applied to the results of the habitat simulation thus resulting in flow rates. These flow rates would be standing for full achievement of the goals for this species and the protection category.

The achievement goal for other species or life stages than the critical target species can be lower than the PC would require. Therefore, different species in the same river reach can have different achievement goals with the critical target species having the highest one, referring to the protection category.

Achievement level: The achievement goals cannot be fully reached in all cases while maintaining an economically viable hydropower operation. Also, in some situations requirements of one species will contradict the requirements of another one or of a different life stage. Consequently, not all AG can always be achieved. It is therefore necessary to develop a range of scenarios where the losses in hydropower generation based on a variety of E-flow regulations are compared with the ecological consequences for different species. The ratio of the actually achieved weighted usable area in comparison with the WUA at the reference flows is called achievement level.

Table 3: Protection categories and achievement goals for WUA

Protection category	achievement goal or achievement level	description
Very high	> 80 %	good ecological status, no loss of species, no significant effect, possibly some alteration in age class and size distribution
High	60 to 80%	moderate impact on species community and composition, generally no loss of species (some benthic species may be lost), impact on age/size classes
Moderate	40 to 60%	strong impact, possible loss of species, reduction of biomass
Low	20 to 40%	very strong impact, loss of species, marginalized populations left.
Very low	< 20%	No fish? Strongly marginalized populations?

Bottlenecks: Bottlenecks can occur independently from general habitat conditions and cause a total disruption of species communities. One obvious example for a bottleneck are migration barriers in or outside the study reaches formed by a single drop or boulder ramp which makes migration impossible below a certain flow. This is something that is not easily identified by modeling results and needs to be evaluated and solved within the monitoring process and the adaptive management. Bottlenecks can also be temperature thresholds or lost access to tributaries or any other single aspect which could stop the successful life cycle completion of a species or population. The Wangdi Rapids on Punatsangchhu are for example a series of individual potential bottlenecks where individual drops may form a migration barrier for some or even all fish.

3.3.2 Preparatory works

The preparatory works include the provision of general information of the planned project including its location within the river system which will allow to assess the general impact the project might have on the ecological situation of the river catchment. Most of the information required here is already available and must also be provided in the prefeasibility or feasibility stage of the hydropower project itself. If the technical and environmental design of the hydropower project is done conjunctively, all the data can be collected and established in one effort.

First, a fundamental set of information and data related to the planned hydropower development must be assembled. This includes:

- A map of the Bhutanese watersheds with all existing, under construction and planned HEPs and showing the HEP under consideration for the particular study.
- A map of the specific basin with all relevant tributaries (e.g. contributing more than 5% of the basin) including the delineation of their catchments, existing or planned dams, reservoirs and HEPs, highlighting the project under consideration.
- A CAD drawing, plan view, 1:1000 to 1:10000 (depending on the spatial expansion of the project) showing all structures of the project, in particular the dam, the intake, the reservoir, shafts, tunnels and penstocks, surge tank, the powerhouse and the tailrace tunnel.
- A longitudinal section of the entire river from the headwaters to the confluence with the next mainstem river showing all existing and planned dams, reservoirs and HEPs, all gauging stations and any other information which might be relevant (e.g. natural waterfalls, natural migration barriers etc.)
- A CAD drawing, longitudinal section, same scale as the plan view, of the dewatered reach, showing the same information as the plan view.
- CAD drawings of cross sections of the dewatered river reach starting from the dam site and reaching at least 100 m downstream of the tailrace tunnel outlet.
- A set of data to describe the planned HEP development including:
  - the design flow and rated head of the turbines
  - the type and number of turbines, including the number of nozzles in the case of Pelton turbines
  - the planned impoundment water level
  - the elevation of the turbine axis and the elevation of the water level at the tailrace tunnel outlet
  - the planned operational mode of the power plant
  - the sediment handling strategy (structural components such as flushing gates and operational concept)

This list should be seen as a general recommendation based on the assumption that all listed information are available from the hydropower development planning and should be made available by the developer to support the E-flow study. If the required information is not available discussions should be held for each specific situation on any other information that may be available or gathered alternatively. In the case of very small diversion type HPP on tributaries less information may be sufficient.

3.3.3 Hydrological analysis

Hydrological regimes of all rivers in Bhutan that are or will be used for hydropower generation have a very similar hydrological regime with only minor shifts in timing. The lean season dry flow is very stable and shows only very small differences between drier and wetter years. Flows during the wet season are more fluctuating. Two distinct flow rates are used as "natural" reference situation for the lean and the wet season Q_{100} and Q_{335}. Habitat conditions shaped by these flow rates are considered as natural reference for the respective season and will be used as benchmark for habitat evaluation.

The climatic and meteorological situation, natural hydrology, basin topography, sediment household etc. has to be briefly described. In some cases and mostly on the mainstem rivers there is a good chance that good hydrological data are available based on gauging stations that have been operated for many years. In other situations rivers might be un-gauged, although, without reliable hydrologic data no HEP can be promoted. It is therefore necessary to provide all information that is available on the hydrology of the affected river system. It has to be described whether and how the data were measured or simulated. The following data give an indication of what should be provided:

- gauging stations including the exact location, the type and technique of the measurements taken and the time and duration since the data have been collected.
- hydrographs at the intake location as available (all years that are available), preferably on daily basis
- mean annual flow MAF
- mean flows during the dry and the wet season
- mean monthly flows for each month of the year
- envelope numbers (minimum and maximum and 95-percentiles) for each month of the year
- mean flow duration curve and the "reference flows" for the wet and dry seasons Q_{100} and Q_{335}.
- Based on an analysis of all data, a representative hydrologic data set such as a "reference year" must be identified. This data set will be used for the analysis described later. The reference year is characterized by a mean annual runoff which is close to the average and a flow duration curve which should

Some relevant biological functions, for example floodplain vegetation rejuvenation, may be tied to specific hydrological situations which only occur during very wet years. In such situations it may be necessary to relate to more than one average reference year and use references for dry, average and wet years instead. It always depends on the biological functions considered and which physical processes can be linked to them.

be close to the average one.

- In addition and based on specific requirements in the conservation plan, it may be useful to select additional years as reference, such as wet and dry years.

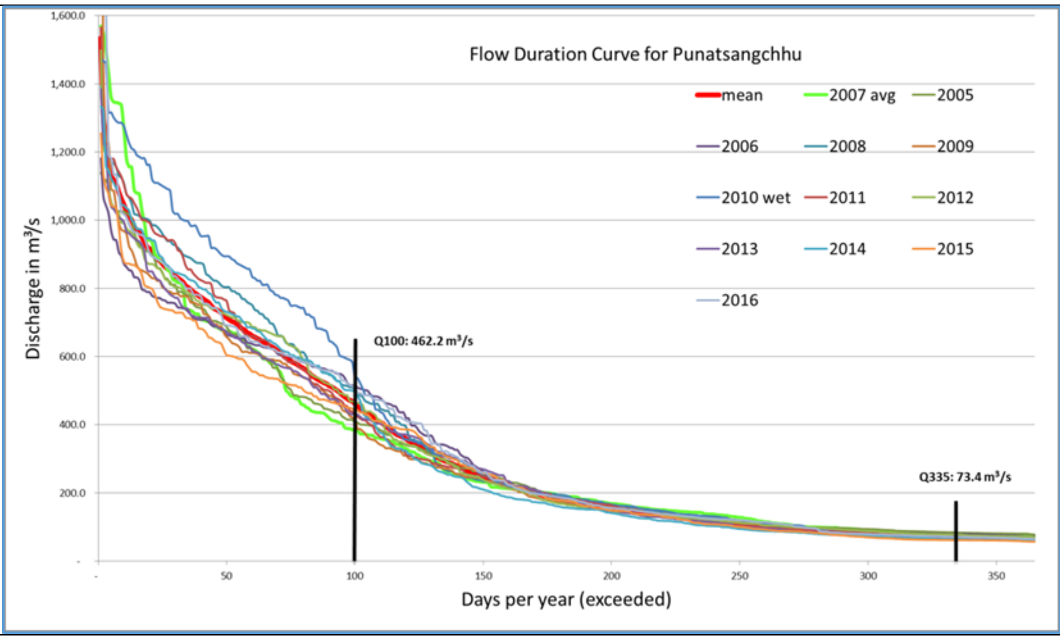


Fig. 5: Flow duration curve and reference flows for the wet and dry season, Q_{100} and Q_{335} based on an example from the Punatsangchhu

The reference flows for the wet and dry season, Q_{100} and Q_{335}, are always based on an analysis of the natural unregulated flow regime. They were chosen because they represent the lean season hydraulic situation and the wet season situation where flooding begins and fishes are seeking shelter. These flows also correspond to international recommendations for reference flows for migrating fish. These reference flows are generally applicable to snowmelt and monsoon driven hydrological regimes in Bhutan and therefore include sites with existing or planed hydropower development. For different natural hydrologic regimes, these reference flows may have to be altered.

To assess how the natural flow at the intake location is changing along the course of the dewatered reach a quantitative analysis of inflow from tributaries or groundwater infiltration into the dewatered reach has to be provided. For ungauged catchments a numerical model developed by Myint[3] or other hydrological modelling results could be used to determine monthly flows.

[3] Moe Myint: Reference unclear, model available in Bhutan

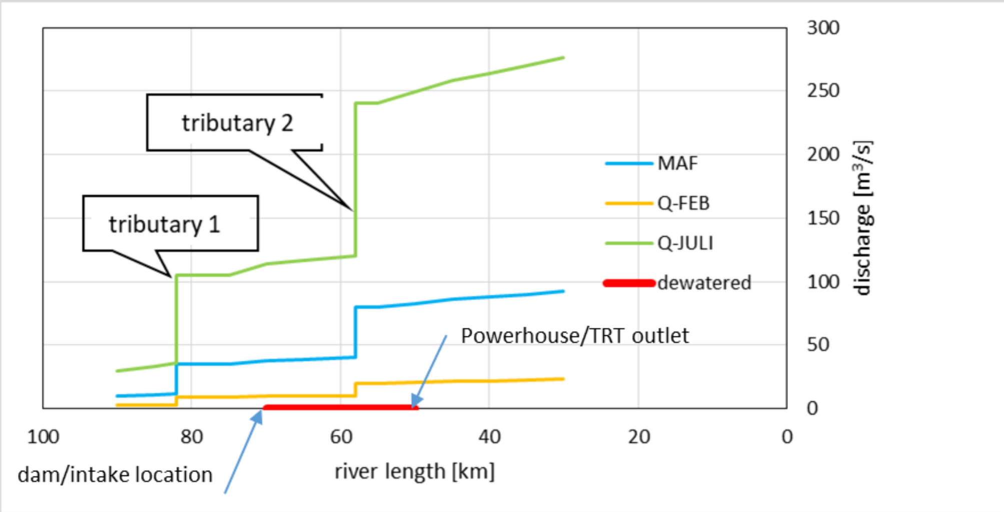


Fig. 6: Example of a simple hydrological longitudinal section of a river with two tributaries.

Fig. 6 is showing a simple example based on mean annual flows and mean monthly flows for the months of February and July of a river with 2 tributaries. It is obvious that the upper part of the dewatered reach is more critical whereas the lower part is fed by natural inflow.

There are situations, for example if the dewatered reaches are very short, where the inflows along the course of the dewatered reach are so small that they are negligible in comparison to the expected E-flow. In such cases this has to be clearly explained and it could be assumed that the flow released at the foot of the dam will remain constant throughout the dewatered reach.

If any other water uses, consumptive or non-consumptive, existing or planed in the future, are known, this information must also be provided, indicating the exact location, the quantity and the timing of the water use.

Methods to determine E-flows based purely on hydrological data are not recommended since they have no quantitative link to ecological issues. Where they are applied they either have to remain very precautionary, leaving possibly more water in the river bed than needed, or they do not support the desired ecosystem protection levels. Exceptions are acceptable for intakes high up in the mountains where no fish occur naturally if no other criteria ask for a detailed study.

3.3.4 Climate change impacts

Climate Change is expected to be a major driver of change to the fragile natural ecosystem in Bhutan. The glaciers in the Himalayas are reported to retreat faster than in other parts of the world, putting mountainous countries such as Bhutan, lying in the region, at greater risk in the future. Bhutan has already experienced partial outbursts of its glacier lakes in some parts of the country and it has been experiencing an increase in frequency of intense monsoon rains causing flash floods and landslides. Generally, the monsoon is expected to arrive earlier and is reported to become more unpredictable. Glacier retreat and warmer temperatures will also thaw permafrost soils and increase sediment supply to the rivers.

The impact of climate change on water resources of Bhutan was carried out as part of the ADB TA BHU: 8623 on Adaption to Climate Change through Integrated Water Resources Management (IWRM) for the National Environment Commission of Bhutan. According to this study, the number of days with minimum flows will be higher in the future (2030s and 2060s) than in the past.

Predicted changes in runoff in all studied river systems are showing that the lean season flows will decrease, but only changes of a few percent in annual runoff. It is therefore assumed that climate change impacts will not have a significant influence regarding E-flow requirements for the upcoming operating license periods. Other impacts such as more extreme events and various consequences from glacier melting will affect the river ecosystems, including the increase of the risk of glacier lake outbursts.

With warmer temperatures and other climate change impacts ecosystems will gradually adapt as can already be seen in various locations all over the world. The possibility of necessary adaptations of the E-flow regulation due to climate change impacts should be considered in the monitoring and adaptive management strategy. Generally it is assumed that E-flow regulations will not need any adaptation due to climate change impacts over the next few decades.

3.3.5 Fish data collection on river/watershed level

Landscapes and watersheds are physically defined by their topography, geology and climate. The landscape template influences hydrologic and sediment supply regimes that control channel forms (Beechie et al. 2013). These authors also emphasize how biological processes influence the biogeography of fish species and operate at long space- and timescales (over tens of thousands of years). Biological processes (migration, colonization, extinction, evolution) resulted in biotic assemblages that are adapted to the local geographic and climate settings of individual river systems and reaches. The range of habitat used by fishes is highly variable. Most of the freshwater habitats will contain fishes. Few streams are devoid of fish (extreme headwaters with high gradient or if reaches regularly go dry or if waterfalls make the colonization impossible).

In Bhutan there is a need for a full understanding/overview of which streams contain fish and which species are living in a specific basin. Local physical characteristics determining the fish assemblage are stream width, water depth, pool-riffle sequences, habitat diversity and longitudinal zonation. Additional important parameters are altitude, temperature and discharge patterns. A concept of regional fish diversity should be developed for Bhutan. It should be based on hierarchical organization of factors regulating fish species diversity. The hierarchical levels are basins, reaches and habitat units. The different morphologies and life histories of fish in Bhutanese rivers and streams should be analyzed. For the different ecoregions the proportion of larger fishes and smaller fishes should be studied. In addition the ecological guilds and population parameters like longevity, age at first reproduction, fecundity have to be described. This is a proposed effort which is outside of this E-flow project but it will help establishing baseline information on fish in Bhutan and develop a conservation plan for the country and the region.

In order to have a national wide overview of fish occurrence in Bhutan a monitoring program is suggested. The fish investigation program should include all water bodies in Bhutan (lakes and rivers). All basins and sub basins (drainages) have to be included. Sampling sites should randomly be selected (simple random or systematic sampling with randomly selected starting points or stratified random sampling). Active and passive fishing gears should be used. A main focus will be on electrofishing. However electrofishing is less efficient with water conductivities less than 50-60 µS or greater than 1000 µS. Time of sampling and sampling effort have to be decided. Electroshockers with constant DC are recommended although pulsed DC may be applicable too. However, continuous DC is general viewed as the least damaging of waveforms (Reynolds & Kolz 2012). In lakes and reservoirs the use of gill nets is recommended. Several locations and depths should be sampled. However gillnets are passive fishing gears and active fish species are easier caught than sedentary species.

The aim of the fish monitoring is to have a good overview of the existing fish diversity and the regional diversity in Bhutan. Freshwater fishes are surprisingly diverse and react to human-induced habitat degradation or fragmentation, e.g. by dams and reservoirs. Habitat loss and modification is the principal cause of declines of fish populations. Future hydropower development and dam building in Bhutan will modify river catchments and have an effect on fish diversity and abundance. The altered hydrological regime may have an effect on the migration, spawning, occurrence and abundance of fish species. Stream assemblages can be replaced by species adapted to habitats with slack or stagnant flow conditions. Intact migration corridors are very important for fish species which migrate over long distances. The migration corridor and spawning areas at the upper end of the migration route have to be preserved as part of a catchment wide approach. This is especially true for the Golden Mahseer, for which spawning areas have to be identified and protected. The life history of Golden Mahseer and additional migrating species has to be explored. Important annual fluctuations in river habitat conditions may be responsible for the life history of migrating fishes. The magnitude of flow varies annually and distinct fluctuations in stream temperature are observed. On a long-term basis the population has to survive and reproduce successfully in this harsh environment. The successful reproduction is depending on the size of a fish and relatively large fishes are capable to reproduce successfully in this environment. Only deep bodied fish can bury their eggs down to 20 cm in the highly dynamic stream bed. The large bodied Golden Mahseer is highly sensitive to modified river flow, to hydropeaking and minimum flow. Not only flow conditions but also substrate conditions and habitat characteristics will be changed by intensive hydropower use.

However many small-sized fish species in Bhutan exist and their distribution and abundance have not been documented systematically. For the protection and conservation of native fish species a comprehensive list of occurring fish species for all the basins and sub-basins is needed. From the conservation point of view, this list has to be urgently developed for catchments that are already or will be used for hydropower (affected river stretches, stretches with power houses under construction, planned and selected potential sites). The fishes have to be classified in a red list indicating the status of conservation (critical – endangered – vulnerable – near threatened – least concern). Such information will help to define conservation goals and identify sensitive fish species that can be used as target species for environmental flow studies.

E-flow studies are seldom performed for all species and life stages occurring in a river reach because the effort is simply too high and the necessary information on habitat preferences is sometimes not (yet) available. It is therefore common to define target species for specific rivers. This will underpin the efforts for the conservation. A target species should be a characteristic representative of a fish community and an indicator for intact ecological conditions. A target species does not need to have the highest numbers of individuals in a fish community. Target species may refer to abiotic factors such as minimum flow or to biotic factors such as ecosystem health. They are also used when referring to species, to their distribution, protection or population size (Caro 2010). Target species are also used to identify which species should be the object of conservation efforts.

Atlantic Salmon started declining in the Rhine river system in the Netherlands, Germany, France and Switzerland more than 100 years ago and finally disappeared in the 1950s. Reasons were industrialization in general, fragmentation by dams and weirs, hydropower development, water pollution and habitat degradation. Efforts to reintroduce Salmon in the Rhine river system started in the late 1980s after water quality had been significantly improved. All measures in the watershed, including e-flow regulations, had to be in agreement with the so-called Salmon 2000 program. Particularly migration barriers had to be removed and fish passes had to be built. The first returning salmon in the Upper Rhine were found in 1995. It is now assumed that in 2020 a stable population will be re-established.

In situations where certain impacts such as existing hydropower development or the introduction of non-native species (e.g. brown trout) have led to the disappearance of what would otherwise be a target species for the reach, it is still common to use “potentially occurring species” as target species. Although this can sometimes be difficult, there should be proven evidence that the specie would occur or has occurred under natural “pristine” conditions in the river reach under consideration.

Pristine reference sites are sometimes difficult to find. Ideally, the establishment of natural fish communities should happen before any influence from hydropower development starts affecting the river, at least 2 years before construction works start. In cases where there is already a severe influence from hydropower operation electrofishing in impacted reaches will yield very disrupted communities which cannot serve as references. In this case reference communities must be established from fishing

One of the pilot sites studied for this project is the dewatered reach of Chhukha HPP on Wangchhu river. Only four species were found of which one is non-native brown trout. The dewatered reach of Chhukha is located in between Chhukha dam upstream and Tala dam downstream and therefore heavily impacted and fragmented in both directions. Downstream of Tala 16 different species are found in Wangchhu river, a highly productive system. The remaining 3 native species are representing an 80% loss of species, quite typical for such situations. To implement a conservation plan for this part of Wangchhu it is necessary to look not only at the species found in the dewatered reach but to address also potentially occurring target species.

downstream of the lowest migration barrier and possibly upstream too.

3.3.6 The conservation plan and establishment of conservation goals

A conservation plan for the entire country and conservation goals for each watershed in agreement with the conservation plan is a mandatory prerequisite to establish ecologically efficient E-flow regimes.

Fishes occur wherever appropriate habitats exist, from big rivers to steep mountain creeks and lakes on high altitude. For Bhutan an analysis is needed as a first step showing where fish diversity is located. This analysis has to be based on a watershed approach with a separate analysis for each basin. The outcome is an overview on the fish fauna of Bhutan and a so-called "red list" of threatened fishes. Each fish species has to be classified in a threat category. IUCN is using three levels of threat (critically endangered, endangered and vulnerable). Additional categories are: extinct, near threatened, least concern and data deficient (see appendix 1 and 2 for definitions and the categories for some fish in Bhutan and used for this study). Classification should be based on a scientific sound fish sampling strategy in all river basins.

Based on the results a national strategy plan for the conservation of fishes should be composed as follows:

- define and list the fish species of national importance
- formulate the sustainable use of river systems and related fish populations
- define the habitat infrastructure and connectivity that is needed (conservation areas/nature reserve and areas important for connectivity)
- prevent the spreading of invasive fish species (formulate measures)
- conserve the genetic diversity of fishes – consider genetic effects from fish stocking
- assess the services of ecosystems and the benefit for the human society
- define the contribution of Bhutan in order to conserve the biodiversity in the Himalayan region
- monitor the changes in riverine ecosystems, species composition and genetic diversity

Based on the results of the overview of fish occurrence in Bhutan and in specific river systems and catchments along with an understanding of the lifecycle behavior of the fish, conservation goals should be established for every river system and consequently for every reach affected by hydropower. Conservation goals are not only referring to fish species that are existing now in specific reaches but they focus on the potentially occurring species. The term "potentially occurring species" is referring to a natural situation without the influence of already existing hydropower or other human impacts. Reaches that are presently dewatered because of hydropower operation obviously have no fish or impacted fish populations but could potentially have more fish species again once a suitable E-flow regulation is in place.

In the pilot study reach of Parochhu only nonnative brown trout were caught during electrofishing. These require no protection. However, snow trout, which were not found, are naturally abundant in this reach, but were not found. It is not yet understood if snow trout were absent because of the season of the year or for competitive reasons because of brown trout, or for other reasons. Snow trout is a potentially occurring species in this reach and therefore used as target species in the study. However, without further evidence it could also be argued that no native fish species are abundant in this part of the river and therefore only migration must be enabled, no habitats.

Conservation goals must be developed based on a catchment wide and cumulative approach. Impacts such as of large dams or reservoirs to be built and operated in the future must be considered. It is meaningless to provide habitat for migratory species if it is already known that fish migration further downstream will be terminally interrupted by a large dam in the future. In this case considering fish habitats for such a species only makes sense if fish migration will be enabled throughout the dam and reservoir planned further downstream. This aspect applies specifically for Golden Mahseer. Golden Mahseer is not endemic to Bhutan. It occurs in several countries in the Himalayan catchments (Nepal, India, Bangladesh), however, the population in the Punatsangchhu and other rivers has to be considered to be unique concerning the genetical aspects its contribution to the local biodiversity.

Conservation goals should specifically list what habitat requirements must be fulfilled by the E-flow regulation. Habitat requirements refer to individual species and life stages (e.g. spawning, juvenile, adult) and possibly also to certain seasons of the year, for example the spawning season. Conservation goals are not linked to the level of habitat availability and quality, but the list of specific types of habitats which are to be protected in a certain river reach influenced by hydropower.

The quantification of habitat quality and availability will be done during the E-flow study based on a comparison of habitat type, quantity and quality under natural conditions, without the influence of any hydropower, and the situation under the influence of hydropower operation and certain E-flow regulations.

Related to hydropower development, the downstream and upstream reaches of a dam are separately considered. In general, river health and river integrity have to be ensured in order to sustain fish biodiversity. Biodiversity includes the variety of living organisms at genetic, species and higher level of taxonomy, as well as the variety of habitats and ecosystems and the processes that occur in them (Meffe & Carroll 1997). Fish species at risk and related habitat have to be protected.

Source populations refers for example to places where fish are born and grow. Later they outmigrate to other places where they are forming sink populations. Therefore, if the source populations are lost, the fish species disappears.

For upstream reaches it mainly means that the migration/dispersal corridor for fishes is not interrupted. This implies a safe downstream and upstream migration for fish species depending on the reaches upstream of the hydropower plant. It has to be verified that no “source population” of fishes will be negatively affected by dams. Source populations are populations with a high importance for the reproduction and survival of a population therefore inhabiting source habitats. Sink populations in the river depend on the source populations. Plans for dam construction must include the analysis of negative impacts on fish species depending on the upstream reaches of the dam. If important source habitats for a specific fish species are situated upstream of the dam the probability of extinction will be very high.

For downstream reaches of a dam the following criteria must be considered:

- reaches have to guarantee the functioning of a fish migration corridor and prevent the blockage of migration and habitat fragmentation
- are characterized by adequate habitat quality
- should not be affected by severe hydrologic regime modification
- have no altered thermal or chemical regimes and no scour of the river bed because of sediment retention
- do not favor the invasion of nonnative fish species
- have no distinct effect on the life history of fishes (survival, spawning, recruitment)
- do not alter the seasonal migration cycle
- do not decimate fish density

For getting fish past dams limited solutions are existing, however for high dams (> 50 m) finding solutions that work is a challenge. For high dams it has to be discussed if a fish lift, transportation (trap and truck) or the newly developed “whooshh” system can be considered.

With the help of a national strategy plan for the conservation of fishes an illustration of river reaches for hydropower development in the country is possible. In combination with the master plan for hydropower development those rivers and river reaches could be identified where the development may have the lowest impact on fish population and no or very little effect on the biodiversity of fishes. In addition reaches could be identified where hydropower development should be a no-go solution because of the high risk of biodiversity depletion.

3.3.7 Cumulative impacts, consecutive hydropower plants, future developments

Fragmentation by dams and reservoirs, hydrologic regime alterations and river training and channelization are among the key factors hindering fish to successfully complete their lifecycles and maintain sustainable populations. Migratory species, especially long distance migrators such as Golden Mahseer, rely on connectivity within river systems and suitable conditions in time and space.

Therefore the conservation plan and conservation goals must be based on a comprehensive understanding of existing and planned developments of hydropower projects in the entire catchment. This includes dams, reservoirs, run-of-river and storage HPP, as well as pumped-storage projects. It must also consider other existing or planed uses of the river, most importantly consumptive use, which may impact fish and other aquatic species.

In a first step, information on all existing and planned hydropower projects must be collected. Most relevant are:

- Location of the dam and intake
- Location of the power house and tailrace tunnel outlet
- Height of the dam
- Approximate area, length and upper end (backwater) of the reservoir
- Active volume of the reservoir and annual runoff volume of the river
- Type of HPP (Run-of-river, short term hydropeaking, seasonal storage, pumped storage)
- Rated flow, head, capacity and annual generation of the HPP
- Planed measures for the protection of fish and other species (environmental flows, fish migration upstream and downstream, etc.)

This information is used to develop an understanding of the effects of a hydropower scheme on the river system and its aquatic species. Higher dams are more challenging regarding solutions for upstream fish migration than smaller dams where fish passes can be easily built. But feasible solutions for high dams, such as the Whoshh system, are becoming available. Reservoirs are obstacles for fish migration for both upstream and downstream as fish may lose orientation in large reservoirs acting more like a lake rather than a river. For downstream migration, large reservoirs are problematic for small fish which cannot actively swim through a large lake. While run-of-river HPP do not cause any regime changes except in the dewatered reach, large storage HPP with upstream reservoirs may completely reverse the hydrological regime downstream for hundreds of kilometers. Pumped storage HPP, if they use a river reservoir as the lower basin, may or may not influence the flow regime downstream, depending on the size of the upper and lower reservoir and how they are operated.

As a result of this analysis it becomes obvious where the main existing and future problems for the conservation of fish and other aquatic species may be lying and what type of solutions or mitigations are needed.

Similarly, other water uses, such as water abstractions for irrigation, must be identified and included in this analysis.

Based on this understanding and in combination with the knowledge on fish species

There are a number of obvious examples in Bhutan why this is necessary. Discussing the protection of Golden Mahseer in the dewatered reach of PHP II must be done in conjunction with the discussion of fish migration upstream and downstream of the planned Sunkosh dam and reservoir. Another example is the dewatered reach of Chukha HPP which is fragmented and disconnected from its upstream and downstream reaches by Chukha and Tala dams that have no provisions for upstream or downstream fish migration. In addition there are plans to build a storage HPP further upstream, Bhunakha, which has a considerable storage reservoir and will alter the hydrological regime to a limited extent. A meaningful conservation strategy for the Wang Chhu and Chukha HPP must take these limitations into account and address if there are possibilities and the willingness of re-enabling fish migration at Chukha and Tala.

occurring or potentially occurring (as in the case of existing dewatered reaches) in the catchment, their status on the lists (e.g. IUCN) of threatened species and other information, the conservation plan and goals must be developed.

As a consequence, conservation goals for environmental flows and fish migration should always be addressed catchment wide and for all existing or future HPP developments at the same time. Ideally and in agreement with recommendations from the World Bank, this should be done in parallel or even before the hydropower masterplan.

Conservation plans and goals must explore realistic possibilities to protect specific fish and other aquatic species in the short, medium and long term. Where specific goals cannot be achieved because controls and bottlenecks are beyond the country's boarders or are actively abandoned for economic reasons or alternative measures preferred by the decision makers, it should be clearly stated.

Decisions regarding E-flow regulations that are not based on a catchment wide conservation plan can only be considered as temporary and will have to be revisited as soon as the next project impacting the river system is planned and developed.

3.3.8 Fish data collection for the definition of habitat preference

In dewatered or otherwise impacted reaches of a river critical habitat and migration corridors for fishes have to be ensured for sensitive life stages such as migration, spawning, egg development, rearing and juveniles. River fishes have in general clear habitat preferences. Therefore the goal for habitat studies is to know the appropriate habitat requirements of a target species and to preserve the key habitat under the influence of hydropower operation. In order to document the habitat preference the following tasks are essential:

- identification of the target species
- description of the ecology of the target species including the life cycle
- description of the habitat of target species and life stages
- suitability functions of the target species/habitat requirements of the target species

3.3.8.1 Identification of the target species

The selection of the target species is very important and should include indicator species that define a trait of the fluvial ecosystem. Indicator species are a small set of species with occurrence patterns that functionally are related to species richness of a larger set of organisms (Caro 2010). The target species should be a keystone species which affect the organization of the community to a considerable degree and whose presence or absence influences many other species. Protecting keystone species is a main goal for conservation. However, the target species could also be an emblematic species that has priority for conservation from the societal perspective. The target species has to be ecologically sensitive and suitable for monitoring. The selection of the target species needs local knowledge of the fish community. Large-sized fish species with special habitat requirement should be included (Himalayan trout, asla, Golden Mahseer). Small-sized fish should also be considered. Finally, the distribution of the selected target species in the basin or sub-basin needs to be documented.

3.3.8.2 Ecology of the target species

The life cycle of the species needs to be fully recorded. Migratory species spend their life in different riverine environment and the habitat requirements change during the life cycle. In connection with future hydropower development, the possible extinction and biodiversity loss has to be considered. Also non-migrating fish species often change their habitat requirements during the life cycle. In order to survive, spawning, rearing, juvenile and adult habitats have to be ensured.

3.3.8.3 Habitat use and habitat preference of target species

Habitat can be measured at the location where fish are observed or caught during electrofishing through qualitative and quantitative analyses. Common variables measured are channel data such as:

- depth
- velocity
- substrate
- cover
- large woody debris

Riparian data may be included additionally.

In general, habitat use studies can be based on different knowledge bases. Type I criteria are based on expert opinion and judgment of fish ecologists knowing the target species. However, each habitat definition by experts should be followed by field validation studies. It is recommended to use Type I criteria only if no other studies are possible.

Type II criteria includes observing fishes in the local habitat (habitat use studies). Curves derived with this approach are so called habitat-use curves. The method has to be adapted to the river characteristics and fishes are observed in the microhabitat. Possible methods are mainly underwater observations or electrofishing. The use of PIT-tagged fish would be a very interesting alternative method.

> One of the key concerns related to the construction and operation of Punatsangchhu I and II HPP are Golden Mahseer which occur in the lower part of the dewatered reach of PHP II. As no GM were caught during electrofishing the officials had to rely on suitability functions from data from other rivers published in peer-reviewed scientific journals. As Bhutanese data on fish become more and more available, the suitability functions used now can be verified and/or adapted if necessary. At the moment, the best available scientific knowledge is based on published material by other experts. While this may be questioned it remains the best available option for this study.

Type III criteria will be adjusted for availability of occurring habitat types and consider the fact that a fish may use a particular microhabitat in a higher frequency than it is available in the fluvial environment. Type III criteria are called preference criteria. Type III habitat suitability curves can be quite different from habitat-use curves. It is recommended to use a stratified (by habitat type; shallow-fast, shallow-slow, deep-fast, deep-slow) equal effort approach (Bovee et al. 1998). Each occurring habitat type is sampled (electrofished) with an equal amount of effort. In habitat type A, for example, that is present twice as much as habitat type B, twice as much sampling points have to be placed. Stratification (classification of habitats according to their availability) compensates partly for the fact that availability of habitats is not considered.

Caught fishes are measured (total length), checked for injuries and determined by the species. Data of injured individuals should not be included in the habitat analyses. At each focal point of the microhabitat of the fish the parameters listed above are measured and recorded.

The suitability curves are established for different life stages of the target species. Bovee (1986) suggested sample sizes of approximately 150 individuals to gain a good perspective of the distribution of the fish use of habitat. The greater the variability in habitat use, the larger the sample size should be to capture this information. Fish species with very specific habitat preferences may require fewer observations (Newcomb et al. 2007).

Sampling site-specific habitat criteria is time consuming and expensive. Therefore transferability from one stream to describe fish habitat preference in other streams is desirable. However data collection from a river system that has the functional hydrologic and instream habitat characteristics of a high-quality system should be used for a standard comparison (Newcomb et al. 2007). Additional tests (goodness of fit of the distribution) should be included for the transferability of curves. Finally, the derived habitat requirements will be the base for the habitat model. The precision of the CASIMIR-model will highly depend on the quality of the defined habitat requirements.

3.3.9 Other relevant species

While fish are affected by water abstraction directly and most severely it is obvious that there are also other species or communities which may be relevant. Among them are benthic species, mammals (e.g. fish otters), birds (e.g. White Bellied Heron), amphibians and other animals but also vegetation communities typical for floodplains depending on specific inundation dynamics.

It is quite common to assume that it is sufficient to conserve a sufficiently stable fish population. Benthic species will shift in their community composition due to water abstraction but it is commonly assumed that if there is enough water and habitat for fish there will be benthic species as well. Another common assumption is that birds or mammals feeding on fish will also keep using the habitat of dewatered reaches as long as there are fish in them.

If other relevant species occur in or near the dewatered reach they should be observed closely and the linkages between species' activities and habitat use and the river and its physical characteristics such as water depths, flow velocities and turbulences, smooth or broken surfaces, backwaters, eddies, water table elevation, water table widths etc. should be observed and documented. It is necessary to try to identify which physical properties of the river the animals are using for their activities. There are no standardized procedures for such observations and data to be collected.

In river reaches which naturally[4] do not support fish stocks, benthic animals are the most relevant aquatic species. Modeling of benthic habitats is also possible with a different module of CASiMiR but is not applied in this project as all existing or planned hydropower projects in Bhutan are in rivers supporting fish populations.

3.3.10 Study reach identification

The study reach is usually a part of the dewatered reach of the river and should be representative for the dewatered reach in terms of fish habitat, riverbed bathymetry and hydrology. The study reach should be at least 5 to 10% of the total length of the dewatered reach and its length should be at least 10 to 20 times the average river width. However, the length of the reach and the level of detail of the necessary survey works will depend on its heterogeneity. In a rather homogeneous river the length of study reaches can be shorter, while in a heterogeneous river with varying characteristics, several sites might have to be selected. The study reach can also be represented by a so-called hydro-morphological unit in situations where such units can be identified for example on Google Earth. Typical hydro-morphological units are riffle-pool sections (1 riffle + 1 pool), one braided section or one meander bend etc.

Another criterion for study reach identification is that it should be a “critical” reach. For fish migration, where minimum water depths are needed, the most shallow riffle in a dewatered reach may be critical whereas confined narrow channels are not critical.

In summary the study reach or reaches or the hydromorphological units should quantitatively and qualitatively represent the dewatered reach or the parts of the reach which are considered important for fish.

Other aspects to be considered are accessibility and safety of work during data acquisition. Also the aspect of the later modelling is of importance. For the hydrodynamic model it is crucial that proper boundary conditions can be defined. It is, for example, not advisable to define beginning and end of an investigation stretch in braided sections but rather in compact channel sections. Also the flow field close to the boundary cross sections of the model reach should be rather homogeneous, particularly in the inflow cross section. In case this kind of conditions cannot be found, the hydrodynamic model can be extended upstream and/or downstream by artificial in- and outflow channels with gradients close to the ones found in nature. Before the following step of habitat modelling these channels can be removed again from the hydraulic model in order to avoid distortion of model results. It is therefore important that an experienced hydrodynamic modeler is part of the team identifying the study reaches.

[4] “naturally” means that they are not supported by artificial stocking, e.g. from hatcheries

The selection of a suitable study or study reaches can be quite challenging and sufficient time and team expertise must be allocated for a good decision. If no agreement can be found for the selection, several reaches should be selected and studied.

3.3.11 River bed bathymetric data collection

Collection and processing of bathymetric data as input for the hydrodynamic model is the most laborious part of an E-flow study and provides the underlying data set for everything that follows. Inaccurate bed bathymetric input data is extremely problematic for hydrodynamic modeling because models cannot be calibrated to perform well over a large range of flows if the geometry is misrepresented. This applies obviously most of all for very low flows where only the deepest parts of the channel cross section are wetted. Therefore it is highly important to have a very good understanding of the survey methods and to apply the most efficient and reliable method for a specific situation. The rivers in the country are extremely challenging with a majority of them steep and wild and often difficult to access. It is also problematic that data gaps and errors cannot always be immediately identified in the field and that it is costly and laborious to go back to collect additional data once gaps and errors have been identified in the office. Since this is such a fundamental component of E-flow studies, this part is described in more detail.

Physical surveying techniques in rivers include terrestrial, boat and remote sensing data collection methods. The surveyed surface is referred to as the river bathymetry, which covers the entire surface of the river bed, and contains both the wetted part and the riparian area. Depending on the river type, the bathymetry may extend laterally outwards into a floodplain as well. Critical for the assessment of environmental flows are the wetted regions during low flow conditions and the collection of nonwetted, lateral bathymetry, typically up to bank-full discharge. For most environmental flow studies for dewatered reaches, the inclusion of the floodplains is therefore neglected during bathymetric surveys. For evaluations of regime changes this may be different. For riparian vegetation modeling flood water levels during 5 or 10 year floods may be relevant. It is therefore absolutely essential to identify the required range of the survey so that all areas which will eventually be inundated and/or modelled will be covered.

In the case of dewatered reaches the survey should extend as a general rule at least to the waterline of a flow where the influence of the hydropower plant becomes negligible. This could be a 1-year flood flow in the case of small reservoirs.

An overview of different bathymetric survey methods including their strengths and weaknesses is provided in Table 4.

All bathymetric surveys require the collection of a series of point data (x,y,z coordinate “triplets”) which are then interpolated into cross-sections or a triangulated surface model. These data sets can then be combined and refined using “data fusion” with additional existing datasets such as contour and break lines in order to produce a grid of evenly spaced x,y coordinates, or a raster. This “bare-earth” raster data forms the basis of the digital elevation model (DEM), the standard bathymetric data product used in mapping and hydraulic modelling. The most common way of collecting point data to create DEMs is to carry out a terrestrial survey. A detailed overview of DEMs is provided in the next section.

Terrestrial surveying is a manual point measurement method which requires a team of two or more surveyors and a measuring device. A minimum of two people are needed in order to carry and install the equipment in the field, and for safety in case of injury. The most common system used for terrestrial surveying is the total station, which is an optical surveying device which measures the distance and angle between the fixed base station and the surveying rod. The surveying rod has a reflector prism on the top, and is kept at a fixed length during each point measurement. The height of the bathymetry is calculated simply as the height of the reflector, minus the fixed height of the rod. Older total stations require that the second surveyor stays at the device at all times and manually follows the rod using an optical viewfinder. Modern total stations are capable of automatically tracking the reflector as the surveyor with the rod moves from point to point. Using a total station has both advantages and disadvantages. Total stations, when set up in the field correctly, are capable of sub-centimeter accuracy for each point measured, and an experienced surveying team equipped with automatic tracking can record more than 1,000 points over 8 hours. One downside of the total station is that it relies on line of sight for measurement, meaning that trees, bushes, boulders and meandering rivers require that the base station be repositioned multiple times in order to collect a complete set of point data. Setting up the device per location also requires the use of at least three “fix points” which are common to each setup, so that all of the surveying data can be georeferenced to a global coordinate system.

Table 4: Comparison of methods to survey river bathymetry for e-flows

Category	Survey technology	Major advantages	Major disadvantages
Terrestrial	Total station	Easy to use, reliable and highly accurate, can collect dry and underwater data	Large time requirement in field, data must be manually georeferenced
	GPS	Does not require line of sight, automatically georeferenced, can collect both dry and underwater data	Requires satellite contact, can be unreliable in remote regions
Floating platform	Echosounder	Can map un-wadable regions of river, cover large distances	Requires off-line data processing, minimum depth, only for underwater data
	ADCP	Provides both depth and velocity data	Expensive and has narrower range of operating conditions than ecosounder, only for underwater data
Remote sensing	Unmanned aerial vehicle	Inexpensive, high spatial resolution, can capture entire study reach with multiple flights	Extensive data processing, manual georeferencing, limited underwater bathymetry
	Airborne (airplane or helicopter)	Entire study reaches can be surveyed in a single flight	Data processing, and low flexibility in time, difficult to obtain underwater bathymetry
	Satellite	Entire watersheds can be mapped	Relies on existing data, low resolution surface bathymetry only, expensive

In the last decade, the uses of the satellite-based global positioning system (GPS) have also increased for terrestrial surveying. These systems function by collecting coarse, global position data (x,y,z coordinates with 3-10 m accuracy) and then applying a correction using data from a known set of local reference stations. Once the correction data has been applied, it is often possible to achieve up to 1-5 cm spatial accuracy. The correction can be performed during the field survey or can be completed using special software in the office after the GPS coarse positions have been recorded. The GPS field measurements also make use of a rod which the surveyor holds at each position until the required accuracy is obtained. There are two different types of GPS field survey systems which may be used for bathymetric surveys. The first method uses a rover, which is a receiver antenna and data collection module directly fixed on the rod, and the data collection module connects to a local reference system via cellular connection. This method depends on local weather conditions and connection to a reliable cellular network in order to consistently produce measurements with a high accuracy. The other method, called real time kinematic (RTK) is more similar to a total station system. It makes use of a single fixed base station which is usually setup at a known location. Once the base station has been set, it is possible to collect real time correction data for multiple mobile receivers. Since the system relies only on the correction data from a local base station, RTK has the advantage that it is less prone to weather based problems and has the added advantage that multiple receivers can be used so that two or more surveyors can measure the bathymetry at the same time. The advantages of GPS based systems are that they do not require line of sight, and thus do not suffer the multiple setups of total stations, in addition the point data collected using terrestrial GPS are automatically stored in a global reference frame, most commonly using the World Geodetic System 84 (WGS84). A disadvantage of using GPS is that is can sometimes be unreliable, especially when satellite coverage is poor. Thus before deciding to use GPS it is best to check the satellite reception at the proposed investigation site, which can be done with most modern smart phones, as they can provide an estimate of both satellite and cellular network coverage.

Terrestrial methods have the strict requirement that the rivers are wadable, meaning that the surveying team can safely stand in the water during each point measurement. In many cases, especially considering larger rivers, only the riparian and nearshore regions are wadable. Collecting bathymetry in the wetted regions which are deep and fast-flowing therefore requires the use of a floating platform such as a raft, kayak or boat in order to traverse the water surface. The choice of using a raft, kayak or boat largely depends on the depth and flow conditions of the river when the bathymetric survey is performed. Rafts are normally used in calm, but non-wadable waters with short bank-to-bank widths (< 10 m) so that a rope can be spanned from bank to bank and the raft can be pulled across it, measuring cross sections. Kayaks are more common for the measurement of long river reaches where the flow is shallow (< 2 m deep) and too fast flowing to maintain a stable raft or boat. Boats are usually motorized and perform the best in larger, deeper rivers where the water surface remains stable but where large bank to bank distances make the use of a raft and kayak impractical. When considering a surface water measurement system, it is important to consider how the raft, kayak or boat can be transported and launched into the water. For example, a raft or kayak can be carried by a two person team into the field over short distances of hilly and rocky terrain, whereas a boat commonly requires a launch ramp or nearby roadway to place it into the river.

Once the choice of floating platform has been made, the next step is to determine which measurement device should be mounted on the platform. There are two choices, either an echosounder or acoustic Doppler current profiler (ADCP). Both devices make use of high-frequency sound waves and consist of a calibrated acoustic probe which uses the principle of the Doppler shift, wherein the change in the frequency of the emitted soundwave is recorded as it travels back to the receiver in order to estimate the distance between the probe and the river bed surface. In this way, the device is capable of providing bathymetric data without physically making contact with the river bed. The echosounder is capable of recording only the distance between the bed and the boat, whereas the ADCP delivers the bed elevation as well as an estimate of the flow velocity profile and its distribution in the vertical direction. As the system is platform based, georeferencing is required so that the data can be combined with the additional non-wetted bathymetry data sets. This requires that the position of the boat is continuously recorded using either an on-board total station or GPS system. As the floating platform based bathymetric measurements are relative to the boat position from the bottom, it is necessary to post-process the data in the office in order to obtain georeferenced (x,y,z) coordinates. The resolution and accuracy of both the echosounder and ADCP depend on the water depth (min 20 cm), water surface conditions, salinity, turbidity and level of turbulence. In general, acoustic devices perform the best in larger, gradually-varying waters with > 1 m depth and low turbulence. The advantages of the acoustic, floating platform based measurements are that they allow for bathymetric data collection in deep or fast-flowing wetted areas which cannot be measured terrestrially. In addition, acoustic methods can provide non-contact measurements of the bathymetry and in the case of the ADCP, estimates of the vertical velocity distribution as well. The downside of the acoustic methods is that they are largely dependent on the local flow conditions and require expensive professional-grade equipment and software for post-processing and georeferencing. Air bubbles from turbulence and sediment motion at the river bed can disturb the signal and make the data collected useless. It is therefore important to control the quality of data as soon as possible while the crew is still in the field.

In cases where the study river reaches are many kilometers long, or where difficult terrain does not allow for terrestrial or floating platform surveys, it is sometimes an option to collect bathymetric data from above. Similar to the non-contact acoustic methods, remote sensing uses non-contact optical methods to collect bathymetric data using an unmanned aerial vehicle (UAV), airborne data (airplane or helicopter) or using satellite imagery.

The use of UAVs to collect remote sensing of rivers is rapidly increasing due to the large spatial range, ease of use and availability of low-cost camera systems capable of delivering high quality aerial imagery with resolutions of 1 cm/pixel or better. A typical application of a UAV for bathymetric surveying consists of a two-person team with a pilot and a spotter whose responsibility it is to aid the pilot in ensuring that the UAV flight does not put nearby people, property and animals in harm's way. A river site is typically flown not all at once, but in a series of multiple flights at two or more heights, normally 50 and 100 m above the river. Depending on weather conditions, the pilot may need to land more frequently and examine the images to make sure that the data collected has consistent brightness (cloud cover can make images too dark, bright sun can cause reflections which "white-out" the images) and sharpness (vibration from wind or fast flying can cause blurry images). Once the UAV imagery has been collected, it is processed using structure from motion (SfM) software which detects unique features in each image and uses them to recreate a 3D point cloud of the region. Ground control points are needed (measured with total station or GPS) in order to georeference the point cloud (> 10 cm mean error). Once the point cloud has been brought to a global coordinate system, an orthomosaic of the region can also be exported. A major advantage of the UAV/SfM workflow is that it is capable of quickly and efficiently collecting high-resolution (1 cm/pixel) data which can then be used to generate large point clouds with high density (10+ points/m²). Disadvantages of using the UAV/SfM approach are the need to purchase a UAV and train a drone pilot, and the requirement of professional software which can take days to weeks to process and develop the point cloud and orthomosaic. Collection of underwater bathymetry is also limited to a refraction-based correction of data in shallow and calm regions; SfM cannot deliver underwater measurements in highly turbulent waters.

Airborne platforms such as airplanes and helicopters can cover much larger ranges in a single flight, were tens of km² can be flown in a single day. Due to their large size, airborne systems can also carry more advanced laser optical measurement systems using light detection and ranging (LiDAR). Laser pulses are sent out rapidly from a fixed device. Red LiDAR can be used to collect non-wetted regions, and more recently green LiDAR systems have become available which can measure up to 2 m water depth, as long as the water is clear and without turbulences. The advantages of LiDAR systems are that they can quickly collect data from large regions which cannot be achieved with UAVs and can have high spatial accuracy (< 10 cm error). Major disadvantages are similar to UAVs, where specialized aerial systems are required and long-data processing times should be expected. In addition airborne measurements are typically much more expensive than UAVs for river bathymetric surveying.

> LIDAR system are becoming lighter and more capable to capture underwater bathymetry from one year to the next. Globally operating specialized companies operate their own planes or hire local planes or helicopters. It should be closely observed how far the limits for underwater surveys can be pushed in the future.

> Generally surveys of the dry areas should be done during the lowest possible flows to cover as much bathymetry as possible in the safest and most reliable mode. If the inundated parts of the channel are well accessible and safe to work in, the inundated part should be surveyed during somewhat higher water levels in order to achieve some overlap between both measurements. In Bhutan all fieldwork must be accomplished during the lean season months.

> Rapid control of the data measured in the field is particularly important in Bhutan’s steep and turbulent rivers to make sure the measurements actually worked and were not disrupted by turbulent waters, particularly when using echo sounders and ADCPs. Since the data processing and model development takes weeks to months after the fieldwork it is too late if data gaps are discovered then because the lean season for field measurements is long gone and at least one year is lost before measurements can be repeated.

Remote sensing with UAVs and airborne systems still require the physical presence of a pilot to fly over the investigation reach and obtain aerial imagery. Satellite imagery can be very useful when the project sites are very remote and too dangerous to fly, or when baseline data for prefeasibility studies are needed over very large regions such as entire watersheds. Imagery data with up to 1 m/pixel can be commercially obtained, and can then be processed using traditional photogrammetric methods, which make use of the shift between two images in order to obtain coarse DEMs of 10 m resolution or more. A major benefit of using satellite data for bathymetric evaluations is that the data have already been recorded and do not require time-consuming field work. However, the resulting data have considerably coarser resolution than UAVs and airborne measurements and dependence on expensive, commercially available data can be limiting, especially for smaller projects in very remote areas where there are no other options for the collection of remote sensing data.

In Bhutan the choices will be terrestrial data collection, kayaks and unmanned floating platforms and UAVs. The morphologic character of the country's rivers makes field work extremely challenging. Careful planning and site selection, experienced teams and equipment operators, fully reliable equipment and rapid control of the quality of the data collected are most important.

3.3.12 Surface models

Once the bathymetric survey has been completed, it is necessary to post-process the x,y,z triplets into a single georeferenced data set, the point cloud, which can be used as the basis for the hydraulic model. The georeferenced data set often contains survey points from multiple sources. As an example, an investigation reach may include terrestrial total station data for the near shore wadable region, echosounder data of the deeper wetted areas, and UAV SfM points including the water surface, dry near shore as well as the surrounding vegetation. Before the point cloud is incorporated into the hydraulic model, it is important to consider the differences in bathymetric data for 1D and 2D hydraulic models.

1D hydraulic models typically require only the use of cross sections, which can often be surveyed directly in the field. However, the spacing between individual points within a cross section can be uneven and may include some data gaps where large boulders or pools make direct measurements challenging. Furthermore, a simple linear interpolation between cross sections may also be problematic, especially in mountainous rivers where the bathymetry changes widely between cross sections due to pools, boulders and branching. 2D hydraulic models generally require continuous, high resolution base bathymetry data which is then interpolated to the model mesh. It is therefore beneficial for both 1D and 2D models to make use of post-processed surveyed point data. Depending on the model requirements and available data, there are several categories of post-processed bathymetric data which can be used. A table of the different categories as well as the time effort required to create them and the advantages and disadvantages of the different categories is provided at the end of this section in Table 5.

The point cloud is the most basic bathymetric data set. It is created simply by geo-referencing all survey points from the different measurement systems into a single common reference system. This data is then imported into the modelling software as either a single common data set based on each of the measurement systems as a “partial point cloud” or as a single data set after merging all point clouds as a “master point cloud”. The advantage of using a master point cloud is that it provides a single data set which can be quickly interpolated to the hydraulic model geometry. However, if the master point cloud includes UAV SfM or airborne laser scan data, it may include many points from buildings and vegetation which are not needed in the hydraulic model. Thus when working with point clouds, it is normally preferred to import the partial point clouds so that the user can more easily determine which points need to be manually removed before interpolating the point cloud data into the model mesh.

Often it is desirable to have a continuous distribution of points from which the bathymetry can be interpolated. This is especially true for highly heterogeneous bathymetries commonly found in Bhutanese river systems. In order to convert a series of points into a surface, it is necessary to connect neighboring points in such a way that a continuous surface can be created. This process is called mesh generation, and most frequently uses an algorithm called Delaunay triangulation which creates a series of interconnected triangular surfaces between the point cloud points such that the average smallest angle of all the triangles is maximized. This is desirable since the ideal triangulated surface mesh should consist of triangles which can accurately reproduce the bathymetry between measurement points. An advantage of using a surface mesh over a point cloud is that it provides a continuous set of bathymetric data, and can be created very quickly with little specialist knowledge. However, if the point clouds used to generate the surface mesh have large distances between neighboring points, such as for cross-section point clouds, a manual reordering of the connecting triangles is often required. Furthermore, in cases where remote sensing data are included, the surface mesh may include large numbers of undesirable points corresponding to trees and buildings.

A surface mesh can be improved substantially for use in a hydraulic model by further post-processing of the data into a digital surface model (DSM) in which the user includes additional information about not only the point’s x,y,z position in space, but also provides a classification such as river bed, vegetation, building, etc. Thus the difference between a surface mesh and DSM is that the latter includes additional information regarding what type of surface is being represented. Classification of UAV SfM data can be performed with commercial software which takes into account the local steepness of the mesh, the deviation of small mesh regions from the overall relief, and the color of the individual points. As an example, by choosing settings which locate “steep, high and green” points from the SfM point cloud, the user can efficiently locate large amounts of points in a cloud corresponding to vegetation. The creation of a DSM therefore requires the use of specialized software and trained staff, but can aid in rapidly determining which points may not be useful for the creation of river bathymetry in a hydraulic model.

Once a DSM has been created, it is then possible to remove unwanted point classes such as vegetation, creating a digital terrain model (DTM), which represents only the “bare-earth” bathymetric data needed for either 1D model cross sections or a 2D model mesh. A major consideration when removing unwanted classified points is that they may leave large gaps, for instance if trees are removed along a river bank. Filling these gaps requires that the points on either side be newly interpolated using the desired classes. If it is known beforehand that UAV SfM or airborne data will be collected for the creation of a DTM, it is strongly suggested that the survey team in the field attempt to measure some terrestrial data in regions which are expected to be filtered out. This commonly occurs in areas with patchy to dense vegetation, where the terrestrial surveyors measure some additional points outside the near shore region, but within the vegetated regions. This small amount of point data can be used to improve the interpolation across gaps and also provides a baseline estimate of the overall accuracy of the DTM in data sparse regions. Thus the advantage of a DTM is the removal of unwanted data, but has the disadvantage that the resulting bathymetric model is unlikely to have uniform spatial accuracy. Another drawback of fusing multiple point clouds, performing classification and removing and newly interpolating the surface is that the user is often left with a very uneven bathymetric model with a wide range of triangle sizes.

Table 5: Comparison of spatial data sets used for bathymetric representation

Category	Level of effort	Major advantages	Major disadvantages
Point cloud	Very low	Inexpensive, fast and flexible, can incorporate multiple measurement methods and new data easily	Lack of uniform detail, large data sets may require significant field and data processing time
Triangulated surface mesh	Low	Baseline surface representation with continuous elevation data	Quality of mesh highly dependent on point cloud, interpolation quality dependent on choice of software
Digital surface model (DSM)	Medium	Higher quality surface representation than mesh with classified regions	Requires specialist, often long processing time
Digital terrain model (DTM)	Medium-High	Trees and buildings are removed, mostly “bare earth” representation of surface	Significant manual processing is required by specialist with professional software
Digital elevation model (DEM)	High	Highest quality raster surface data product, only “bare earth” data is present	Most expensive to create considering both time and cost

If the resulting DSM can be validated to have a sufficient continuous quality, a final post-processing step can be carried out to create a digital elevation model (DEM) by interpolating the unevenly spaced DSM as a raster file with uniform spacing. As a rule of thumb, the DEM raster should have between 1m and 10 m spacing, ideally with a spatially uniform accuracy in the range of 5 to 10 cm in both the vertical and horizontal directions. Additional survey points with a minimum of 30 total and spread equally across the investigation site should be collected in the field to validate the model accuracy and locate potential problem areas in the bathymetry.

At the end of this process an input data file of the river bed geometry is available in the format suitable for the hydrodynamic model to be used.

3.3.13 Collection of additional field data needed for habitat modeling

In addition to the river bathymetry and topography of the river and its riparian zones, it is required to collect information of all habitat parameters that are considered as important and therefore will be integrated in the habitat model. Most fish species have specific habitat requirements related to morphologic features – such as substratum or cover – these features have to be mapped and incorporated in the numerical model. Aerial pictures taken with a drone or from a higher elevation can accelerate this process significantly.

Therefore, it must be known which parameters will be considered in the habitat model for fish or other species and how they will be characterized (numerical or linguistic description) before the fieldwork is planned.

3.3.14 Hydrodynamic modeling

The goal of hydrodynamic modelling is to describe the hydraulics in the study reach detailed enough to be able to identify habitats for selected target species including their quality, quantity and location for different flows including flows outside the range, which can be visually observed. In general, there are 1D and 2D hydrodynamic models that can be used for such studies. These two types of models use fundamentally different numerical approaches to describe the hydromechanics of flowing water. 1D models are using a rather crude simplification of the underlying hydromechanic principles based on energy and momentum conservation. 2D models are solving the so-called Navier-Stokes differential equations. 2D models describe the hydromechanics far more accurately and especially allow an extrapolation towards flow rates where no measurements for calibrations can be taken which is the case for very low flows in river reaches where hydropower development is planned in the future[5].

The model type to be chosen and the spatial resolution depend on the scale that is considered and the heterogeneity of the river bed and in particular the information which is needed from the model. For a homogeneous channel and large scale investigations, a 1D model based on cross sections can be sufficient especially for average and higher flows, because flow is considered to be oriented primarily in one direction, there is no splitting of the flow (see Fig. 7 top) and the information resulting from a 1D model which is water level elevation and mean cross section velocity is sufficient. For investigations in the smaller scale and heterogeneous rivers with e.g. bolders, lateral flow and backwaters, a 2D model has to be applied. The assumption for this is that flow velocity does not vary strongly in vertical direction which is true for many shallow water situations, i.e. depth is comparatively low compared to the other two dimensions (see Fig. 7 middle). In complex geometries and hydraulic situations with high variation of velocities in vertical direction, 3D modelling is necessary. Due to the high requirements related to the computing capacities 3D investigations are usually performed for local problems only with limited spatial extension.

[5] For more detailed information on hydrodynamic modeling in ecohydraulics see Tonina & Jorde (2013)

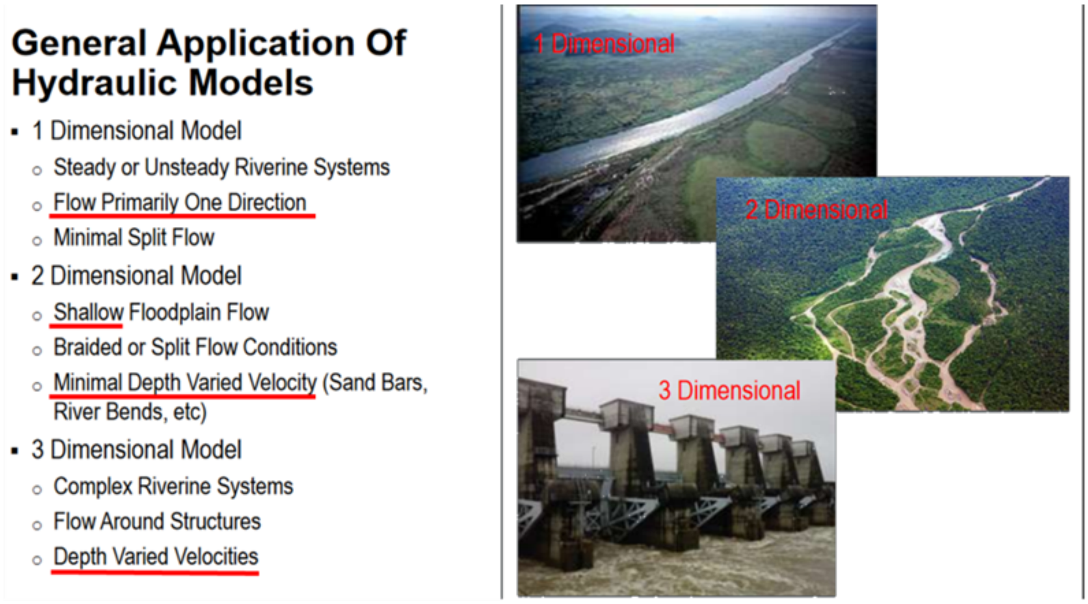


Fig. 7: Application of hydraulic models, (modified from Brinton Swift, www.floods.org/ Files/Conf2015 _ppts/G7_Swift.pdf

The possible information generated by the model types differs fundamentally. One of the main constraints of 1D-modelling is that usually only cross-sectional average velocity is provided. In some cases zonal flow velocities are provided, e.g. for main river and floodplains (Fig. 8 top). This spatial resolution of flow velocities is usually not adequate for habitat investigations (exception: extremely homogeneous rivers with no variability in lateral direction). 2D models with a sufficient mesh resolution deliver more realistic flow patterns, particularly in situations with diverging flow, flow splitting, lateral flow and backwater areas or different inflow locations as e.g. downstream of power plants (Fig. 8 middle). 3D models provide a similar detailedness of flow patterns additionally in vertical direction (Fig. 8 bottom).

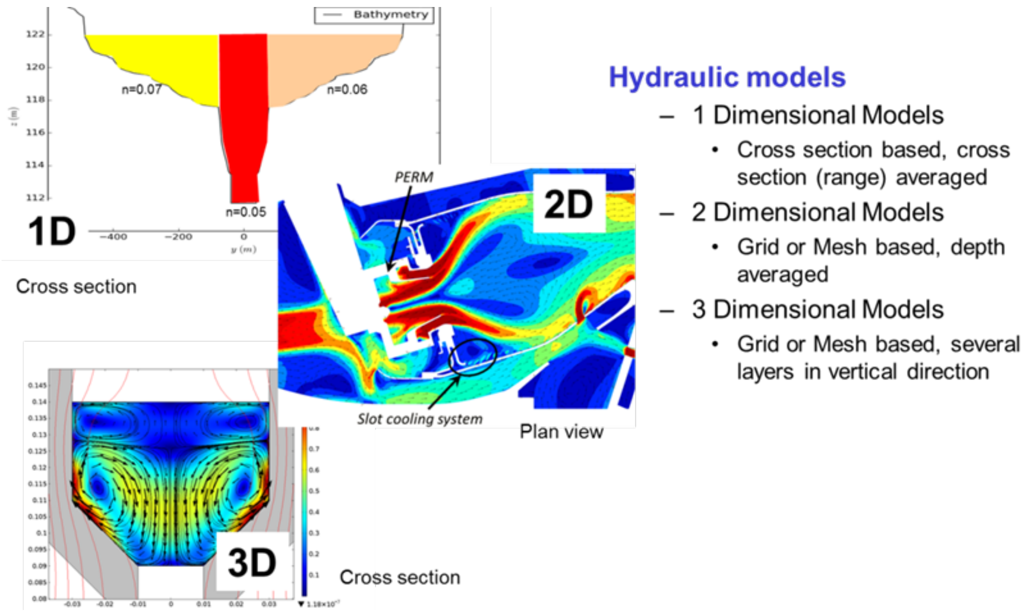


Fig. 8: Flow velocity in different types of hydraulic models

The other main constraint of 1D models is the simplification of geometry and morphology. Since 1D models are based on cross sections only and the geometry and structure in between cross sections is lumped into calibration coefficients, it is difficult to derive a good representation of rivers with a variability in width and morphological features such as islands, braiding, bank breaklines or large boulders etc. The 1D digital river model is derived purely by interpolation between cross sections, resulting in a linear course and in constant or linearly changing morphological features. Even in situations with a high density of cross sections the resulting river model is very simplified and in highly heterogeneous rivers, the interpolation is not producing anything meaningful.

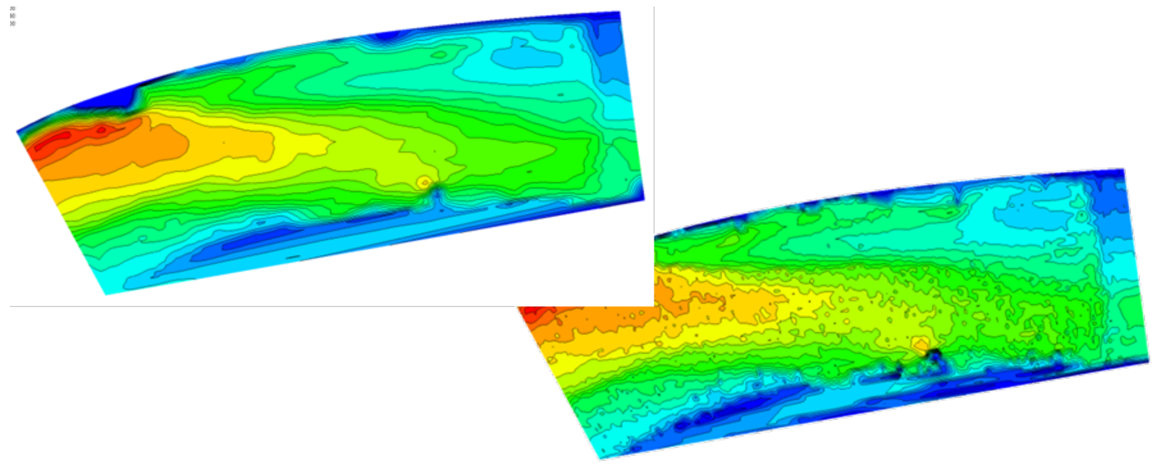


Fig. 9: Comparison of cross section based and scatter point based model of the same river stretch

The use of 1D hydrodynamic models is therefore only advisable a) in rivers or river sections that have an extremely uniform bathymetry (canal like rivers), b) in investigations that are focused on water level calculations with good calibration data (e.g. flood level calculations where heterogeneity is considered via increased roughness coefficients or c) large scale investigations where micro- and mesoscale habitats are of minor interest. Nonetheless, all these criteria do usually not apply for E-Flow studies, where the change of habitats due to flow modification is the main goal of the investigations.

Hydraulic models deliver the input for an aquatic habitat model in form of maps of flow velocity and water depth for different discharge situations. Some derived parameters (for example, FST hemisphere numbers) are required for special application cases, such as the CASiMiR model for benthic invertebrate habitat quality (Kopecki, 2008; CASiMiR manual]).

In general, the procedures of 1D or 2D hydrodynamic modelling are similar and consist of the following steps:

1. Definition of model geometry and setup of boundary conditions: For 1D models this step is concerned with definition of a river centerline, distances between cross-sections and their geometry, positions of river confluences and boundary conditions (see Fig. 10 left). For the 2D model, the computational mesh (or the grid) should be created, mesh points elevations should be interpolated from the DEM (see 3.3.12) and the inflow and outflow boundaries should be defined (Fig. 10 right).

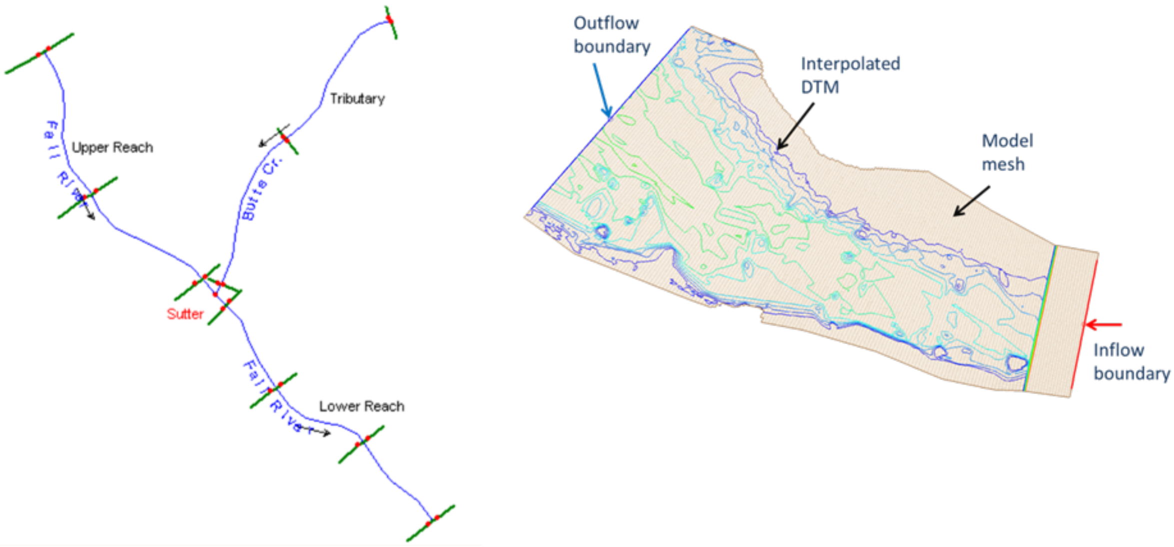


Fig. 10: Setup of geometry and boundary conditions for 1D model (source [HECRAS manual]) (left) and 2D model (right)

2. Calibration of the model: The model should be calibrated by comparing measured water level elevations and flow velocities at some points with computed ones. A comparison of local water depths instead of water level elevations is only meaningful over smooth river beds, not where the river bottom is covered with large roughness elements such as large boulders. Calibration can be achieved by manipulating the bottom resistance parameters of the model, usually roughness coefficients (Manning's n or Manning-Strickler coefficient). Modern methods allow flexible adjustment of roughness parameters thus reducing calibration efforts [Kopecki et al, 2016]. Ideally, computed and measured values should be compared at least for three discharges: one set of comparative data sets for a low flow condition, one for a high flow and one for a medium flow.
   The outcome of a 1D model is usually the water level at the cross sections used as input data and, if the cross sections were chosen appropriately, a longitudinal water surface profile connecting the cross sections by linear interpolation. These can be compared to measured water surface elevations (see Fig. 11) for calibration.
   For 2D models there are more calibration possibilities: water lines derived from aerial photos can be compared with the water surface line obtained from the 2D model, absolute values of water surface elevation can be compared to the measured ones (see Fig. 12). It is important to ensure the model quality in the whole range of relevant discharges. Measurements of flow velocity are rarely available and require much more measuring efforts. If an ADCP is used for river bed bathymetry data collection, local flow velocities are included in the data. Calibration by means of flow velocities is highly recommended whenever possible. Predicted flow velocities are quite dependent on the model mesh size and stay in the close relation with the predicted water depth (water surface elevation).

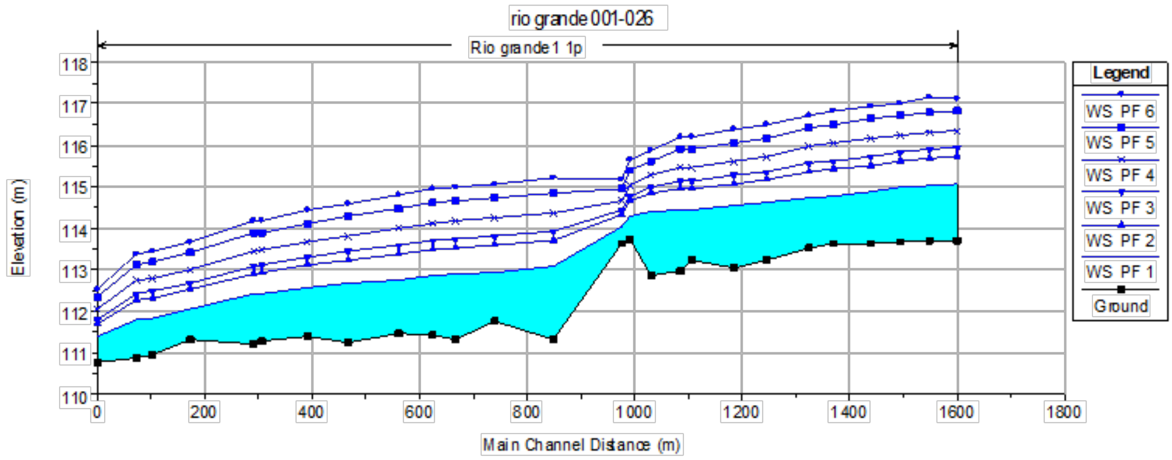


Fig. 11: Calibration of 1D model by means of longitudinal free surface profiles for six different flow rates.

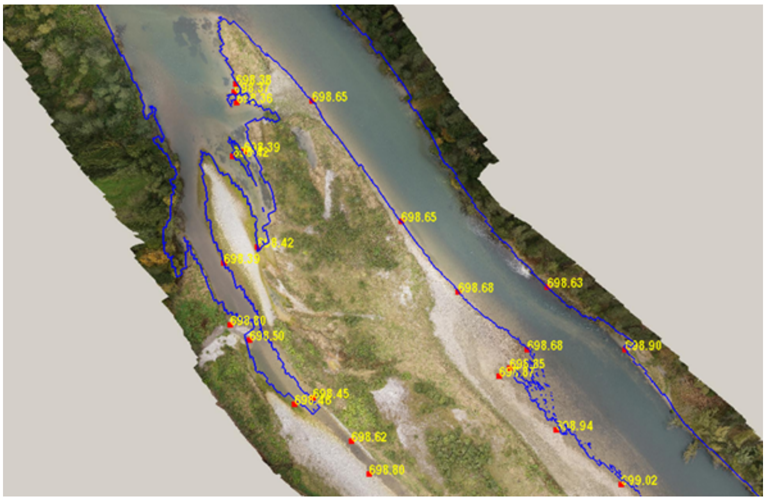


Fig. 12: Calibration of 2D model by means of aerial photo and measured values of water surface elevation

3. Hydrodynamic simulation: After a successful calibration, the model is used to simulate the hydrodynamics for the number of discharges in the range relevant for the determination of E-flows. As a general rule of thumb the range could be between 5 % of the lean season base flow up to the mean annual flow.
4. Visualization and analysis: The results of hydrodynamic models can be visualized and analyzed either before or after import into the habitat model. In the case of a 1D model the main results such as mean water depth and mean cross-section velocity can be imported, transformed (see for example 1.5D CASiMiR approach as described in the CASiMiR manual) and visualized in form of 2D plans or categorized diagrams (Fig. 9:, left, right). Results of 2D models can be imported directly or interpolated on the habitat model grid and analyzed similar to 1D results.

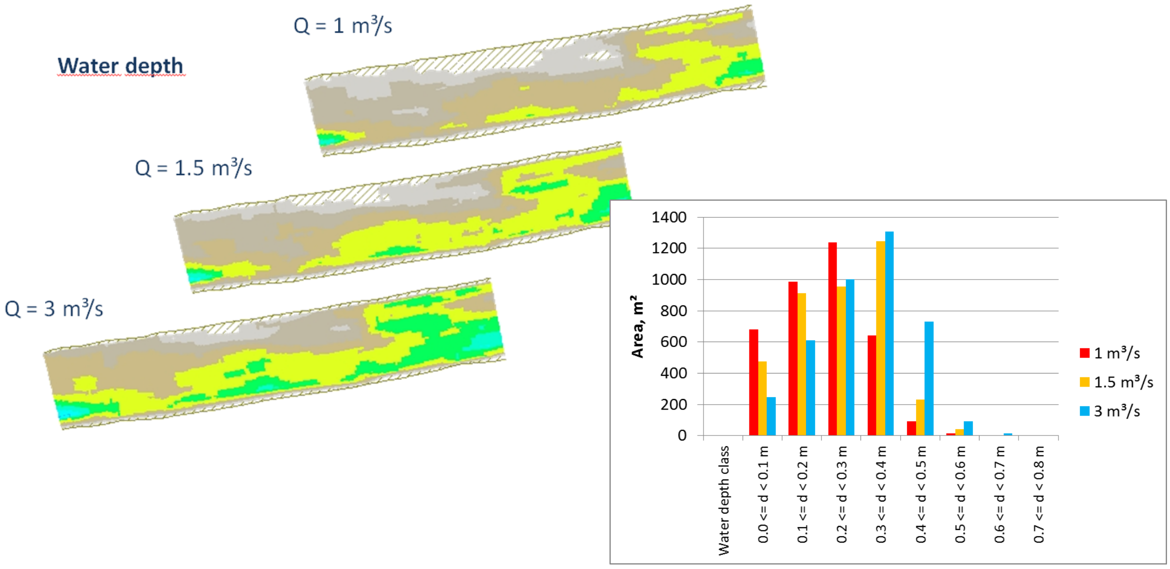


Fig. 13: Visualization and analysis of 1D and 2D model results: example of water depth

In addition to the choice of a 1D vs 2D model there is also a choice between steady and unsteady hydrodynamic modeling. Unsteady modeling is needed for example to simulate flood wave propagation or rapid flow fluctuations caused by hydropeaking. For this project and as a standard approach for dewatered reaches a steady state 2D model was used. This is probably the appropriate approach for all dewatered reaches in the country where E-flow regulations have to be determined.

Hydrodynamic modeling is a rather complex process and many different things can be done wrong, in particular applying the wrong modeling approach to address a certain problem is a common mistake. It is absolutely important that a modeler has sufficient understanding of underlying hydrodynamic principles and/or enough guidance from experienced modelers before modeling tasks are attempted.

The result of the hydrodynamic modeling part are water depths, wetted areas, flow velocities, water level elevations for a series of different flows. These results can be visualized in maps or in various types of diagrams, cross sections, longitudinal sections etc.

The physical part of the river bed is described with these models. Various questions related to any of the hydraulic data can be investigated based on these data. Hydraulic rating methods, described in the following chapter, or fish migration in the dewatered reach can be addressed with these results.

3.3.15 Hydraulic rating

Hydraulic rating is a method where flows in a study reach or a cross section within a study reach are related to physical parameters which are affected by the flow and which have ecological, socioeconomic or other relevance. Typical parameters are wetted width, water depth and mean flow velocities. Fig. 14 shows an example where wetted width in a cross section was evaluated. Obviously an increase of the discharge above the 85% percentile (flow which is exceeded 85% of the time) does no result in much increase of the wetted width. Wetted width is an indicator for water surface area which could be an indicator for waterfowl habitat. The analysis shows that an increase of the flow up to the 85% percentile would significantly contribute to more waterfowl habitat, further increases however are rather useless.

The data for this analysis can either be taken from direct field measurements or from the output of a hydrodynamic model.

The parameters to be analyzed depend on the question asked and there is a wide variety of possibilities. In situations where there are too many different and too many unknown fish species or no fish at all, hydraulic rating is a common tool and also used within holistic methods.

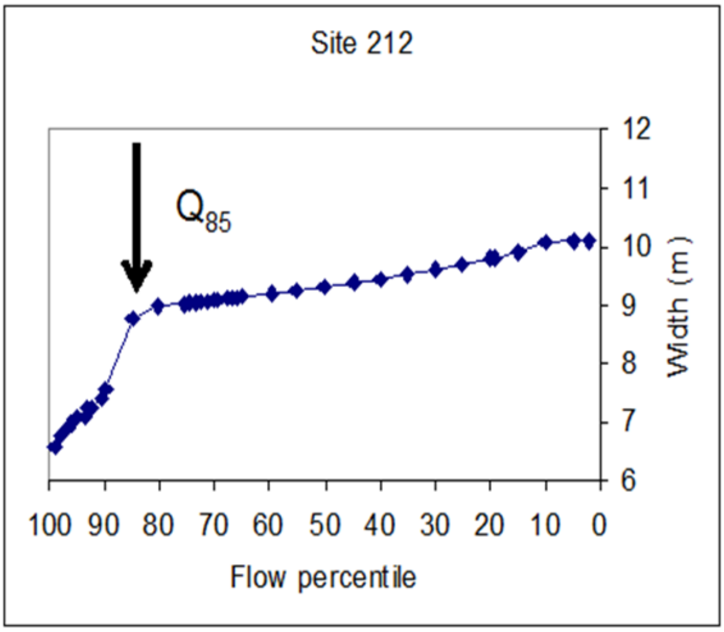


Fig. 14: Visualization of wetted with in a cross section as a function of flow.

If a relevant aspect has been identified and needs to be covered in the E-flow assessment it is necessary to establish a relationship between the aspect and physical parameters of the river in the reach under investigation. For example if feeding habitat for fish otters is to be maintained, one should observe otters in locations where they are existing and doing well and see what kind of water they prefer for feeding, fast or slow flowing, deep or shallow, wide or narrow river beds etc. These parameters could then be evaluated as shown above and determined how they change with flow. Some examples are listed below.

An analysis of the maximum water depth along the migration path for a fish is among the most common applications and will be further explored in the chapter on fish migration.

A specialized fauna of spiders and beetles are living on open gravel bars, also some birds are breeding on such bare areas. Hydraulic rating could be applied to study how much open gravel bars remain after a regime change caused by reservoir operation.

For abstracting water for flood irrigation a certain water level is needed to convey the water into a channel system.

River reaches used for kayaking and rafting need certain flow velocities and standing waves (Froude numbers) to be attractive for these sports. This could be observed and measured in preferred kayak and rafting reaches and then hydraulic rating could be applied to see how much water is needed to fulfill these criteria along a certain percentage of river length as a function of flow.

For reasons of tourism and landscape water has to cover a certain portion of the river bed, depending on the time of the season, otherwise it becomes an obviously impacted system which is less attractive.

Sometimes rivers act as a divide between habitats and animal populations, e.g. predator and prey. If such a divide is to be maintained it must be investigated which physical features shaped by the flow of water are causing the divide. Most likely a combination of water depth and flow velocity keep certain animals from crossing the river. To maintain such a function, certain flow velocities and water depths need to be preserved.

These are just some random examples, there is no limitations how hydraulic rating can be applied. In the pilot studies for this guideline hydraulic rating was not applied since fish habitat modeling was used in all pilot reaches and other criteria were not critical.

3.3.16 Aquatic habitat simulation

Aquatic habitat simulations are the key element within the methodology to determine E-flow regulations and should be applied in all rivers where fish naturally occur. Aquatic habitat modeling is based on two input data sets, (a) the results of the hydrodynamic model and (b) habitat suitability or preference functions which describe what range of physical parameters are most suitable for a fish species and its various life stages. Linking the two input data sets together generates as outcome flow dependent maps of habitat suitability.

The main goal of the simulation of aquatic habitats for E-Flow setting is to simulate qualitative and quantitative information on habitat availability mainly for fish, but also for other species, if relevant. Flow dependent hydraulic variables are used as input for the simulation and therefore the derived values of habitat quality are also flow dependent. Habitat quality is simulated for each individual spatial unit of the hydrodynamic model used:

- 1D: cross sections with influence area
- 2D: model areas (2D grid cell)
- 3D: model volumes (3D volumetric cell)

For this project 2D models were used. The derived result is spatially explicit, showing maps with location of habitat quality, and the information is

> Different simulation models for aquatic habitats are existing. PHABSIM (Bovee 1986) and its various derivatives is the most well-known model. For this study, CASiMiR (Jorde 1997, Schneider 2001) is used. While PHABSIM is using univariate habitat preference functions as input parameters, CASiMiR has the advantage of using alternatively a fuzzy logic approach to couple physical parameters with biological preferences of fish. This is better representing the interdependency of physical input parameters such as water depth and velocity and it is also more suitable in data scarce situations, where not too many fishes have been caught. The fuzzy logic approaches is resulting in more robust modeling results. CASiMiR is a toolbox and has components for simulation of fish habitats, benthic habitats, floodplain vegetation and a simulator for hydropower plants

quantitative.

The simulation for different flows allow to evaluate the rate of change of habitats with respect to the flow change. Situations in between flows modelled are interpolated linearly. This is the basis for the assessment of flow dependency and recommendations of flow rates providing sufficient quality and quantity of habitats.

For this project the habitat simulation model CASiMiR was used, a toolbox developed originally at the University of Stuttgart, Germany. CASiMiR has certain advantages over other models but generally any model can be used if it is producing similar types of output based on similar types of input data.

3.3.16.1 Approaches for physical habitat modelling

The modeling process is linking habitat requirements of fish to physical parameters such as flow velocity, water depth and morphological features of the river, normally bottom substrate and sometimes also certain types of cover/shelter. The parameters considered in the simulations depend on the fish species of interest. There are two fundamentally different approaches to describe habitat requirements of fish for physical habitat simulations: (a) suitability curves and (b) fuzzy rules and sets.

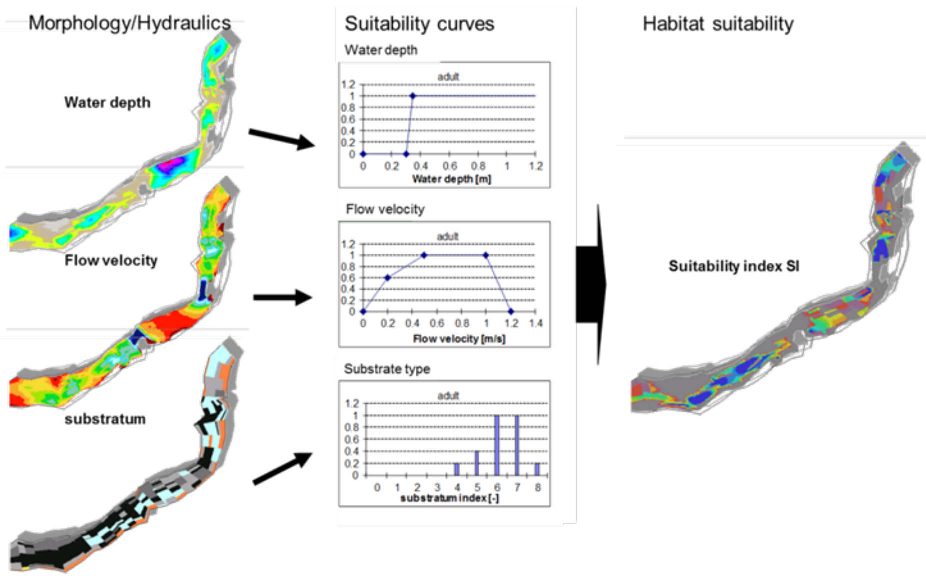


Fig. 15: Habitat modelling using suitability curves (feasible with CASiMiR)

Suitability curves are classified in different categories (category I = derived from expert knowledge, category II = derived from field data, and category III = derived from field data in relation to availability). All of them define the suitability of habitat usually on a scale between 0 (=unsuitable) and 1 (= perfectly suitable). Suitability curves are usually univariate, i.e. they are related to one habitat parameter such as water depth. The suitability curves are developed for 3 – 5 parameters, independently from each other, and used for modeling. The total habitat suitability (composite habitat suitability CSI or often simply SI) is derived by different methods of integration for each individual grid cell in the river and for different flows. However, these methods do not consider the interaction of the habitat parameters and therefore the approach is not multivariate. Fig. 15 shows the general procedure.

CASiMiR is able to process univariate suitability curves, but its main difference to other models is the application of multivariate fuzzy logic as interface between hydraulics and biota for habitat simulations. Within the fuzzy rule-based approach fish habitat requirements are described via rule systems. These rules cover all combinations of habitat parameters and their instances in categories (named with linguistic terms "Low", "Medium", High…). Based on expert knowledge and on fish data available from the investigated river, suitability categories (also named as "Low", "Medium", "High"…) are appointed to the combinations of rules. All these categories are described by fuzzy sets. These sets are different to classic mathematical sets since they allow for the integration of a certain degree of impreciseness. Further information on the fuzzy approach is found in the manual for CASiMiR Fish. Thus, the approach is particularly interesting for data scarce situations with limited information about fish habitat requirements, as in Bhutanese rivers. Though the input data for the model are defined as a fuzzy rule system, using imprecise fuzzy sets, the output of the simulation is a habitat suitability with a value between 0 (=unsuitable/low suitability) and 1 (=perfectly suitable/ high suitability) as for the suitability curve based approach.

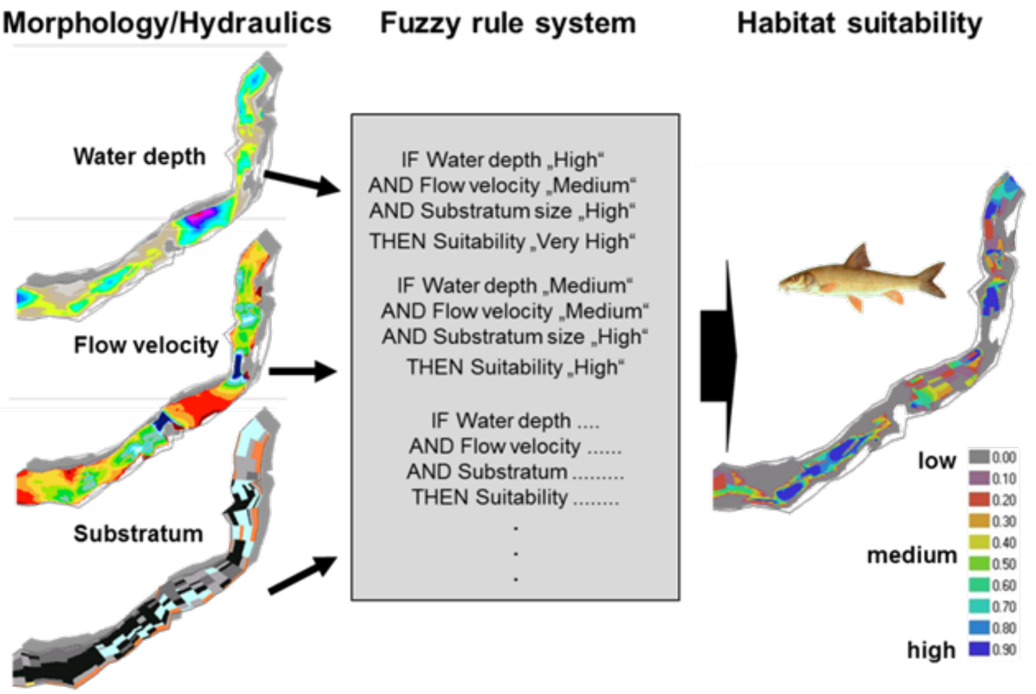


Fig. 16: Habitat modelling using a fuzzy rule based approach (CASiMiR main processor)

The primary results, habitat quality maps for a river reach and different flows, appear identical but the internal modeling approach is a very different one.

There are two reasons why CASiMiR was recommended and used for the pilot reach studies. First of all, the fuzzy logic approach allows to consider combinations of physical parameters which matches the real world better than addressing parameters independently. Secondly, the fuzzy logic approach allows the development of suitability functions even in situations with limited data from field observations by making use of expert knowledge. This corresponds well to the situation in Bhutan and produces rather robust and stable models and results.

3.3.16.1 Simulations

CASiMiR simulations are to be carried out for all fish species, identified to be protected, that are actually or potentially occurring in the dewatered reach and all their life stages. The selection of species to be modeled depends on the conservation goals for a specific river or river reach.

Simulations are usually done by combining the results of the hydrodynamic model for each individual flow with the suitability functions of the target species. The direct outcome of the CASiMiR simulation are habitat maps for different species and life stages and a series of flows identical with the ones used for the hydrodynamic model.

While CASiMiR has interfaces for several different hydrodynamic models, proper assessment should be made on the availability of the interface before choosing the hydrodynamic model. If no interface is available, a new one must be developed which could be avoided otherwise.

3.3.16.2 Results of the simulation

In order to assess the aquatic habitats in a river and their changes with the flow, the results of habitat simulations have to be analyzed. The most common ways are habitat maps and weighted usable area (WUA).

Habitat maps

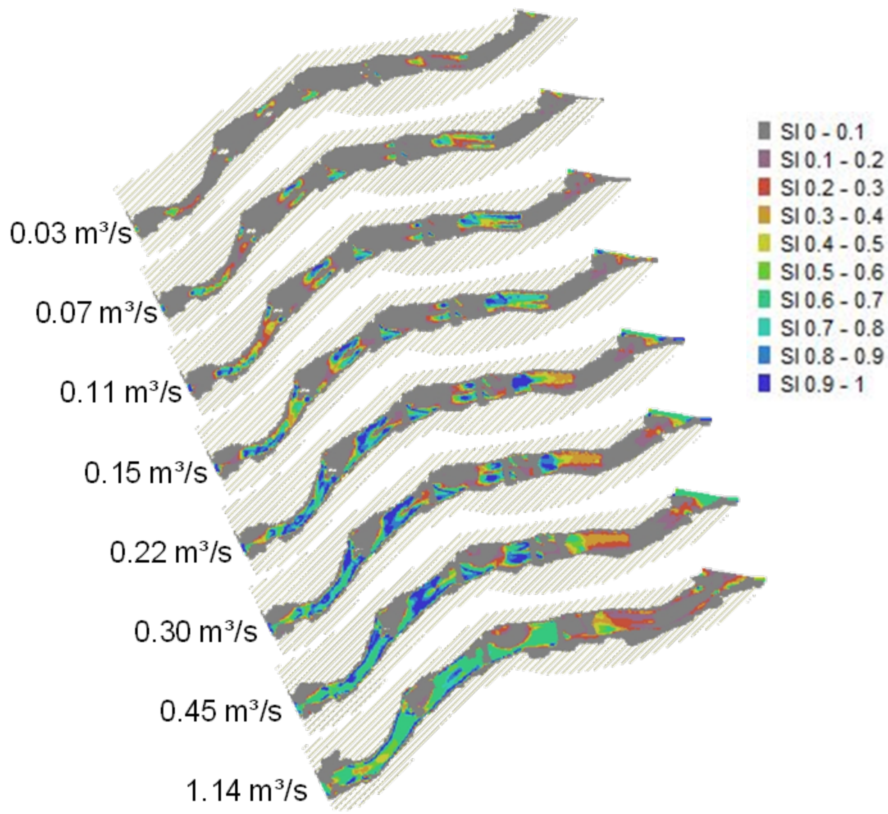


Fig. 17: Habitat suitability maps for spawning brown trout at different flow rates in a German river

Habitat suitability is the primary result of the habitat simulation. Habitat quality or suitability has a value between 0 and 1 and is assigned to each model element. This value is the habitat suitability index HSI or simply SI. The HSI can be visualized in form of habitat maps using a color code to visualize habitat quality. Habitat simulations are performed for one species and life-stage at a time but for different flow rates. Thus, the related habitat maps show the spatial variation of habitat suitability and the change of the habitat pattern with the flow rate. An example is given in Fig. 17. The information shown there is the direct result as generated by the habitat model. All other results can be derived from this information.

The spatial information of habitat maps is important for interpretation, firstly to see if and where there are good habitats and their spatial distribution. Maps also allow to analyze if and how well habitats are connected and spatially distributed or the distance between high quality habitats. Maps also show how suitable habitats shift within the river bed as the flow changes. Therefore the first evaluation of the simulation result is always a close look at the habitat maps and how they change with the flow. However, the maps do not directly deliver quantitative information except as graphical display. Therefore further evaluation is usually needed.

Weighted usable area (WUA)

The so-called weighted usable area (WUA) is commonly used as integrative parameter and equivalent of habitat availability. The WUA is based on the assumption that multiplying the area of each model element with its habitat suitability index SI (between 0 and 1) and adding up these products is a suitable indicator for the total habitat conditions at a given discharge.

In case all elements have optimum suitability (SI = 1.0) the WUA equals the wetted area, in case no element is suitable (SI = 0.0) the WUA is 0. Since WUA is the sum of all model elements weighted by their suitability, it has the unit [m^2]. Without an indication of the inundated area of the study reach of the river, the absolute value of WUA has little meaning. Thus it is considered in relation to the wetted area for interpretation. The WUA is usually plotted as a function of flow rate. This function shows how habitat availability changes with discharge. The WUA function is a commonly used way to assess habitat change with flow and flow recommendations are often derived from it. Assessment is frequently performed related to the shape of the curve (clear maximum, inflection point, distinction between ranges with significant or negligible flow related increase).

Since WUA depends on the river size it is not directly suitable for the comparison between different study reaches. For this kind of comparison, the HHS (Hydraulic Habitat Suitability) function can be applied. It is the WUA divided by the wetted area, so its dimension is a percentage or a value between 0 and 1.

The HHS does not reflect the total increase of habitats but the increase related to the wetted area. If habitats and wetted area increase exactly with the same rate, HHS stays constant. Fig. 18 shows an example of the results from a simulation for brown trout in a small alpine stream in Switzerland. Adult brown trout find the best habitat conditions at a flow of 1.5

m³/s, if the flows increase further, overall habitat quality (WUA) remains almost constant but normalized or average habitat quality (HHS) is decreasing. Interpretation tells that higher flows only add low quality habitat which does not support an increase of the WUA and therefore HHS drops with higher discharge.

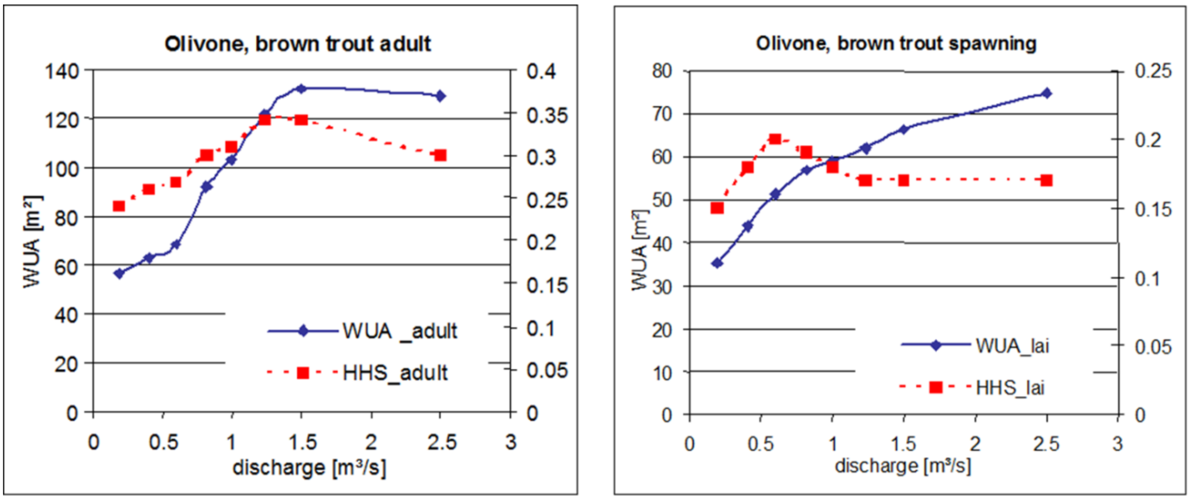


Fig. 18: Weighted Usable Area WUA and HHS for adult (left) and spawning (right) brown trout for different flows in a river in Switzerland.

Neither WUA nor HHS give information on the distribution of quality classes and therefore of availability of high quality habitats. A large area of low quality habitats can result in the same WUA as a small area of high quality habitats. However, a comparatively small amount of habitats might be sufficient to satisfy the demands of a fish population (e.g. spawning habitats). Thus, it is necessary to look at the percentage and spatial distribution of different habitat quality classes as well.

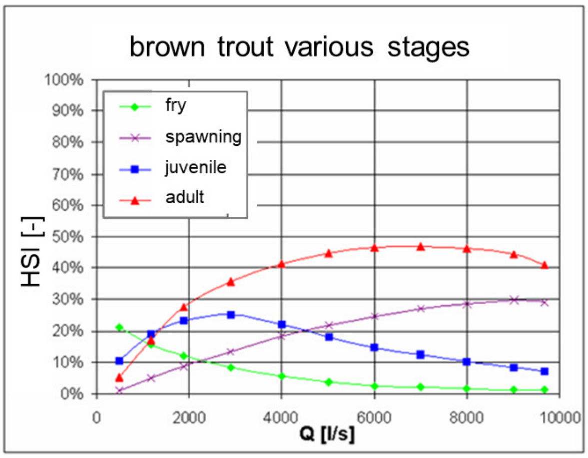


Fig. 19: HSI for different brown trout life stages

It is quite common that different species or different life stages of one species have different preferences and therefore WUA or HSI curves behaving in opposite directions. In such a situation the natural flow regime is the reference situation and the most vulnerable species or most critical life stage with the highest protection status is to be investigated first and will control the overall outcome while the other ones are given lower priorities. The problem is a multi-objective decision making problem which may not have an obvious solution. The development of scenarios is therefore required.

Habitat quality class distribution

Usually the habitat suitability index SI is classified on a scale between 0 and 1 using five or ten habitat suitability classes (compare e.g. Fig. 20 and Fig. 23). The portions of the different classes are known for all modelled flow rates. Thus, same as for the WUA and HHS, a diagram showing the change over flow rate can be generated. This evaluation gives the important information about habitats with high suitability and their occurrence in different flow ranges. Fig. 20 shows an example for two life stages of brown trout. The diagram for adult brown trout shows that below a flow rate of about 0.20 m^3/s there are no areas with high suitability (>0.7) available and good habitats keep continuously increasing as flow rises. For spawning trout (right diagram) the amount of high quality habitats is maximum for a flow rate between 0.25 and 0.3 m^3/s and decrease slightly as flows are rising. The upper envelope is representing the inundated area. These diagrams should generally be generated for flow rates up to at least the MAF.

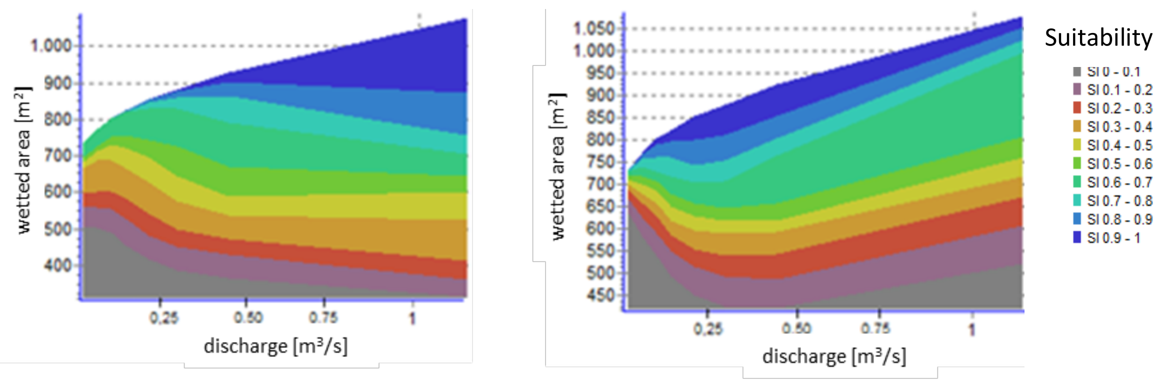


Fig. 20: SI-class distribution over flow for adult (left) and spawning (right) brown trout

Habitat time series, temporal availability of habitat

Since habitats change over flow rate habitats are time dependent. For time series analysis the assessment parameters as listed before can be linked with a flow time series, or hydrographs. That way a habitat time series is derived illustrating the change of habitat over time and e.g. in different seasons of the year. Fig. 21 is showing an example where at relatively low flows (e.g. January through April) a slight increase of discharges improve habitat quality whereas high flows and short floods during the summertime cause considerable reductions of habitat quality and fish possibly need to seek refuge. If natural base flows are known for certain (bio-) periods of the year (such as spawning, migrating, etc.) these can be used as reference situations for habitat quality during specific life stages. Such diagrams also show when bottlenecks might occur.

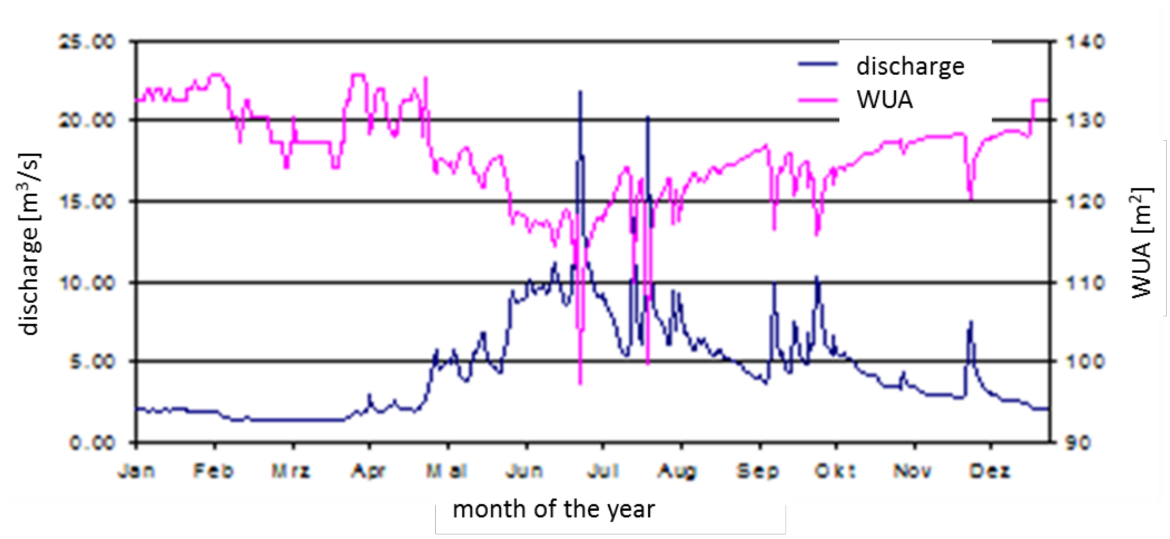


Fig. 21: Time series of flow (blue line) and WUA (pink) in a Swiss mountain stream

Habitat time series can also be transferred into a habitat duration curve by sorting the habitat values in a descending order. That way exceedance durations and related habitat values can be defined. Locke (1996) has e.g. used 20%, 50% and 80% durations of exceedance and defined habitat qualities found for these durations of exceedance as minimal, medium and optimal. The approach can be extended by the continuous exceedance of certain threshold values. However, to apply this kind of analysis a profound knowledge about the ecological significance is needed, which can only be achieved by intensive monitoring over long periods and comparison of fish abundance with habitat quality. Therefore, this approach is mentioned here but will probably not be used any further.

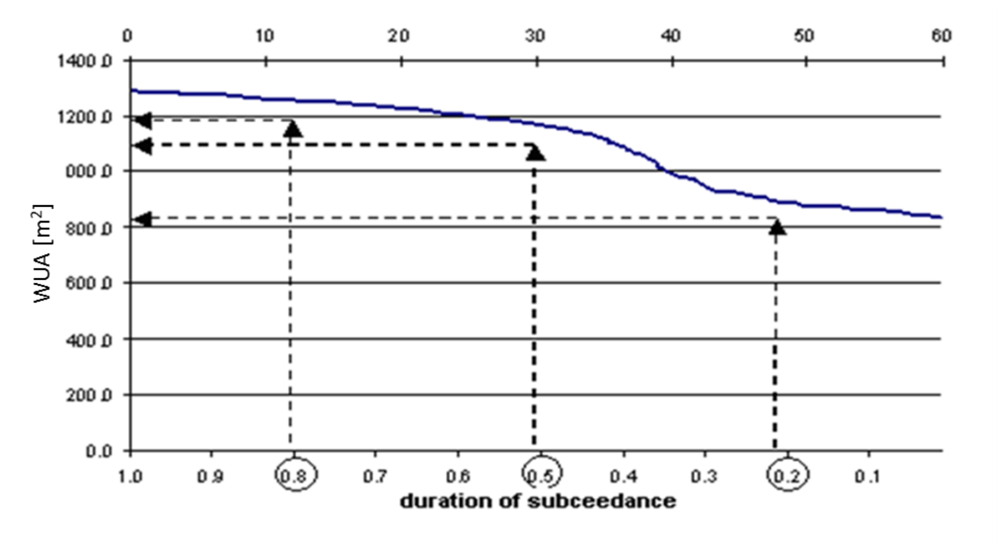
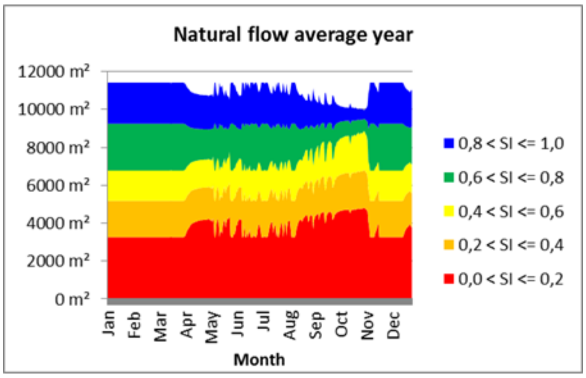


Fig. 22: Habitat duration curve with WUAs subceeded 80%, 50%, and 20% of the time

As the hydrological regime of most rivers has a very distinct pattern, this needs to be considered on top of the duration curves of the habitat quality. The analysis may serve as an indication what level of habitat quality is still acceptable for a species.

Temporal availability of habitats: SI-class distribution

More detailed information is derived by the time series of the SI class distribution. Fig. 23 shows the temporal availability of habitat quality classes during a hydrologically average year, without (left) and with flow diversion (right). In the illustrated diversion scenario the minimum base flow remaining in the river is 3.9 m³/s. The amount of high class habitats with an SI >0.6 (green and blue color) is almost disappearing and only during periods with a flow higher than the capacity of the turbines and resulting weir overflow habitats are similar to the unaffected situation. These periods are mainly in the wintertime and have, based on their randomness and short duration, no positive influence.



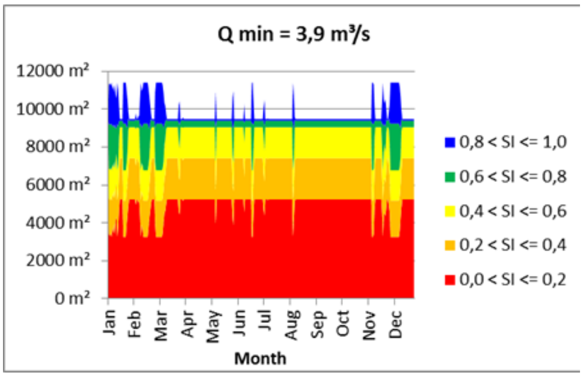
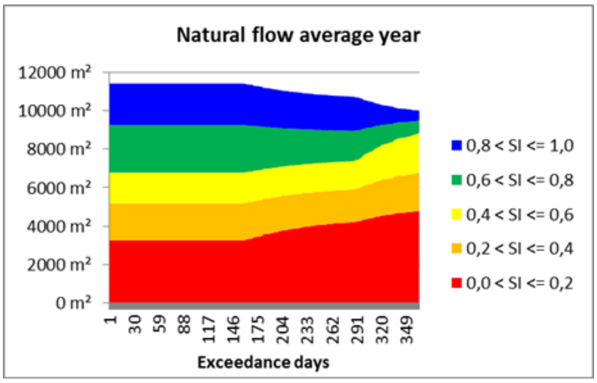


Fig. 23: Time series of SI class distribution for an average year without (left) and with flow diversion for a base flow of 3.9 m³/s (right), adult grayling.

In the example presented here the change in temporal availability of high quality habitats becomes even more evident in the duration curves illustrated in Fig. 24. Without diversion habitats with an SI > 0.6 are found in roughly 1/3 of the wetted surface over almost 200 days of the year (Fig. 24 left), whereas under the E-flow regulation of 3.9 m³/s the amount of high quality habitats is available only for about 60 days per year (Fig. 24 right) and most of the time no really good habitats are available.



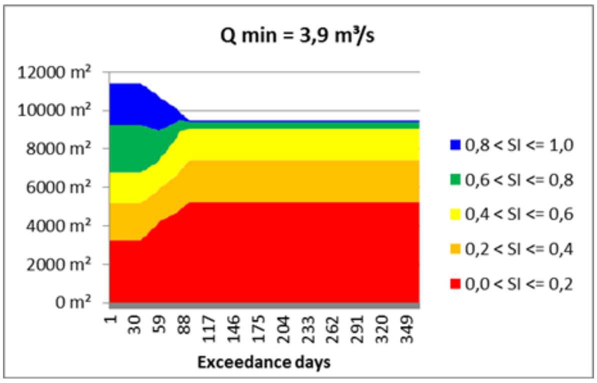


Fig. 24: Duration curves of SI class distribution for an average year without (left) and with flow diversion for a base flow of 3.9 m³/s (right), adult grayling

The temporal availability of habitats and the dynamics of habitat (disturbances/temporal variation) should be more distinct and closer to the natural flow regime for higher the protection levels. Fig. 25 shows the results of an analysis for different E-flows in comparison with natural (no water abstraction) wet and dry years.

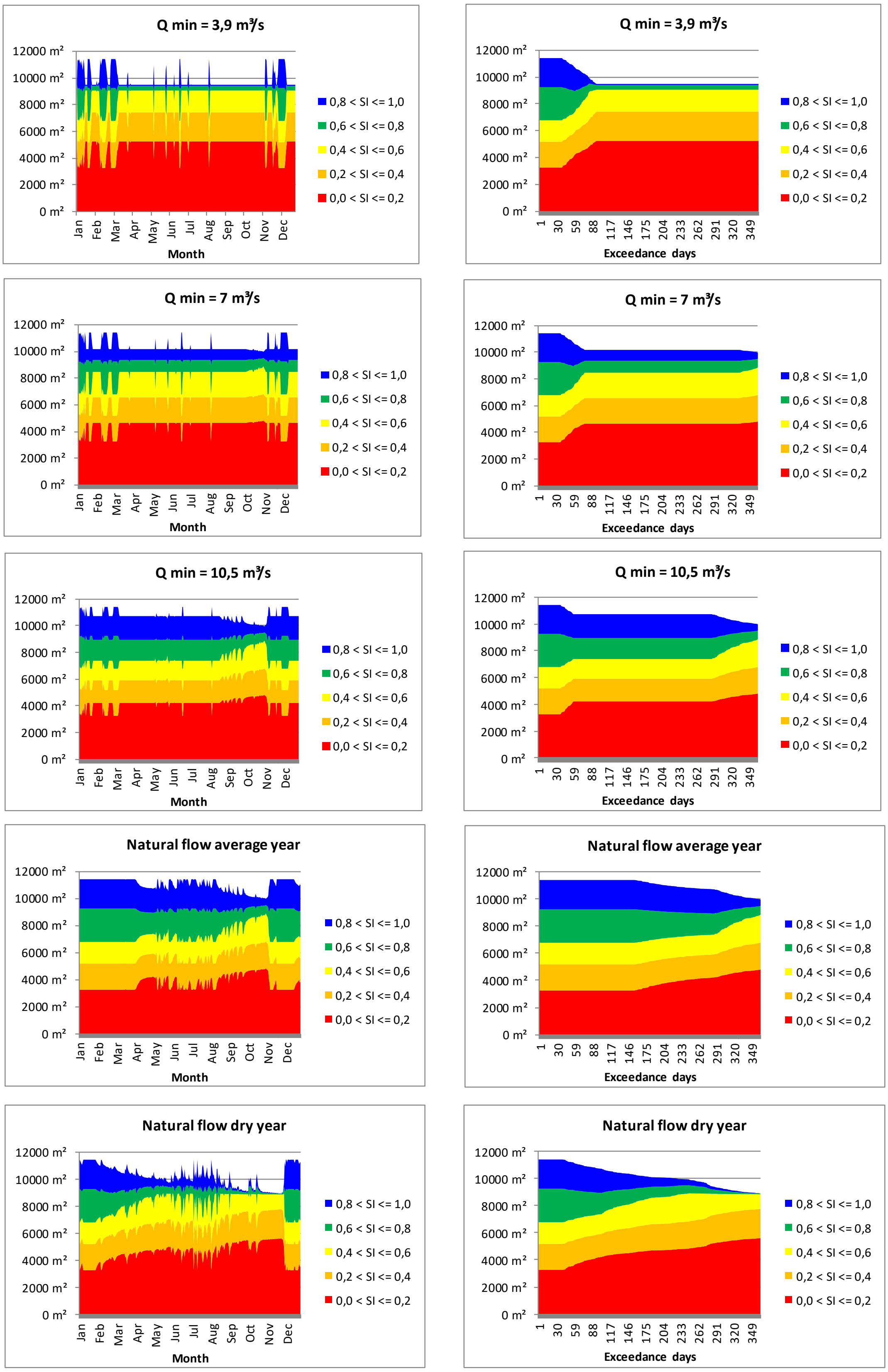


Fig. 25: Temporal habitat pattern for adult European grayling (Thymallus thymallus) in a stretch of a midland river for different flow rates in an average year and for natural flow in two different hydrological years, habitat time series (left) and habitat duration (right).

Based on this quantitative information, the fish ecologist can set thresholds for the availability of habitats in amount and duration that can be used to find flow regulations. However, setting these thresholds requires good knowledge about the fish ecological properties of the considered river system and depends on the spatial and temporal patterns of habitats and their relation to flow. The next paragraph gives some basic rules for the interpretation of simulation results.

3.3.17 Evaluation of the simulation results

The conclusions and recommendation drawn from the model results depend on several aspects. The countrywide Conservation Plan and the river or reach specific Conservation Goal have been set up in previous steps. Based on these documents, a protection category has been set up for the river and species living there, including potentially occurring species, if applicable.

> The constitution of the Royal Kingdom of Bhutan and all legal and regulatory documents related to the protection of nature and habitats call for the protection of habitats and species, especially rare or endangered ones. Freshwater ecosystems are amongst the most vulnerable worldwide. Therefore, per default, all habitats for fish and other aquatic species should be fully protected. Putting this directly into practice would more or less put a halt on hydropower development in Bhutan, realistically. However, maintaining at least 80% of all habitats is one of the scenarios to be considered. The other extreme end of possible scenarios is an operation without E-flow releases as currently practiced at Chukha or Tala HPP where an 80% loss of species was observed in the Chukha dewatered reach. This makes it clear that a spectrum of different scenarios must be considered and no easy solution is at hand.

Step 1: A Protection Category PC on a scale from “VERY HIGH” to “VERY LOW” is appointed to the considered river stretch. This Protection Category is based on previous investigation on river ecology and the importance of the river stretch for the whole river system, i.e. on the conservation goal and conservation plan.

Protection Categories:

- **PC VERY HIGH** – affected river stretch has very high importance for river system and is inhabited by threatened species or source populations, habitats for whole community available that are otherwise rare in the system or subpopulations depend from the affected river stretch: the source population and the habitats have to be conserved for all relevant species and life stages, no deterioration allowed.

- **PC HIGH** – affected river stretch has high importance for river system, habitats are available for selected species and life stages otherwise rare in the system: habitats have to be conserved for selected species and life stages, deterioration is not allowed for those, high level of habitats to be sustained for the other species

- **PC MODERATE** – affected river stretch has average importance for river system and is inhabited by one of several existing source populations. No threatened species occur. High quality habitats are available but they are also found in various other parts of the river system: habitats have to be conserved but minor deterioration is allowable (reduction of habitat surface) to a certain degree as long as main habitat functions are conserved

- **PC LOW** habitats inhabited by sink populations that are not threatened (sink habitats), affected river stretch has minor importance for river system. Habitats are available but they are found in high amounts in many other parts of the river system: moderate habitats deterioration is allowable as long as basic habitat functions are conserved, however the migration corridor of fishes has to be ensured and is the main aspect of conservation.

- **PC VERY LOW no fish found,** affected river stretch has very little importance for river system. Almost no habitats for fish available, these habitats are found in high amounts in many other parts of the river system: habitat deterioration is allowable

The Achievement Goals are specified, according to the protection category. Achievement goals are a percentage range according to Table 3, which can differ from one species or life stage to the next and can also include temporal aspects. A fish and its habitat must be protected only during the season or months while it is naturally in the concerned river reach. This applies to migratory fish which are using certain river reaches only during certain periods.

Step 2: The simulations are performed as described in the previous chapter and both, WUA functions and SI classes are available for all relevant species and life stages. WUA and high SI classes are determined for each relevant specie and life stage for the reference flows Q_{100} and Q_{335} for the wet and dry season, respectively.

It is then determined how much of the flow must be maintained to preserve the percentage of WUA and of high SI classes that is indicated by the AG.

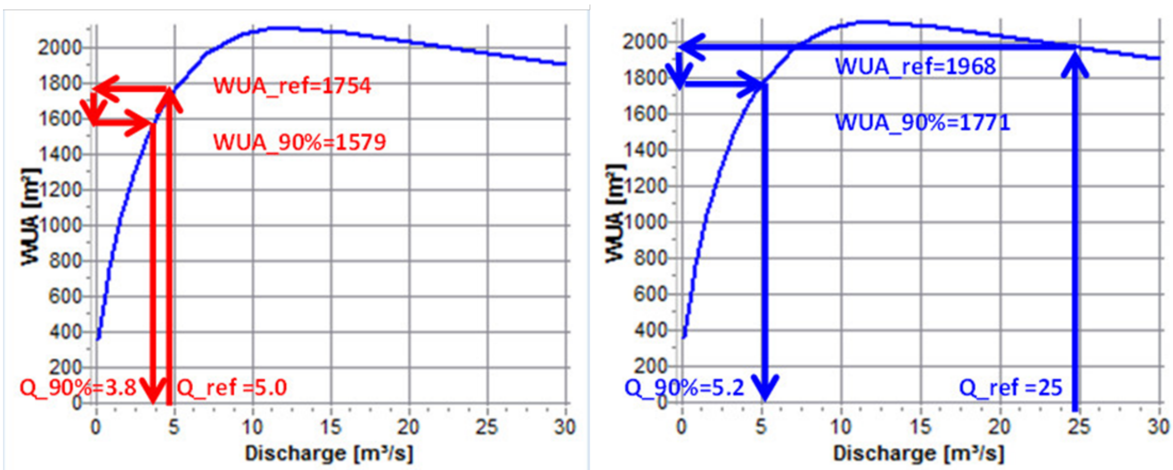


Fig. 26: Determination of required flows to preserve 90% of WUA as compared to reference flows.

Fig. 26 shows an example where the same WUA function is used to determine required flows during the dry season (left side) and during the wet season (right side). The reference flows are:

Q_{335} = 5.0 m^3/s for the dry season resulting in a WUA of 1759 m^2

Q_{100} = 25.0 m^3/s for the wet season resulting in a WUA of 1969 m^2

In this case it was determined by the achievement goals AG that 90% of the habitat had to be preserved, in the case of the dry season this would be 1579 m^2 which corresponds to a flow of 3.8 m^3/s. The remaining results are summarized in Table 6.

Table 6: WUA functions and flows required to preserve 90% of the WUA at reference flow.

	Reference flow [m^3/s]	**WUA [m^2]**	**90% WUA [m^2]**	**Q_{90WUA} [m^3/s]**
Dry season	5.0	1754	1579	3.8
Wet season	25.0	1968	1771	5.2

The same analysis is then done with the “good” habitat portions only, based on the assumption that a small share of good habitats cannot be adequately replaced by large areas of poos habitats although it might result in the same WUA. The analysis is shown in Fig. 27 and the results are summarized in Table 7.

Obviously the two different approaches result in different required flow rates for each season. Both, WUA in general and good habitat areas with SI > 0.6 must be preserved and the higher flow from either one analysis is relevant. This would result in a flow requirement of 3.9 m^3/s during the dry season and 5.2 m^3/s during the wet season.

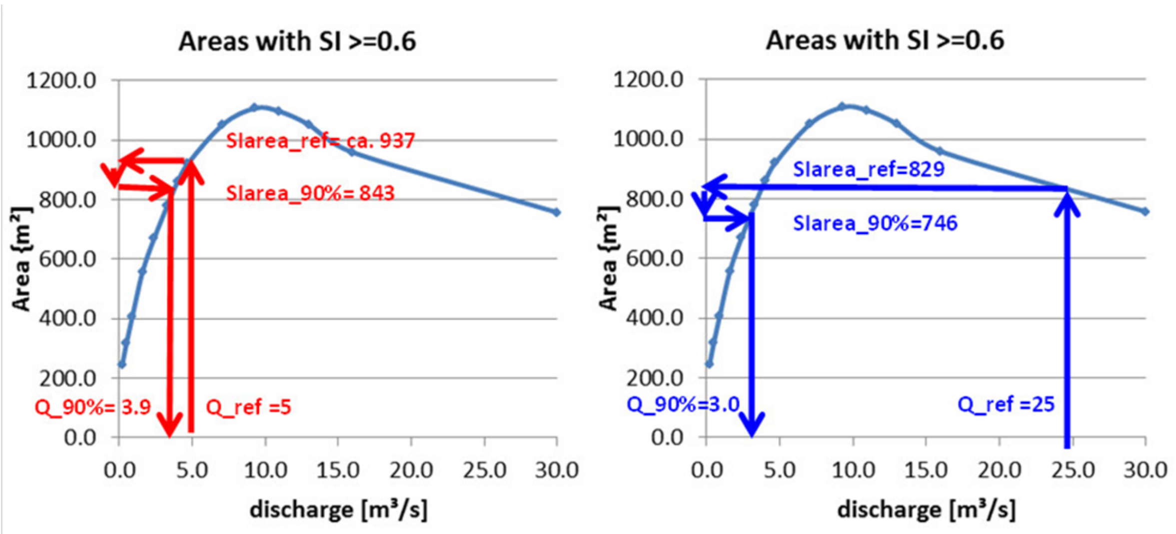


Fig. 27: Example for the determination of flows required to maintain 90 % of good habitats with SI > 0.6

Table 7: SI > 0.6 functions and flows required to preserve 90% of the habitats with SI > 0.6 at reference flow.

	Reference flow [m³/s]	SI > 0.6 [m²]	90% SI > 0.6 [m²]	$Q_{90SI>0.6}$ [m³/s]
Dry season	5.0	937	843	3.9
Wet season	25.0	829	746	3.0

What is being observed in this example is quite typical. More or less all WUA curves originate at 0, since without water there is no fish habitat. And as flows are more and more increasing the WUA function reaches a maximum at some point and starts dropping, sooner or later, depending on the river morphology, species and life stages. Sometimes the range of flows studied do not include these minima and maxima, however, they are there. If fish living mostly in the lower reaches of rivers (so called Potamal) move into the higher reaches (so called Rhitral), they will find their best habitat conditions at lower or medium flows whereas the fish typically living in fast mountain streams will prefer higher flows. If the target species are chosen correctly there will most likely be fish which need higher flows as compared to the example shown here where the required wet season flows are lower than the required dry season flows.

What is striking in this example is that during the wet season a very large percentage of water can be abstracted with no significant loss of habitat as compared to the reference flow. The reason for this is the general shape of the WUA curve and the fact that the reference flow is beyond the flow with the maximum WUA. By applying the 90% criterion the required remaining flow is determined on the rising limb of the WUA function. Analytically this is correct but it must be verified by looking at the habitat maps. It usually means that the location of good habitats shifts from along the banks at high flows during the wet season towards the center of the river bed at very low flows while the overall suitable area remains the same. In the example shown in Fig. 26 and Fig. 27 the required flow during the wet season would be even smaller than during the dry season if only SI > 0.6 habitats are considered. That, however, would be overruled by the requirement that the hydrological regime must be maintained. Consequently, habitat would be even better during the wet season E-flow than under the reference flow for the wet season.

Integrated results (SI class distribution and WUA)

The integrated results in terms of SI class distribution and Weighted Usable Area can occur in different patterns. Interpretation and recommendation is depending on these patterns but generally following the procedure as described above. Diagrams should be generated for flows up to MAF at least or whatever flows may be relevant.

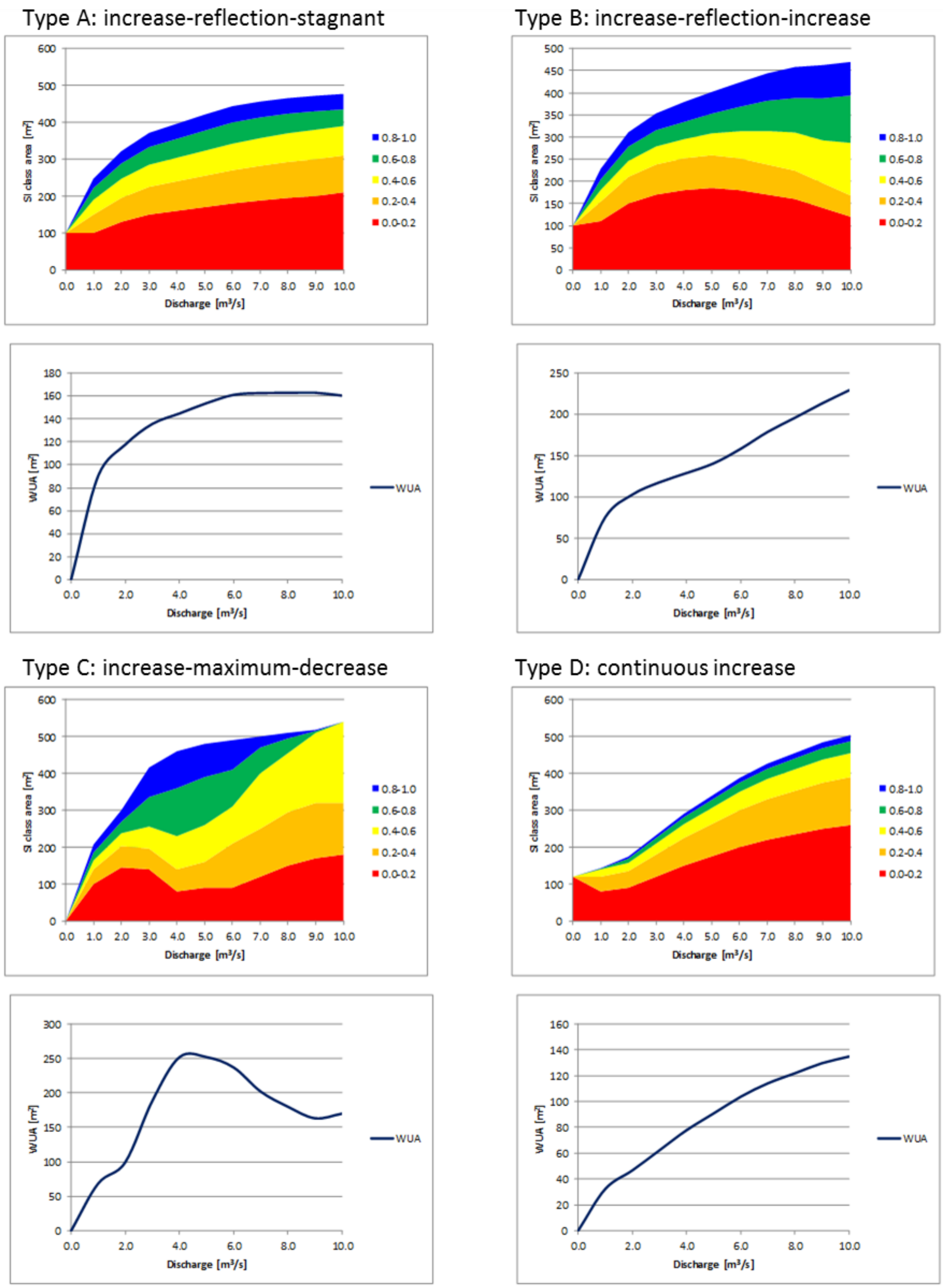


Fig. 28: Characteristic types of results for SI-class-distribution and WUA generated from habitat simulations

Flow scenarios

The flows which are derived based on these diagrams and different AGs are describing the flow of water required to provide a certain percentage of the habitat quality and availability as compared to the seasonal or monthly reference flow in this river reach. However, the AG may not always be the final choice, depending on various aspects such as economic issues or optionally applying compensation measures. Therefore, in addition to flows necessary to reach the AGs, higher and lower levels of habitat quality and availability should be investigated as well. This is done the same way as described above except that the share of WUA or SI > 0.6 to be preserved is variable. The analysis can be done in any direction, either based on different achievement levels (AL) in comparison to the AG or by using flows as starting point by moving in the opposite direction against the arrows in Fig. 26 and Fig. 27. The final result of this analysis is demonstrated in Table 8.

Table 8: Achievement goals or achievement levels for different flows

snow trout medium								
Period	Low flow season				High flow season			
Ref flow	4.0 m^3/s				22.0 m^3/s			
period	Dec - Mid June				Mid June - Mid Sep			
achievement goal	WUA	flow	SI>0.6	flow	WUA	flow	SI>0.6	flow
100%	2306	4.0 m^3/s	1941	4.0 m^3/s	4152	22.0 m^3/s	3859	22.0 m^3/s
90%	2075	3.4 m^3/s	1747	3.5 m^3/s	3737	12.4 m^3/s	3473	11.8 m^3/s
80%	1845	2.8 m^3/s	1553	3.1 m^3/s	3322	8.8 m^3/s	3087	8.2 m^3/s
70%	1614	2.2 m^3/s	1359	2.6 m^3/s	2906	6.5 m^3/s	2701	6.4 m^3/s
60%	1384	1.7 m^3/s	1165	2.2 m^3/s	2491	4.7 m^3/s	2315	5.1 m^3/s
50%	1153	1.3 m^3/s	970	1.8 m^3/s	2076	3.4 m^3/s	1930	4.0 m^3/s
40%	922	0.9 m^3/s	776	1.4 m^3/s	1661	2.3 m^3/s	1544	3.0 m^3/s
30%	692	0.6 m^3/s	582	1.0 m^3/s	1246	1.5 m^3/s	1158	2.2 m^3/s
20%	461	0.2 m^3/s	388	0.4 m^3/s	830	0.8 m^3/s	772	1.4 m^3/s
10%	231	0.1 m^3/s	194	0.1 m^3/s	415	0.2 m^3/s	386	0.4 m^3/s

If in this case the achievement goal is 40 % for PC “moderate” it would require flows of 1.4 m^3/s during the lean season and 3.0 m^3/s during the wet season. Other achievement levels based on steps from 10% to 100% can be read from the table.

Spatial pattern of habitats

A further important criterion for E-flow setting is the spatial distribution of habitats. Beside the integrated quality of habitat a certain minimum area and the spatial connectivity is necessary to ensure that habitat can be used by fish. European grayling, for example, does need a minimum length of habitat patches with an approximate area of several tens of square meters and the distance between suitable habitats should not exceed several tens of meters if they are very patchy.

In the example in Fig. 29 the change of habitat suitability for adult European grayling (Thymallus thymallus) in a stretch of a midland river (mean flow around 18.0 m^3/s) is shown. First patches with habitat suitability >0.6 show up at around 3.2 m^3/s. With an increased flow rate of 5.5 m^3/s they become larger and are partly connected. With further increased flow of 7.0 m^3/s the high quality habitat patches become more distinct and form larger connected areas. With the highest modelled flow rate of 18 m³/s the areas with SI>0.6 become maximum, while in some areas the habitat quality is slightly reduced compared to the lower flow of 10.5 m³/s. This is because flow velocities in the deeper central part of the river are partly higher than the most preferred range of adult grayling.

Related to the protection levels listed above the following basic rule can be defined:

The higher the protection level the more distinct and closer to the situation at natural flow should the size of single patches and their connectivity be.

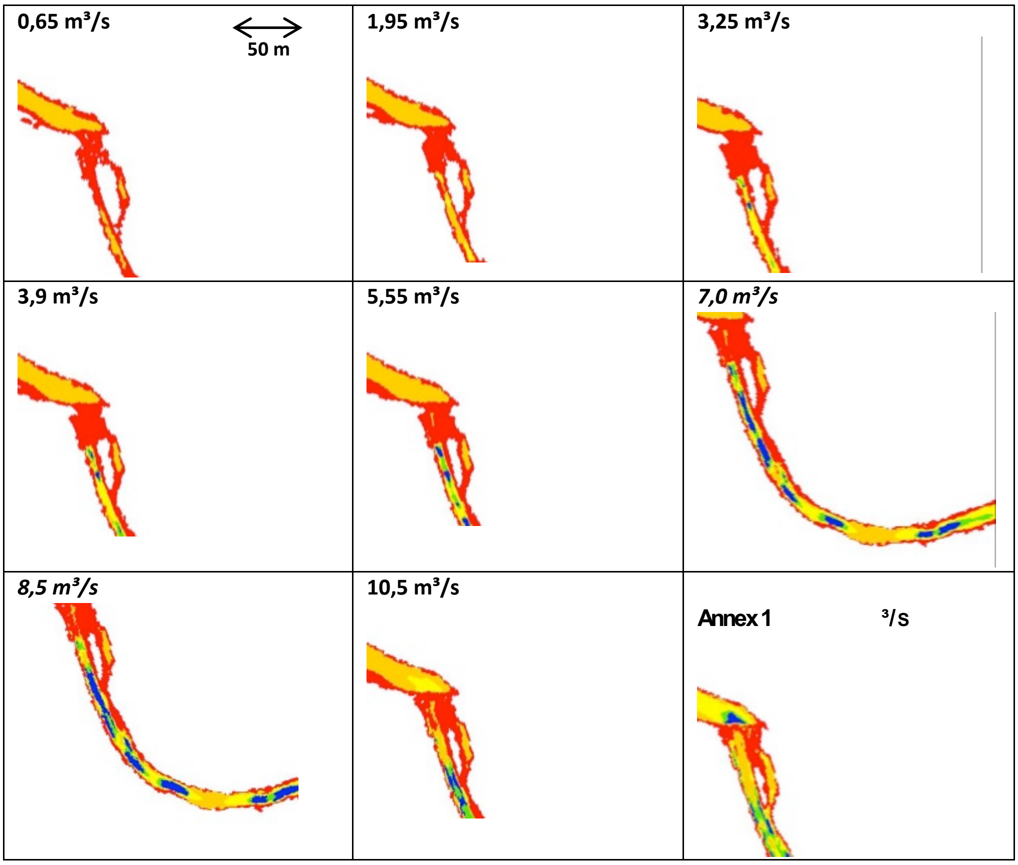


Fig. 29: Spatial habitat pattern for adult European grayling (Thymallus thymallus) in a stretch of a midland river with changing flow rate

Temporal pattern of habitats

As stated before, the temporal availability of habitats is another important aspect that has to be considered in E-flow setting. Particularly for diversion plants with limited rated flow, there are usually periods in the year where the natural flow exceeds the capacity of the turbines. In these periods the minimum flow set as a base flow to conserve habitats is augmented by the weir overflow. The example shown in Fig. 25 illustrates the temporal availability of habitats over a whole year. The pattern is shown for a hydrologically average year with different minimum flow settings as well as for the unmodified flow in the average year and in a dry year.

It can be seen that even in low flow season of the dry year there are a lot of small "disturbances" in terms of short but frequent flow increases. Under E-flow conditions the number of disturbances increases with higher E-flows since the design flow of the turbines is smaller. Only in between day 290 and 330 (October/November) there is a period with constant low flow.

In the average year with a minimum flow of 7 m^3/s high quality habitats (SI>0.6) are available all year long (second row right), whereas in the dry year, there is a period of about 40 days with virtually no high quality habitats to be found (last row right).

Again these results have to be interpreted against the background of the indicator species, the river ecology and the natural flow regime. However, another basic rule can be defined as follows:

With respect to temporal availability of habitats and the dynamics of habitat (disturbances/temporal variation) the higher the protection level the more distinct and closer to the natural flow regime it should be.

Summary

Aquatic habitat modeling is a powerful tool to address impacts of changed flow regimes on the living conditions for fish and benthic species. The results as presented in the examples are fairly complex and a sound understanding of the entire modeling process and some experience is required to interpret the results in such a way that meaningful E-flow regulations can be derived. It allows however a very fine distinction between where additional flow rates contribute to significantly improved habitat conditions and where it does not. Therefore, the tools and the results are highly suitable for fine-tuning flow releases to benefit both, living conditions for fish but also the water available for power generation.

3.3.18 Fish Migration

Migration through the dewatered reach (not across dams and through reservoirs) is treated here in a separate subchapter. It is usually treated within the habitat simulation procedure but in reality it is more a hydraulic rating approach. Migration is essential if migratory species occur upstream or downstream, habitat in the dewatered reach is not considered essential and passage across the dam is possible. In such cases the habitat aspect can sometimes be reduced to enable migration only through the dewatered reach. The criterion is usually a minimum water depth of 2.5 times the body height of the fish. The results of the hydrodynamic model can be used for evaluating how much flow is needed to enable migration.

Since the study reach is not always completely representative for the entire dewatered reach it is necessary that migration is first analyzed using the results of the hydrodynamic model but the result must be verified by an inspection of the entire dewatered reach within the monitoring program. If necessary, local migration barriers caused by low water depths must be improved to allow migration or the flow needs to be increased.

Migration is the absolute minimum requirement if habitat is not considered important enough to release certain E-flows because of the energy generation losses.

The internationally applied standard for minimum water depths necessary for fish migration is a water depth of 2.5 times the maximum body height of the fish under consideration. It is frequently argued that fish can be observed to migrate also in shallower water than 2.5 times their body height. This may be true but could cause delays or enable predators to prey more easily on migrating fish. If this ratio is to be lowered it should be done based on field observations and sufficient evidence only and be limited to short sections or individual locations within the dewatered reach.

Since the models to study critical water depths are only developed for the representative study reach within the dewatered reach, it has to be demonstrated either by evidence (fish are migrating) or by inspection during the monitoring program that there are no critically shallow sections within the dewatered reach which act as migration barriers. This is very challenging considering the steep and rocky river beds but has to be done. The criterion of 2.5 times body height as minimum water depth is rather conservative and one can hope that the rest of the dewatered reach will satisfy critical migration criteria. However, a proof is needed.

3.3.19 Habitats for other species

The general approach of considering the physical parameters and processes of habitats used by fish species under consideration can be applied for other species as well. The obvious lack of data describing habitat preferences for other species should not be an excuse for not applying such approaches.

There are cases where fish are not the main indicators for the ecological status of a river, for example high and steep headwaters upstream of natural habitats or reaches above migration barriers such as water falls. In this case benthic species can serve as an indicator. Many macroinvertebrates have specific hydraulic and morphologic preferences similar to fish. Particularly flow forces near the river bed and bottom substratum are crucial for the habitat choice of benthic species. CASiMiR has a module that allows for the calculation of hydraulic forces at the river bottom, a combination of drag and uplift, from depth averaged flow velocities as they are provided by 2D hydrodynamic models. Similarly as for fish, suitability curves or fuzzy rules can be used to link the hydraulics and morphology with habitat requirements. Data processing and evaluation of the results is equivalent to the methodology described above for fish.

Habitats for other species have to be evaluated individually. There are no quantitative tools like the ones for fish available. Fish otters, for example, are living in swiftly flowing water and are feeding on fish. To maintain habitat for fish otters, water depths, flow velocities and the width of the water surface of the remaining river is most likely relevant. This can be studied along with the aquatic habitat simulation and evaluated based on a hydraulic rating analysis. Most importantly, if there are no fish to feed on, there will be no otters. Similar approaches could be applied to fish feeding waterfowl and birds such as the White Bellied Heron.

Floodplain vegetation is particularly sensitive to the duration and timing of flooding. Hydraulic forces and related erosion may also play a crucial role in the succession processes of these very dynamic floodplain forest ecosystems. Water abstraction or storage in large reservoirs may affect not only the low and average flow situation but can also change flooding events. There are models available to investigate the long term effect of flow regime changes on floodplain vegetation (CASiMiR-vegetation). This aspect is beyond the focus of this report. The dewatered reaches investigated for this study were all rather narrow and deeply incised river sections with no significant adjacent floodplains.

3.3.20 Protected areas

If any protected areas are located in the region of the dewatered reach it must be evaluated if the dewatering and its consequences have any effect on the objectives and target species of the protected area. This should be done by looking at the seasonal and life cycle strategies of the target species of the protected area and if there are any linkages to the river system. If so, it needs to be determined which features, properties, services or functions of the river are relevant for the target species. What is relevant for the target species of the protected area (e.g. fish as food source) must be maintained so that the objectives of the protected area are not compromised.

An evaluation if the dewatering and setting of E-flows are relevant or not must be done case by case.

3.3.21 Sediment management

Among the key impacts a dam and reservoir have on dewatered reaches is the lack of supply of sediments leading to depth erosion downstream and the forming of armor layers. How strong this effect applies depends on the size of the dam and volume of the reservoir. If the reservoir is small, sediments must be flushed through during the wet season. If the reservoir is large, e.g. close to the annual runoff volume, most of the sediments and suspended particles are deposited in the reservoir. The dam and reservoir should therefore have a sediment handling strategy in place. Otherwise, the dewatered reach will change its bathymetry, morphology and surface texture. To maintain riverbed bathymetry it is necessary to ensure a well-balanced supply of sediments and to maintain the dynamic equilibrium of supply and transport. The supply component must be insured by somehow routing sediments through the reservoir and dam and this must be supported by the design of the dam itself, including bottom outlets or sediment flushing gates. If the supply of sediments from upstream is interrupted, other sources can possibly be identified such as from lateral erosion, supply of sediments from tributaries, supply of sediments from dredging of the reservoir etc.

Maintaining the sediment transport regime is highly critical to maintain fish habitats by avoiding depth erosion downstream of the dam and by maintaining suitable grain sizes for spawning instead of stable armor layers. Most importantly the design of the dam and the bottom outlets must be such that sediments can be routed through. It is not fully known at this moment what provisions are considered in the design of the dams in Bhutan.

The second component governing the sediment regime in the dewatered reach is the transport capacity, which is determined by the flow. An analysis of the sediment regime under operating conditions must be done by a joint analysis of the sediment handling strategy and the E-flow regulation.

Dams and reservoirs in the Himalayas which have a small reservoir must be flushed regularly to maintain the active storage volume. In the case of seismic events triggering landslides, massive sediment influx can happen. Such situations are natural catastrophes for aquatic species and handling such situations lies beyond the scope of this environmental flow guideline. It is much more a safety issue for the dam and reservoir and must be handled accordingly.

For this guideline there was no information on sediment management for any of the power plants under construction or in the planning stage. It is therefore proposed to release the full flow of the river during or close to the highest flows of the wet season for two full days (48 hours) to guarantee that the river bed is flushed and sediment is moving. This is happening during a period of several weeks after spilling has started and still occurs, e.g. in the middle of the wet season. While this is done, sediment from upstream must be available or should be supplied in sufficient quantities. This aspect of the E-flow regulation should be discussed with the HPP operator to agree on a solution fulfilling the purpose but minimizing the generation loss for the power plant. If the reservoir is being flushed annually or regularly, this should be combined. In such a situation the requirement is most likely automatically fulfilled by the power plant operation itself.

3.3.22 Maintaining the hydrological regime

The landscape aspect is important not only for tourism but also for the local population. It is not only an aesthetic criterion but the landscape aspect is closely connected with the hydrological regime which is driving the entire ecosystem and is therefore extremely important.

The general requirement is to maintain a dampened hydrological regime, similar to the natural one. This is implemented as follows: The increase of the wetted area by higher E-flows during the wet season should result in a similar ratio as the increase would be under the reference flows Q_{335} and Q_{100}. This is addressed in a hydraulic rating approach based on the results of the hydrodynamic models.

In the pilot studies for this report this criterion has led to generally higher flow requirements during the wet season than fish habitat requirements did. The maintenance of the hydrological regime as the main driving component of aquatic ecosystems became therefore the critical flow requirement during the wet season.

The transition between the dry and wet season E-flows must be gradual, not an instantaneous increase. Instead, the transition should be stepwise with daily or weekly increase until the new level of flow is reached. The following rules should be applied:

The period should be based on a hydrograph of daily average flows. The transition period starts when natural flows start increasing and ends when Q_{100} is reached.

Additionally, during this period a so-called spring "trigger flow" should be released for 2 full days. This increased spring runoff is simulating snowmelt and triggering upstream migration of certain species, it also serves the purpose of cleaning potential spawning gravel. The flow rate is to be increased by the same ratio as the ratio between Q_{100} and Q_{335}. The exact dates when these flows are released can be set approximately based on the natural hydrograph but should be applied when the inflow to the dam increases by the same ratio based on rain and actual snowmelt conditions. The actual days of the release may therefore change from year to year. The increase and decrease must be gradual, simulating the natural gradient.

Releases of full floods (e.g. between a 1 year and a 5-year flood) within a certain time span of several years is ensuring the reorganization of the riverbed bathymetry and limits vegetation encroachment from the river banks and floodplains. As a general concept, the full natural flood flow should be released into the river bed at least once in a period of 3 to 5 years. Every year a flow close to the maximum of that specific year should be released for 48 hours into the dewatered reach. This can usually be done in coordination with the operation of the power plant during spill, reservoir flushing, maintenance works etc.

Finally, random high flows naturally occur because of spilling, depending on the size of the reservoir and the capacity of the turbines.

The decision of how exactly these components should be defined in detail must be done in conjunction with the sediment handling strategy and the dam and reservoir operation in general. It should be done in such a way that the additional loss in electricity generation is reduced to a minimum.

3.3.23 Additional aspects: hydrologic connectivity, landscape, water temperature and water quality

Additional objectives of environmental flow releases have to be evaluated by experts based on the design of the power plant, particularly the intake, the planned operation, specifically planned sediment flushing strategies for the reservoir, and the various investigations and results of the environmental flow study regarding hydraulic parameters.

Hydrologic connectivity is most relevant in longitudinal direction in dewatered reaches serving as fish habitat. A common situation is that the study reach has been evaluated regarding its provision of a suitable migratory path for fish upstream and downstream, but this does not necessarily imply that the entire dewatered reach does not include any other critical bottlenecks. Once the environmental flow regulation is determined and implemented it must be determined if such bottlenecks exist. It depends generally on riverbed topography if such bottlenecks are to be expected. It should be determined by visual inspection (by foot, UAV inspection), if any critical bottlenecks exist in longitudinal direction, especially for upstream fish migration. If such barriers are identified they must be either removed or mitigated physically or a change in the E-flow regulation is required.

Hydrologic connectivity in lateral direction includes the access to and from side channels and, most importantly, tributaries. Tributaries, significantly smaller than the mainstem river, are frequently used for spawning or as refuge during harsh conditions such as floods. In conjunction with e- flow regulations the access into tributaries for spawning and as rearing habitat for small fish is of highest importance. Every single tributary must be evaluated regarding its accessibility during unregulated flow conditions and under e-flow regulations. It is quite common that the low flow, concentrated in the center of the mainstem river bed, is causing a disconnection between the tributary and the mainstem river. If this is the case it must be mitigated physically so that the access is possible similarly to unregulated conditions or the E-flow regulation must be changed.

Vertical connectivity is usually maintained if clogging and siltation of the riverbed is avoided. This is done by maintaining the sediment transport regime and therefore no special attention is given here to vertical connectivity. Similarly, the temporal connectivity (sometimes also called hydrologic connectivity) is maintained by the combination of maintaining the general hydrological regime and avoiding at the same time rapid flow fluctuations.

Water temperature changes in dewatered reaches can be problematic if the flows are too small. Since temperature is a key factor in the life cycle of fish and other aquatic species, multiple effects can come up if critical temperatures are reached. In general, the water in dewatered reaches is warmer during daytime and colder at night as compared to the unregulated river. This results from shallow and almost stagnant water if E-flows are too low. The monitoring will therefore include temperature monitoring to provide evidence that temperature changes are acceptable.

Water quality in dewatered reaches is sometimes problematic if wastewater is released into the dewatered reach and the necessary dilution is too small. Therefore, untreated wastewater should generally not be released into dewatered reaches without detailed assessment.

3.3.24 Socioeconomic and sociocultural impacts

The provision of water, including flow rates, volumes and timings to maintain downstream aquatic ecosystems and provide services to dependent communities has been recognized in developed countries for decades. Thus, Environmental flows (E-flows) must also consider anthropogenic utilization of water in a river course. This aspect of E-flows is often referred to “social flows”, which include all types of benefits that people draw from the existence of a watercourse, directly or indirectly.

Water courses can be directly used to maintain livelihoods by commercial or subsistence fisheries, or indirectly by harvesting building materials in floodplains or running operations for tourists such as river rafting or kayaking. Social flows also refer to cultural and ethnic uses of the benefits of the river and the adjacent floodplains. In terms of E-flow, the following issues need to be taken into account but partly go beyond the determination of E-Flows:

- Downstream effects (considering water intakes further downstream)
- Timing and flow fluctuations (diurnal and seasonal fluctuations, predictable vs. unpredictable)

- Remaining surface E-flow (the amount of water left on the surface in case water is flowing in a subterranean gravel bed)
- Long term development perspective (regional and local) as society and communities are subject to change over time (in terms of demography, culture, economic activity…)

Next to obvious links between E-flow regulations and socio-cultural as well as local economic issues such as impact on river-based recreation and tourism, water intake for irrigation, livestock keeping or households, or fishery, there are a number of less or invisible local impacts (such as the harvesting of a specific river-based plant species, locally important religious or cultural sites at the river…), which are unpredictable and different from place to place.

3.3.24.1 The Eco System Services Approach

A set of general approaches to assess the consequence of an activity on the economic, social and cultural well-being of the people living along the river corridor have to be applied. There are multiple linkages with environmental flows because people make use of certain physical properties (e.g. water levels) of the river which usually occur during specific phases of the hydrologic cycle. In general, people are affected by any changes to these physical properties in a positive or in a negative way.

In order to take these aspects into account and to prepare a comprehensive tool to address the large number of potential influences at the local socio-cultural level, a broad approach is required. Therefore, the assessment is based on the ecosystem service approach (Millennium Assessment 2005, The Economics of Ecosystems and Biodiversity (TEEB) Project 2010) as an instrument to systematically screen possible impacts on rural communities. The concept of Eco System Services (ESS) covers all benefits which humans derive from natural resources such as rivers and was already previously used to analyze impacts and benefits of large infrastructure projects such as hydropower plants (e.g. Getzner et al. 2011).

The TEEB-Project's Eco System Services (ESS) are categorized into four main groups:

- Provisioning services: These services include the supply of materials or energy from ecosystems. With regard to the effects outside the frame of hydropower operations, they include primarily food and water but may also comprise other resources.
- Regulating services: In this category services provided concern regulating effects, e.g. on the quality of water, air quality or soil fertility. In this context the effect on sanitary uses is specifically addressed.
- Habitat services: Ecosystems provide various habitats necessary for a species' lifecycle. Genetic diversity provides the basis of a well-adapted gene pool which again allows for further development of commercial crops and livestock. The effect of biodiversity conservation in this framework is deemed a supranational interest.
- Cultural services: Ecosystems and biodiversity represent an important contributor to both the national leisure but also aesthetic and spiritual relations towards nature as well as in international tourism. In addition, the latter provides a source of income on a local and consequently national scale in Bhutan.

The methods to assess the socio-cultural impacts are purely qualitative and do not allow for an economic valuation. Some ESS allow for a monetary valuation. The procedure is described in detail in Chapter 3.3.25.

3.3.24.2 Qualitative assessment of socio-cultural services

In order to assess socio-economic and socio-cultural impacts of different E-flow regulations, the following work steps are required:

Step 1: Carry out socio-cultural screening

- Are there any traces of human settlement or use in the area or proximity of the dewatered reach?
- Are there any traces of human settlement or use in the area immediately below or within a 3-5 km radius of the dewatered reach?
- ➔ *If any of the answers is yes or remains unclear, continue a socio-cultural-economic assessment is required. If both answers are "no", no socio-cultural-economic assessment is required for this reach.*

Result: Decision whether a socio-economic and cultural assessment is required

Step 2: Identify potentially affected villages and area

- Identify villages, settlements and communities potentially affected
- Collect basic data on the village (size, population, main economic activities, maps etc.)

Villages or communities along the dewatered reach are the main target communities. However, villages further down the river may be also affected (e.g. by hydropeaking). If notable settlements are found within this area, additional studies may be required, but are not included in this guideline.

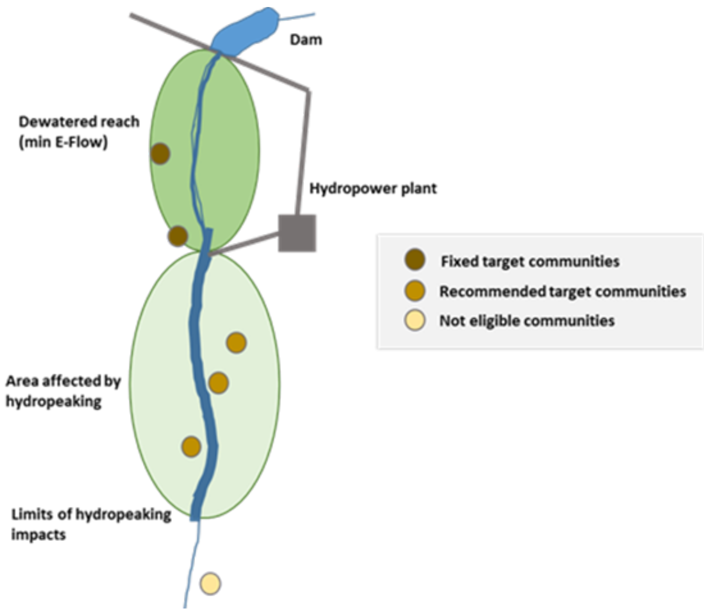


Fig. 30: Identification of target communities

Result: Definition and delineation of the scope. Name of affected villages and areas determined.

Step 3: Describe the socio-economic environment with specific focus on the river

Due to the large variation of possible activities and social meanings of rivers, an on-site assessment including interviews and discussions with local stakeholders needs to be carried out.

The following methods are to be applied by an expert/group of experts:

- Visit the river reach and communities potentially affected for visual inspection (Photo documentation)
- Carry out interviews with village representatives or stakeholder groups in the villages to clarify the economic, social and cultural relationship with the river
- Collect available data on river uses and importance in the target area (maps, historic pictures, oral history, village chronicles etc.)

For each reach, the following checklist should be completed by the information collected in order to be able to identify a) the role of riverine services and b) how changes in the flow of the river might affect these services.

Table 9: Checklist for identification of relevant socio-economic or cultural implications of changes in river flow. Grey colors indicate no relevance; white colors are relevant for assessment.

	Ecosystem service	Examples	Local relevance (none-low-medium-high)	impacts by river flow changes (none-low-medium-high)
1	**Provisioning services**			
a	Food	Food production, fishing, algae collection,		
c	Raw materials	Fiber, stone, sand, fuelwood collection		
d	Genetic resources	not applicable		
e	Medicinal resources	Resources of the river used for medicinal purposes, herbs, insects…		
f	Ornamental resources	Provision of ornamental resources (e.g. harvesting of flowers, collection of stones etc.)		
2	**Regulation services**			
g	Influence on air quality	More dust affecting communities; relevant for broad society		
h	Climate regulation	relevant for broad society		
i	Moderation of extreme events	n.a. (dams could possibly provide improved flood protection)		
j	Regulation of water flows	relevant for broad society		
k	Waste treatment/water purification	Use as drinking water, water for sanitary purposes		
l	Erosion prevention	not applicable		
3	**Habitat services**			
m	Maintenance of soil fertility/nutrient cycling	Flood irrigation systems; relevant for broad society		
n	Pollination services	not applicable		
o	Biological control	River based organisms relevant for pest control		
p	Lifecycle maintenance (esp. Nursery services)	Sustaining local fishery		
q	Maintenance of genetic diversity	not applicable		
4	**Cultural services**			
r	Aesthetic information	Temples, buildings, monuments in a riverine setting		
s	Opportunities for recreation and tourism	River-bound tourism (present or potential), kajaking, rafting, local recreation, swimming, children's playground		
t	Inspiration for culture, art and design	Existence of riverbound routines and traditions of daily live (meeting points, rituals, art work, stories, myths and legends referring to the river), Typical or traditional architecture (e.g. mills, watering-systems)		
u	Spiritual experiences	holy river, holy spring, religious place, memorial sites, burial sites, river related festivities, pilgrimage sites, lamas, holy caves		
v	Information for cognitive development	not applicable		

Result: Comprehensive documentation of local uses and importance of the river available for assessment by means of a completed checklist

Step 4: Assessment of potential socio-cultural impacts of different E-flow scenarios

In order to assess various E-flow scenarios each identified parameter should be assessed with regards to local relevance and the likeliness of an impact of change of flow on the identified parameter. The matrix below serves as a tool to identify the most critical parameters. With regards to E-flow regulations, the scenario with the least critical impacts should be selected. In any case, mitigation measures should be discussed in case critical impacts prevail in all scenarios.

The assessment of the relevance and local importance should be evaluated by means of local stakeholder workshops, the likeliness of adverse impacts will depend on the individual scenarios and should be carried out by local experts. A quantification of the socio-cultural impacts (cultural or spiritual) is hardly feasible and mostly impossible. Thus, the qualitative information shall serve as a decision-making tool and allow for a transparent discussion of trade-offs and impacts of individual scenarios.

Based on the results from interviews, observations and official statistic data, the potential impacts are assessed. This must be carried out for each ecosystem service to give a detailed overview of the types of impacts.

The assessment follows two key questions:

- Does this ecosystem service play a role for the surrounding communities?
- Will the type of use or service be affected by changes in flows?

In a further step both parameters are combined and displayed in a colour code.

Table 10: Impact matrix

Socio-economic relevance

Likeliness of impacts	none	low	medium	high
none				
low				
medium				
high				

	No social impacts to be expected, river and riverine services have no importance for local communities.
	Social impacts cannot be excluded, impact on specific non-fundamental livelihood aspects (either importance low or impact low)
	Impact on fundamental livelihood aspects most likely, impact on lifestlye/economic activities, mitigation measures required (increased E-flow or alternative options)

Thus, it needs to be considered that the description of impacts in this section strictly refers to the changes in flow within the dewatered reach and does not allow to draw conclusions regarding impacts from dam construction or affected areas further downstream (e.g. hydropeaking), even though the same methodology can be applied in these cases as well.

Table 11: Detailed overview about assessment of ecosystem services

Likeliness of impacts	**Explanation**	**Examples**
none	Changes in flow do not affect this service at all as it is not related to flows	People not using water from the main river but solely from tributaries (water availability for residents remains the same), children playing along the river, collection of stones along the river
low	Some minor changes in the availability of the service might occur	Temple in the surrounding of the river, washing clothes in the river, collection of selected raw materials
medium	Changes in the availability of this service are to be expected but service remains generally available	landscape changes for hikers, collection of raw materials along the river, scenery of spiritual places related to the river are changing

high	Serious changes in the availability or loss of it are likely	insufficient flow for rafting boats, loss of fish as a source of food, no drinking water availability, no drinking water during dry season
Socio-economic relevance	**Explanation**	**Examples**
none	Service does play no role at all at local level	Local residents use no water from the river as it is too deep in the gorge
low	Service is occasionally used, no economic relevance	washing of clothes in the river, occasional fishing, occasional collection of firewood, river supplementary source of water (if water mainly taken from tributaries)
medium	Service is frequently used, no or low economic relevance	frequent collection of fire wood, individual households taking water for livestock or paddy cultivation, occasional kayaking, river important source of water
high	Service is frequently used, essential for local residents and/or of high economic importance	Water used for irrigating a large number of paddy cultivation, important rafting route for tour operators, water temples, river sole source of water

Fig. 31 shows examples of activities linked to the rivers. All pictures except the last one were taken along the pilot reaches for this project.

Fig. 31: Overview on different potential uses of river ecosystem services in Bhutan

Result: Assessment of impacts of different E-flow Scenarios and how they affect individual parameters available for decision-making and determination of E-Flow.

Economically relevant characteristics of socio-economic livelihoods are further investigated in the economic valuation (Chapter 3.3.25).

3.3.25 Economic valuation

For the economic valuation of impacts on stakeholders from the limitation of water flows in river sections downstream of hydropower plants, among other approaches, the concept of Eco System Services (ESS) is also used. This procedure undertakes to quantify and monetarize effects of identified impacts on the ESS applicable in settlements.

In the framework of TEEB a database has been developed, which summarizes the valuation evidence through meta-analyses. It lists monetary valuations as developed in a large number of studies elaborated over the last few decades. In these studies, estimates of the monetary value of ecosystem services have been established across a wide range of applications.

While the indicator values provided by the TEEB database are used for comparison in the economic valuation approach to be applied for environmental flows in Bhutan, they are to be viewed as an additional yardstick from a broad international background. The authors of the TEEB database caution the user to observe some limitations regarding the application of values provided. These limitations pertain to:

Systematic approach: The review of the valuation studies did not use predefined search terms or data sources so the identification of the studies is not to be considered fully systematic and comprehensive with no updates for studies dating after 2008.

Purpose: Studies have been taken from a variety of sources and originally carried out for different purposes and with varying standards. The use of indicators is therefore recommended only after review of the original studies.

Further advice on limitations pertains to the meta character of the database and the use of values for benefits transfer also with regard to the socio-cultural background of the original studies.

In view of these limitations, a requirement for verification through on site data is considered an important part of the economic valuation process. The special emphasis to be laid in the context of environmental flow evaluation in Bhutan based on TEEB categories is further described below.

The ecosystem services in this context specifically refer to the economic benefits derived from riverine services. Starting from generally derived values (particularly for globally important ecosystem services, e.g. biodiversity), specific economic uses are determined at a local level (e.g. use of water). It needs to be pointed out that, in this context, ESS specifically refer to local economic benefits (monetarized), whereas the qualitative assessment refers to the locally relevant ESS irrespective of their economic value. This is a crucial topic as local ESS need to enter the decision-making process in a qualitative way as well. Local ESS cannot be fully monetarized in a way that they can be compared against the economic loss due to E-flow regulations.

3.3.25.1 Procedural Settings

For the implementation of an economic evaluation using procedures from this guideline the pertinent EVALUATION TOOL MODEL is provided.

Objective: It is the target of the socio-economic evaluation of minimum environmental flow regulations to contribute a monetary measure based on a multitude of approaches

Information types: The economic model established for evaluation procedure contains various sets of data for both the national as well as the regional (Dzongkhag) level. In addition, the following types of information shall be collected in order to implement the evaluation procedure:

- Statistical data regarding household income and demographic data
- Geographic measurements regarding project areas (dewatered reach) as well as river (catchment) related
- Survey information on site specific parameters (outside project organisation)
- Project data regarding water flow, energy output and projected revenues

Forms of investigations: Information will be collected from the following sources

- National statistical offices
- Administrative bodies (national, regional, local) in charge of project areas
- Sector specific institutions (e.g. tourism board)
- Interviews with regional/local administrative representatives as well as affected businesses and households
- Project owners and authorities in charge of project approval

Analyses: The review and processing of the investigated data will be carried out using the EVALUATION TOOL MODEL developed for this project.

Results: The evaluation tool model provides an overview of economic effects from the project in question including a valuation range of Economic Net Present Values (ENPV) for consideration in decisions on minimum environmental flow.

The procedure of establishing results based on the evaluation tool model includes the following steps:

1. In an initial checklist various general questions regarding the project area shall be clarified. Subsequently the categories and types of ESS are investigated, if they are applicable in the project area.
2. A range of criteria shall be scrutinized with each applicable ESS type. The data collected will be used for the monetarization of ESS.
3. In a range of valuation approaches, three different data sets are elaborated, which are used in the evaluation model for the projection of economic effects.
4. Ultimately the model provides projection tables and indicators of the economic effects of minimum environmental flow regulations.

3.3.25.2 Checklist

The first step of using a checklist on socio-cultural impacts, as described in chapter 3.3.24.2, is to be carried out as a qualitative assessment. Once effects regarding various ESS have been identified, which allow for an economic valuation, the steps subsequently described use various economically relevant criteria to quantify and monetarize their impact.

General aspects: A methodological subject is the availability of information sources related to the river, which might not be part of official documentation. Questions in this regard are more suitable for local administrative representatives.

3.3.25.3 Criteria

General questions on socio-economic aspects: For the quantification in this framework a number of demographic and economic (income, expenditures) data shall be determined to accompany the local investigations. The model provides values on a national level, which shall be verified for the most recent data available.

Local data may be obtained from specific Living Standards Surveys or detailed census data.

For all valuation approaches a delineation of the affected area is required. The primary subject here is the area of the dewatered reach, as given in the planning documentation of the HPP project. In addition, for the purpose of evaluating effects based on a possible barrier effect of the project, e.g. on fish migration, affected areas upstream or downstream shall be estimated in the context where such effects are observed.

Environmental Services: Regarding the scaling of effects from ESS, questions to be clarified are asking about the estimated effects on income and/or expenditures if the service provided by the water flow in the river were no longer available.

For provisioning services, the main sources of information are presumed to be affected businesses and households. For regulating and cultural services (e.g. tourism), sector specific institutions should be in a position to provide either real data or qualitative estimates.

Table 12: Quantification form for general and ESS specific parameters – Model form

General questions on socio-economic aspects		Value	Unit	Remark
Population				
	HH income characteristics (national)			
	Average HH income	7'512	USD pa.	Bhutan Living Standard Survey 2012 Report
	Average rural HH income	4'716	USD pa.	Bhutan Living Standard Survey 2012 Report
	Expenditures on nutrition		USD pa.	
	Demographic data on a local scale (detailed for evaluation of river reaches)			possible Sources: regional or local authorities
	Population in affected area			
	HH in project (dewatered) area			
	Average HH income in project area		USD pa.	
	Expenditures on nutrition		USD pa.	
Area delineation				according to project survey data
	Direct (Area on diverted stretch) - Area of valley		ha	area potentially affected by changes in flows
	Indirect			
	Upstream		ha	
	Downstream		ha	
Environmental Services				
1 Food				Source: household interviews
	Fishing, other			
	Number of HH affected			
	Share of nutrition - %			
	Share of income - %			
2 Water				Source: household interviews
	Irrigation, transport, other			
	Number of HH affected			
	Share of nutrition - %			
	Share of income - %			
11 Waste treatment / water purification				Source: local or regional authorities
	Number of HH affected			
	Existing			
	Planned sewage infrastructure			
	Alternative service cost (on-site sanitation) per HH		USD	estimated technical life of facility - 10 yrs.
	Operation of on-site sanitation		USD pa.	
19 Opportunities for recreation and tourism	Dzongkhag			
	Total national tourist spending		USD pa.	Airfare, official rate, out-of-pocket, Bhutan Tourism Monitor 2016
	Tourism spending in Dzongkhag - %			Bhutan Tourism Monitor 2016
	Nature Tourism spending - %			
	Area share in Dzongkhag useful for nature tourism - %			
	Expected average growth rate next 10 years - %			
	Estimated tourism spending on site		USD pa.	referring to dewatered reach

3.3.25.4 Valuation Approaches

The evaluation of ESS in the model uses three different approaches, which are derived from the sources previously described in this guideline.

The TEEB Valuation Database[6] provides a number of indicators for monetary valuations based on studies established during the last few decades. Specifically, the indicators are taken from the summary of monetary values of services provided by Rivers and Lakes. This framework provides values for only a selected number of ESS, while for the others, values are not determined due to lack of evidence in scientific papers. Indicators from the global database are applied based on USD values per hectare per year attributed to area of dewatered reach. USD values as taken from the TEEB database are purchasing power parity (PPP) adjusted international Dollars, which have been brought to 2007 values based on World Bank Development Indicators series 2009. The same source of indicators is used for the conversion to 2014 (latest value available in 1/2016)[7] in the framework of these guidelines.

While the TEEB indicators are introduced in this model, the resulting approach is taken with the limitations cited in chapter 3.3.24.

In 2012 a study[8] was undertaken to estimate the value of ESS in Bhutan. This paper uses the same framework as TEEB. Data from its section on Lakes and Rivers was applied in a second approach. Again the values provided by this study are introduced using the values for ESS in USD per hectare per year attributed to area of dewatered reach. This is particularly helpful if the ecosystem services provided are not finally used (final ecosystem services) by the population and therefore it is important that global ecosystem services are not neglected in the process.

In a third approach the data investigated and surveyed in previous elements of the procedure are applied in a Site Specific Valuation. Investigated and estimated data are used to calculate valuations of economic effects from the use of ESS. This section explicitly refers to final ecosystem services (what people really extract from the river). However, if no economic use is taking place, the site specific value is likely to remain very low.

With regard to biodiversity conservation, the benefits/value transfer method is chosen for the site specific approach also in order to account for the national and global importance of biodiversity.

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[6] Sander van der Ploeg, Dolf de Groot, Yafei Wang - Foundation for Sustainable Development - The TEEB Valuation Database - overview of structure, data and results, Final report December 2010

[7] The World Bank - World Development Indicators - 29 December, 2015

[8] Ida Kubiszewski, Robert Costanza (Institute for Sustainable Solutions, Portland State University, Portland OR, USA), Lham Dorji, Kuenga Tshering (National Statistics Bureau, Royal Government of Bhutan, Thimphu, Bhutan), Philip Thoennes (Northwest Power and Conservation Council, Portland OR, USA) - An initial estimate of the value of ecosystem services in Bhutan. Ecosystem Services (2012)

Table 13Summary table by ESS and approach – Model form

Approach	TEEB 2015	Costanza 2012	Site specific	Chosen approach
Provisioning services	-	-	-	-
Regulating services	-	-	-	-
Habitat services	-	-	-	-
Cultural services	-	-	-	-
Total	**-**	**-**	**-**	

If sufficient data is available, the table above allows to display the range of the value of the ecosystem services at the respective river reach. These values do not reflect the respective changes due to flow changes, but clearly draw the attention to the ecosystem services at stake when determining E-flows.

Considering a thorough aquatic habitat analysis targeting viable fish populations as carried out for each river reach, important conclusions regarding the habitat services and also other services can be drawn. If enough suitable habitat is maintained for key fish species, this is in most cases also an indication that other ecosystem services will not be affected too strongly.

3.3.25.5 Projection

The comprehensive valuation of economic effects from minimum environmental flow must consider

- the losses in revenue incurred by HPP operators due to lower than possible water volumes for power generation and
- the total of external effects as measured by the value of ESS dependent on minimum flow

For the determination of losses in revenue data required relates to

- water flow (flow duration curve)
- resulting power production and projected energy generation
- tariffs for power including their development patterns

The projection model compares the time series data of power output and resulting revenue to the projected values of ESS to be sustained in order to arrive at net economic values per year. These annual values are summarized in order to arrive at an Economic Net Present Value (ENPV) of the environmental flow regulation.

Based on the three valuation approaches described in section 3.3.25.4, the possible valuation results in terms of ENPV is calculated by the model. This ENPV provided by the economic valuation is a further parameter in the holistic approach.

The following Table 14 presents the format used in the evaluation model. While Table 14 presents only the first 5 years, the total projection is designed for a period of 20 years.

Table 14: Projection format of economic effects – Model form

Item	Unit	2016	2017	2018	2019	2020
BTN/USD (PPP IMF WEO)		22.1	23.2	24.2	25.2	26.1
BASELINE						
Average flow	m³sec					
Efficiency	%					
Capacity		GWh				
Capacity factor		96%	96%	96%	96%	96%
Power production Baseline	GWh	-	-	-	-	-
Tariffs						
Estimated long term average price	USD-Cent/kWh					
Growth of average tariff	inflation based		6%	6%	6%	5.6%
	BTN/MWh		-	-	-	-
Average tariff	BTN/kWh	-	-	-	-	-
	USD-Cent/kWh	-	-	-	-	-
REVENUES						
TOTAL REVENUES	1,000 BTN	-	-	-	-	-
	1,000 USD	-	-	-	-	-
Reduction for EF-limitation						
Revenues loss from EF		-	-	-	-	-
External effects from ESS						
Valuation of						
Provisioning services	avoided cost	-	-	-	-	-
Regulating services	avoided cost	-	-	-	-	-
Habitat services	avoided cost	-	-	-	-	-
Cultural services		-	-	-	-	-
Total ESS		-	-	-	-	-
Economic Present Value at	5.5%	-				
Avoided cost of ESS		-	-	-	-	-
Cost from EF regulation		-	-	-	-	-
Net economic value		-	-	-	-	-

An evaluation of ESS, especially the monetarization, is suffering from a number of deficiencies which are compromising the value and interpretation of the results:

- The methodological approach does not consider the value of the ecosystem itself, only the value of the services which the ecosystem provides for humans.
- The spatial expansion of effects of dewatered reaches is very difficult to assess. The dewatered reach, together with the dam and reservoir, may cause a fragmentation of the river corridor, an important migratory pathway, which otherwise reaches from

the Bay of Bengal to the Himalaya main ridge. The effects of fragmentation may reach far beyond the dewatered reach, in upstream and downstream direction, and it is not limited to the river bed but may affect terrestrial parts of the watershed as well.

- The value of these ecosystems and (partially unknown) ecosystem services affecting other ecosystems cannot be monetarized and therefore a comparison with revenue losses at the power plant is not an adequate approach.

It is well understood that HPP operators ask for a rigorous comparison of economic losses and benefits resulting from environmental flows. However, taking the difficulties described above into account, the input information for such an analysis does not really exist and therefore the outcome is highly questionable.

3.3.26 Revenue losses at the power plant

The E-flow scenarios to be prepared for the decision makers must include a quantification of the impact of E-flow regulations on the power generation at the HEP under investigation. Since E-flows are seasonal, the analysis must be based on annual flow hydrographs, flow duration curves are less suitable. It should be done for average years as well as for wet and dry years. Average values such as mean monthly flows are less suitable because they are balancing extreme values and therefore situations with spill or turbine shutoff because of lack of sufficient flow during the dry season could remain undetected.

For this study the hydropower simulation model CASiMiR-hydropower was used. It operates with mean daily flows and allows the integration of any type of efficiencies for both, the head losses in the hydraulic conveyance system and efficiencies of turbines, generators, transformers etc. Varying heads can also be included. The model can also consider operating limitations of turbines or other equipment. In order to include these aspects, it is necessary that the HP developer provides information on the operational mode of the power plant, type and number of turbines, and efficiencies of all equipment. If this is not available, empirical values can be used as done in this study. While the absolute numbers of GWh generated per year may be by one or two percent off, the relative comparison between different E-flow scenarios will be highly accurate. The model also considers the feed-in-tariff and calculates annual revenue from power sales.

High E-flow releases during the lean season may leave only less water for power generation than desired. This can cause additional problems for power plants equipped only with a small number of Francis turbines. Francis turbines need at least 40% of their rated flow to operate efficiently, if significantly less water is available they have to be switched off. Pelton turbines, especially with 5 or 6 nozzles, are much more flexible. It is therefore strongly recommended to clarify E-flow regulations before the final decision is made for the turbines. Having one smaller turbine in the case of several Francis turbines to avoid such a situation may be a good solution in some cases. It lies within the responsibility of the HP developer to consider this obvious issue during the design phase.

For the pilot investigation for this study, models for the power plants were set up with constant efficiencies and constant heads since no more detailed information was available. Models were then run to simulate the energy generation under different E-flow scenarios in an average year. The energy losses are mostly based on the water volume which is not flowing through the turbine, running turbines in less favorable conditions with lower efficiencies is only a minor secondary affect and can be neglected at this stage.

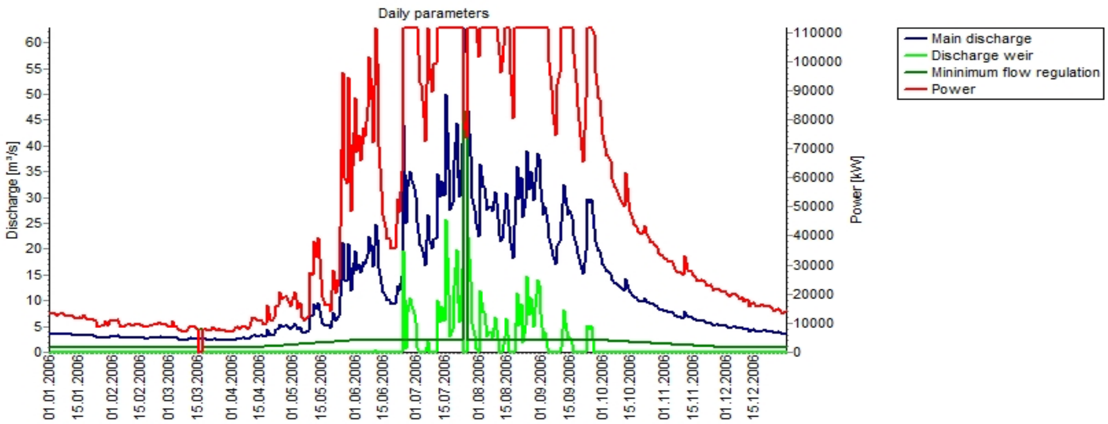

Fig. 32: Results of a CASiMiR simulation of the energy generation for a conceptual HPP on Parochhu

Fig. 32 shows an example of the output created by the model for an average year. All results for the year as well as for daily operation are available as well. An example of the summarized output is shown in the appendix.

These simulations must be based on the flow releases at the dam which are not always identical with the E-flow requirements because of inflow from tributaries below the dam (see chapter 4). In this case the model input should be slightly modified in an iterative process.

3.4 Integration of the results and holistic evaluation, E-flow recommendation

The following aspects must be considered for integration and evaluation:

- Aquatic habitats and fish migration (chapters 3.3.17 and 3.3.18)
- Habitat for other species (chapter 3.3.19)
- Socioeconomic and sociocultural aspects (chapter 3.3.24)
- Channel maintenance flow (chapter 3.3.21)
- Maintaining the hydrological regime (chapter 3.3.22)
- Spring trigger flow and transition between lean season and wet season E-flow (chapter 3.3.22)
- Random flood flows (occurring during spill)

Usually, not all aspects will be relevant in every specific situation.

The results of all individual aspects will have to be integrated into a set of scenarios for E-flow regulations. This will be based on a combination of quantitative analysis and expert panel discussions. The analysis includes not only all ecological flow requirements but also flow requirements from socioeconomic and sociocultural aspects. A consideration of the revenue losses at the hydropower plant and a comparison with the conservation goals underlying the environmental flow requirements are key to this part of the study. Consideration of revenue losses at the power plant may lead to considering different options for E-flows, including options where the achievement goals and therefore protection levels for aquatic habitats are not fully achieved.

As a result, required flows in certain sections of the river along the dewatered reach are identified. This could be for example monthly flows that fulfill the conservation goals set previously. These flows are minimum monthly environmental flows.

In addition, the dynamic flow components described in previous chapters must be included in the environmental flow regulation.

The components can be called blocks where each block is identified by a flow, a time and a duration. All blocks can be superimposed in the diagram showing the environmental flow requirements. Fig. 33 is showing an example of how such a regulation could be looking.

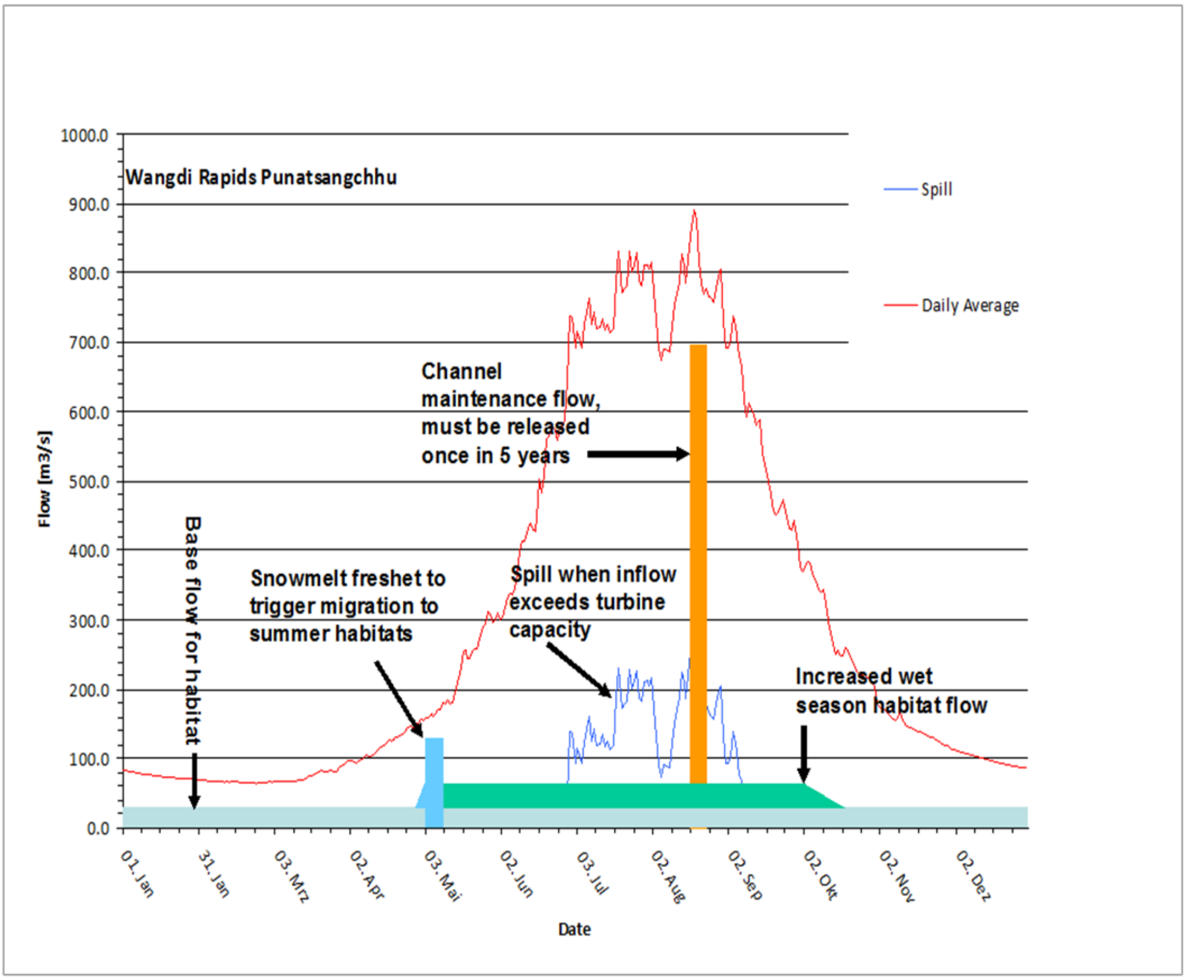

Fig. 33: 11Environmental flow requirements

3.5 Scenario development

Environmental flow releases will have a high impact not only on the integrity of the river and watershed ecosystems but also on the people dwelling along the rivers and particularly on the economic performance of hydropower projects and therefore directly on the economy of Bhutan. There is no easy solution for such situations and for that reason the holistic methods that have been systematically developed over the past two decades mostly in the southern hemisphere are relying on the development of scenarios based on different E-flow regulations and with different predicted ecological and socioeconomic outcomes. The scenarios are developed based on the simulation results and other investigations as described before. A set of scenarios has to be prepared along with the expected consequences and given to the decision-makers for final evaluation and decision-making.

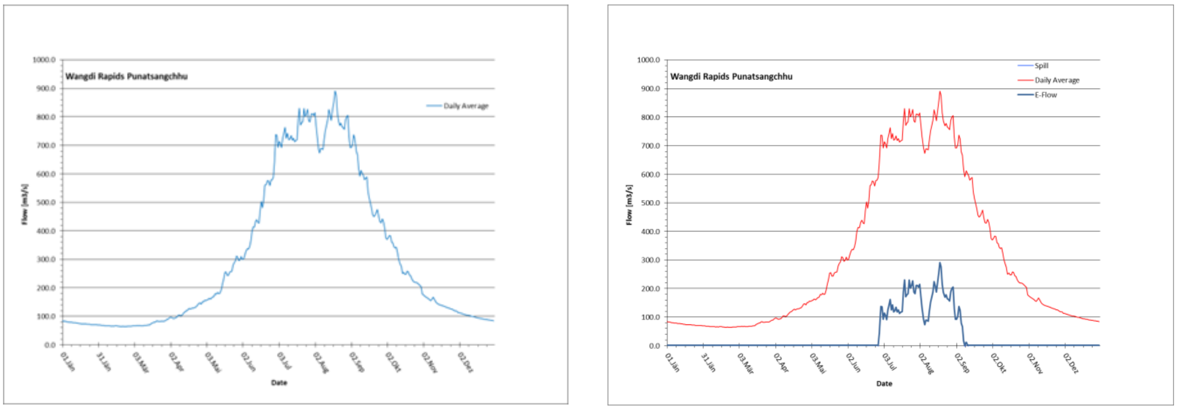

Fig. 34: Hydrographs in the dewatered reach (blue lines) for scenario 0 (no development) and scenario 1 (full development)

Fig. 34 shows an example for the two standard scenarios referring to the natural hydrograph without any hydropower influence, scenario 0, as compared to a full development with no significant E-flow release, scenario 1.

The actual options for e- flow regulations would be a series of 2 to 4 scenarios comparable to the one shown in Fig. 33.

Each of the scenarios will be linked to a predefined set of achievement levels, for example on a scale from 0 to 10, not only for each of the conservation goals but also for the other relevant aspects such as energy generation, sociocultural and socioeconomic impact, along with a clear description and quantification of the relevant parameters to describe conservation goals and other aspects.

Table 15: Outcomes of scenarios for e- flow regulations for different objectives

Scenario	0	1	2	3
Conservation goals	**10**	**2**	**7**	**5**
Energy generation	**0**	**10**	**7**	**9**
Socioeconomic impact	**8**	**3**	**9**	**8**

Socio cultural impact	**4**	**2**	**4**	**3**

Table 15 is showing an example of the final result for the two standard scenarios plus 2 possible E-flow scenarios. It is not foreseen that these numerical scores will be integrated into one final number. The number of objectives can vary from case to case, however, the ones shown in Table 15 are most likely compulsory. It could, for example, be useful to split the term conservation goals into different aspects referring to fish on one side and to other animals, such as critically endangered birds or mammals, on the other side.

Each of the numerical scores will be supplemented with a text description carrying the relevant qualitative and quantitative information, such as weighted usable areas of habitat or GWh generated annually.

3.6 Balancing conservation needs and economic aspects

The results of the E-flow study and the scenarios developed will be given to a panel of decision-makers for the determination of the E-flow regulation to be applied. The advantage of such an approach is that the technical part of the work is ideally not compromised by political preferences or economic requirements, but in the final decision this can be taken into account.

It is obvious that every drop of water left in the river for the benefit of the ecosystem, especially during the lean season, is reducing the revenue for the HPP and therefore also impacts the repayment of loans, fulfillment of energy delivery obligations, etc. As a consequence, the financial amortization will last longer and the cost of the electricity generation and therefore the costs per kWh will increase. The numbers can be calculated based on the data provided in the scenarios. This situation makes it clear why realistic E-flows should be determined simultaneously with the preliminary design of the hydropower plant so that the costs and technical aspects of implementing environmental flows can be integrated into the technical and financial planning in the same way as other environmental and social aspects.

The decision making panel should revisit the conservation plan for the catchment and consider how well each of the scenarios is fulfilling the goals of the conservation plan. If other mitigation strategies are suitable to compensate a lack of fulfillment regarding the conservation goals, such strategies can be discussed and additional concerns and questions can be raised. Once all the data has been collected and the numerical models are developed, it is also easy to simulate additional scenarios. The decision making should therefore be seen as a process which is implemented in several steps. Finally, the decision makers should discuss and decide on the E-flow regulation to be implemented based on the scenarios studied and other information brought to the panel. The chosen scenario specifies certain achievement goals and levels (e.g. maintaining certain fish populations by protecting their habitat). As a part of the monitoring and adaptive management strategy, it has to be demonstrated after the implementation that these goals are achieved.

Because of the existing knowledge gaps regarding fish species and their abundance in Bhutanese rivers, their life cycle strategies including migratory behavior and their specific habitat requirements, more studies on fish are required, some of which are being carried out currently. As the understanding of species behavior and their habitat requirements grows, this information can be included into previous, ongoing and future E-flow studies. Along with the adaptive management process, it is advisable that environmental flow releases should be adapted if relevant new knowledge becomes available and can be integrated into existing modeling frameworks.

4 FLOW RELEASES

Finally, natural inflows from tributaries or groundwater have to be considered to identify which flow must be released at the foot of the dam to achieve the flows identified by the environmental flow requirements. In the case of relatively short dewatered reaches with no significant tributaries, there will be no difference between releases at the dam and required flows in the dewatered reach. Significant inflows from tributaries shortly downstream of the dam, however, would reduce the required releases by the amount of inflow from the tributary.

The operation of the dam and reservoir including the capacity of the turbines must be considered here to identify timing and magnitude of expected spillway operation or reservoir flushing strategies to simulate the flow in the dewatered reach as shown in Fig. 35

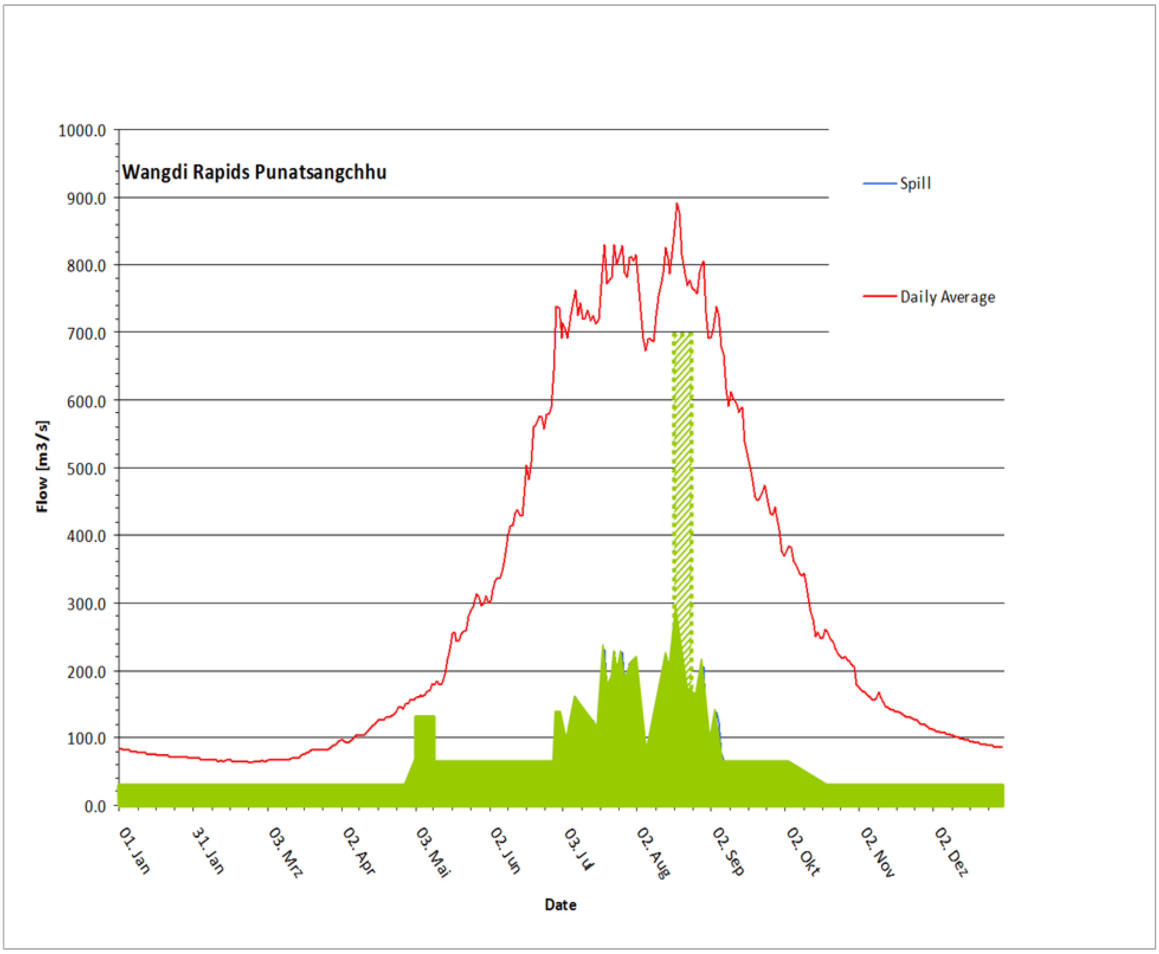

Fig. 35: Example for actual flow (in green) in dewatered reach based on E-flow releases, trigger flows and spill at the dam

Finally the flows to be released at the bottom of the dam must be identified (see Fig. 35) and the flows can

- vary throughout months or the season of the year

- be linked to certain dates
- be based on return intervals within years or decades
- include ramping rates for up- and downramping of flow releases over a period of days or weeks to avoid rapid changes

It is up to the hydropower developer to implement a flow release device (gate, valve, fixed opening) which is capable to release the flows as required. In some cases, it may be feasible to use a simple small turbine to release the flows. So-called E-flow turbines allow to recover part of the generation losses caused by E-flow releases.

If fish migration, upstream and/or downstream is facilitated at the dam, the flows for fish migration and the flows to be released for e-flows can be combined in such a way that a favorable attracting flow is formed which guides migrating fish into the entrance of the fish passage facility.

It is up to the developer to propose a concept where the necessary flows are released from the reservoir in such a way that the water temperature and the water quality of the E-flow released is more or less identical with the temperature and water quality at the inflow into the reservoir. As long as reservoirs are small this is usually the case, because full mixing can be assumed. However, in large reservoirs, especially in deep ones, the water is usually stratified and special provisions such as multi-level intakes will be required.

5 MONITORING

Monitoring is typically a threefold concept. Implementation Monitoring has a focus on technical data such as flow releases, temperature and water quality at the foot of the dam. It determines if regulations are being implemented according to the design (e-flow regulation). This can be easily monitored by automatic sensors and data loggers and integrated into the monitoring and control system of the HPP.

Effectiveness monitoring checks if the flow releases and the habitat created are in agreement with the physical habitat indicators predicted. In the study reach this should normally be the case because the predictive models are directly applied there and it can be assumed that they are fairly accurate. Effectiveness monitoring is more meaningful if applied to the rest of the dewatered reach where no models have been implemented.

Finally, validation monitoring must include ecological studies to determine if the conservation targets of the E-flow releases are achieved or exceeded, for example abundance or spawning success of certain fish species in the dewatered reach or upstream or downstream.

The operational license for the HPP should therefore include the following monitoring components:

- Collect data of E-Flow releases at dam (e.g. automatic hourly measurements) and flow at other relevant locations along dewatered reach (e.g. once or twice a year, at least initially, during relevant periods)
- Start water quality sampling program including stream temperatures at the downstream end of the dewatered reach (automatic data collection, daily to hourly in the case of temperature)
- Start regular survey (e.g. annual during the dry season) of river bed morphology including cross section geometry and substrate composition (surface and subsurface) e.g. through pebble counts at the surface and freeze core samples or dredging samples for subsurface grain size distribution
- Monitoring of fish populations and other biotic responses (establish baseline clearly before construction starts, starting at least 2 years before). To capture natural fluctuations and distinguish them from systematic changes, it is necessary to collect the same type of data with the same methods in regular, e.g. annual intervals. It may be necessary to sample different fish species at different seasons of the year
- Development of the channel and river bed, e.g. vegetation encroachment etc.
- Sociocultural aspects, to be determined case by case

It should be the duty of the hydropower operator to submit an annual report to show the compliance with the license agreement. The field investigations for the monitoring could also be done collaboratively with NEC staff to strengthen the understanding of the adaptation of the river bed to a new situation caused by hydropower operation.

The results of the monitoring program must be integrated into the adaptive management process described in the following chapter.

6 ADAPTIVE MANAGEMENT

Adaptive management is a formalized procedure which is widely used in river restoration taking into account the level of uncertainty often limiting the understanding of complex ecological situations. Adaptive management is also a somewhat structured approach to "learning by doing". In this case here, environmental flows are determined by well understood methods and models but it is not always clear if the real bottlenecks have been identified or if other mechanisms than the flows are limiting the achievement of the conservation goals. Therefore, adaptive management is also a strategy that should be considered in determining and possibly adapting environmental flows. It is generally based on six individual steps:

1. Assess problem: In this step the conservation goals for the dewatered reach in the river system should be identified and the methods (e-flows and supplemental efforts) to reach the conservation goals are specified. Conservation goals should be based on the potential fish populations that shall be supported in the dewatered river reach. It has to be clearly specified what fish species should occur, which ones should be living through complete life cycles in the dewatered reach, which ones should migrate through the dewatered reach or occasionally be found in the dewatered reach and which ones cannot be expected anymore because of other limitations.
2. Design: This step includes the determination of the environmental flow regulations and supplemental mitigation efforts within the context of a complex natural ecosystem.
3. Implement: The implementation of the environmental flow regulations and mitigation efforts over a period of at least one life cycle of any one of the fish species that potentially will occur, not only in the dewatered reach but also upstream and downstream of the HEP.
4. Monitor: The monitoring program is focusing on the goals of the conservation. It is established and implemented on a regular, e.g. annual basis. The monitoring has to start ideally at least one to two years before the first construction works in the river have started.
5. Evaluate: The results of the monitoring program (post-dam) are compared with the results from the "pristine" or pre-dam situation and the level of achievement of the conservation goals is determined by previously identified metrics.
6. Adjust: Should the deviation of the monitoring results from the conservation goals be significant, an adjustment of the environmental flow regulation or additional mitigation measures are required. Alternatively, the conservation goals must be adjusted. The process is then starting from the beginning.

Based on these six individual steps, it becomes clear that the core component of designing the environmental flow regulation is just one step within the entire cycle which describes the adaptive management approach (Fig. 36).

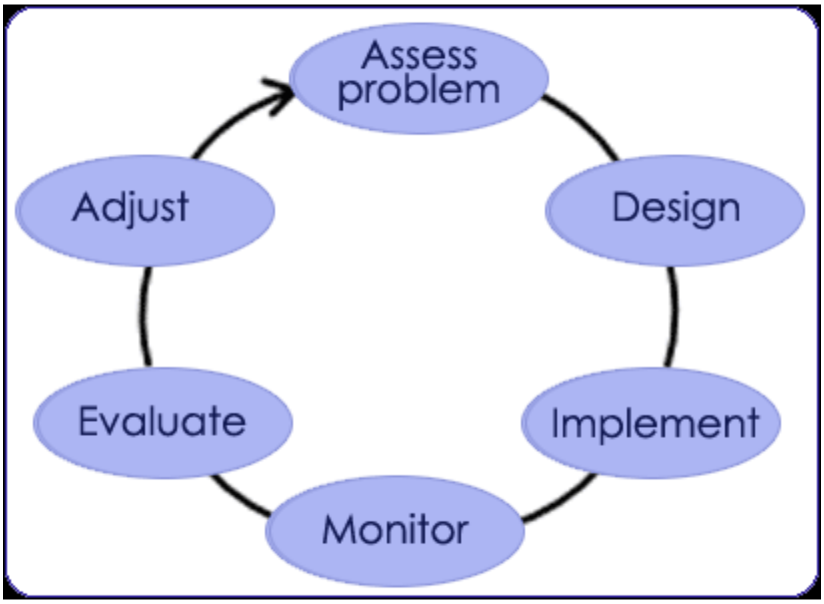

Fig. 36: Adaptive management process (taken from the U.S. Department of the Interior)

It becomes clear that the adaptive management process, specifically the steps of assessing the problem of monitoring the pre-dam situation, has to start even before the E-flow regulation has been determined.

Hydropower developers are usually not in favor of adaptive management because they are claiming that the turbines are being designed according to the available flow of water which is influenced by the E-flow regulation. If this regulation is changed afterwards, the turbines may have to operate sometimes outside of the range of their best efficiencies. This puts, in some cases, certain limitations on the range of possible adaptation of the e-flow regulations. This applies mostly to HPPs equipped only with 1 or 2 Francis turbines.

Climate change impacts as described in previous chapters may have various impacts on the rivers and dewatered reaches in terms of discharges, sediment supply and water temperatures. However, it is expected that these impacts are slow and gradual at least for the next one or two decades and it is not clear if they have any measurable effect on the dewatered reaches. In the longer term, some animals and plants will shift their habitat ranges towards higher elevations as temperatures are rising and at the same time, temperatures, including water temperatures, may become too warm for some species at lower elevations. Since dewatered reaches have increased 24 hour temperature amplitudes, this may be one of the signals where climate change impacts can be detected. If such signals become evident it has to be evaluated if any adaptations are required from there on.

From today's point of view it is desirable to have a meaningful monitoring program in place that allows the detection of climate change impacts. An adaptation of the E-flow regime within the license period should not be necessary in most cases.

7 MITIGATION AND ADAPTATION MEASURES

Mitigations and adaptation measures should be considered wherever feasible. The goal is twofold: firstly, such measures could be applied to reach the conservation goals for the river basin in addition to the E-flow regulations. Secondly, such measures can be applied at individual locations within the dewatered reach to improve the situation at such specific locations and to reduce the necessary environmental flows at that location. Such measures are particularly useful in situations where the entire dewatered reach is supporting sufficient habitats to achieve the conservation goal except for some singular locations and criteria. Typical for such situations are:

- individual steep drops or rapids which could form a single migration problem within a long dewatered reach (bottleneck)
- the mouth of tributaries and the connectivity between the mainstem river's dewatered reach and the tributary

If such situations require comparably much higher flow rates than the rest of the dewatered reach in order to fulfill migration criteria, it should be considered if the riverbed can be adjusted by excavating suitable channels or building small submerged dikes and levies to facilitate migration or to support other criteria in order to reduce the need for higher E-flows.

Such measures may be a useful option in some cases. It must be kept in mind that such riverbed adaptations may have to be renewed every year after the end of the flood season to maintain the functionality during the E-flow period or lean season.

The most important measure in conjunction with E-flow regulations is enabling fish migration across dams and reservoirs. Otherwise E-flows are in situations with high dams only supporting fragmented systems without biological connectivity to the upstream and downstream river reaches.

In the ecological literature, mitigation in the form of supporting fish populations by supplemental stocking from hatcheries has raised more questions than answers. Fish farming, hatcheries and stocking programs may have several negative effects on the wild fishes and natural populations. Rearing of fish promotes diseases and parasites which may spread in natural rivers. In addition, indirect and direct genetic effects can occur. Wild fish populations can be depressed by nonintrogessive hybridization, which means that spawning between wild and hatchery fish produce nonviable or incompetent offspring (Helfman 2007). In a long term, a major concern about fish hatcheries is the inability to manage genotypes. Compared to chemical pollution and diseases, genetic alterations (hybridization and introgression) are irreversible and result in the extinction of wild genotypes (Helfman 2007). Therefore, fish stocking cannot be an alternative to degraded habitat and lacking connectivity. If fish stocking is promoted it should be based on supportive breeding and has to prevent genetic alterations of wild populations.

8 FINAL REMARKS

This guideline has been prepared specifically for the situation and types of rivers and hydropower development in Bhutan. It is based on internationally recognized scientific standards and in full agreement with the World Bank's Good Practice Handbook on Environmental Flows for Hydropower Projects published in 2017.

The guideline is obviously building upon some knowledge and understanding which is presently not available in Bhutan and cannot be created in a few months. Besides the constitution, legislation and general regulatory framework on water, hydropower and environmental issues, there is yet no countrywide conservation plan which is including conservation goals for each individual watershed that will be affected by hydropower use. The knowledge on fish species in Bhutan in general and in certain watersheds, rivers and river reaches is increasing but still limited. Moreover, lifecycle strategies and the habitat range used from the Brahmaputra to the headwaters in the mountains of the Himalaya, especially for long-distance migratory fish, is only partially understood. Where fish inventories have been studied in the past years, no systematic data related to their habitat use were collected. Even during the fishing campaigns for this study, only a relatively small number of species was actually caught and for several species there were not enough data to develop statistically sound habitat preferences. Nevertheless, the guideline and the pilot site studies are building on this knowledge.

Data acquisition concerning habitat preference has to be increased. For many species the habitat preferences are unknown or only little knowledge exists. It is envisioned that the efforts to establish a fish inventory and to include habitat parameters will eventually fill the gaps of today in the future. This is an ongoing process which has now picked up momentum. The EIAs necessary for hydropower development must put much more focus on the effects on the most vulnerable ecosystem and could contribute with each study to the further development of the necessary knowledge base.

In the future large reservoirs will be built and operated in Bhutan which will cause a change of the annual hydrological regime and have wide reaching effects on downstream river corridors. It is also assumed that hydropeaking will be used, as the power plants under construction are already designed for this purpose. The data and knowledge which is now missing will all be necessary for such future projects as well. The tools presented und used in this pilot study will also be applicable for those future projects.

Therefore, the pilot site reports prepared for four different rivers within this project should be seen as working documents, therefore. The field data have been surveyed, the hydrodynamic models, aquatic habitat models and hydropower models have been developed and are available also in the future. As new knowledge on additional fish becomes available and a conservation strategy is developed for each watershed, it is a minor effort to integrate such knowledge into the existing models and fill in the gaps still open in the analysis of the pilot study reaches and their watersheds.

It will take some years before the HPP under construction today are entering the operational phase and it will take years before HPPs, where construction has not yet started, will go into operation. The pilot studies prepared for this project should be taken as open studies which must be supplemented with more information as it becomes available. This relates to both, conservation plans and targets for each river system and additional data on fish and their habitats.

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Annex 1:

The following text is an excerpt taken from the IUCN redlist webpage:

http://www.iucnredlist.org/static/categories_criteria_3_1#categories

1. THE CATEGORIES

EXTINCT (EX)

A taxon is Extinct when there is no reasonable doubt that the last individual has died. A taxon is presumed Extinct when exhaustive surveys in known and/or expected habitat, at appropriate times (diurnal, seasonal, annual), throughout its historic range have failed to record an individual. Surveys should be over a time frame appropriate to the taxon's life cycle and life form.

EXTINCT IN THE WILD (EW)

A taxon is Extinct in the Wild when it is known only to survive in cultivation, in captivity or as a naturalized population (or populations) well outside the past range. A taxon is presumed Extinct in the Wild when exhaustive surveys in known and/or expected habitat, at appropriate times (diurnal, seasonal, annual), throughout its historic range have failed to record an individual. Surveys should be over a time frame appropriate to the taxon's life cycle and life form.

CRITICALLY ENDANGERED (CR)

A taxon is Critically Endangered when the best available evidence indicates that it meets any of the criteria A to E for Critically Endangered (see Section V), and it is therefore considered to be facing an extremely high risk of extinction in the wild.

ENDANGERED (EN)

A taxon is Endangered when the best available evidence indicates that it meets any of the criteria A to E for Endangered (see Section V), and it is therefore considered to be facing a very high risk of extinction in the wild.

VULNERABLE (VU)

A taxon is Vulnerable when the best available evidence indicates that it meets any of the criteria A to E for Vulnerable (see Section V), and it is therefore considered to be facing a high risk of extinction in the wild.

NEAR THREATENED (NT)

A taxon is Near Threatened when it has been evaluated against the criteria but does not qualify for Critically Endangered, Endangered or Vulnerable now, but is close to qualifying for or is likely to qualify for a threatened category in the near future.

LEAST CONCERN (LC)

A taxon is Least Concern when it has been evaluated against the criteria and does not qualify for Critically Endangered, Endangered, Vulnerable or Near Threatened. Widespread and abundant taxa are included in this category.

DATA DEFICIENT (DD)

A taxon is Data Deficient when there is inadequate information to make a direct, or indirect, assessment of its risk of extinction based on its distribution and/or population status. A taxon in this category may be well studied, and its biology well known, but appropriate data on abundance and/or distribution are lacking. Data Deficient is therefore not a category of threat. Listing of taxa in this category indicates that more information is required and acknowledges the possibility that future research will show that threatened classification is appropriate. It is important to make positive use of whatever data are available. In many cases great care should be exercised in choosing between DD and a threatened status. If the range of a taxon is suspected to be relatively circumscribed, and a considerable period of time has elapsed since the last record of the taxon, threatened status may well be justified.

NOT EVALUATED (NE)

A taxon is Not Evaluated when it is has not yet been evaluated against the criteria.

Note: As in previous IUCN categories, the abbreviation of each category (in parenthesis) follows the English denominations when translated into other languages (see Annex 2).

2. THE CRITERIA FOR CRITICALLY ENDANGERED, ENDANGERED AND VULNERABLE

1. CRITICALLY ENDANGERED (CR)

A taxon is Critically Endangered when the best available evidence indicates that it meets any of the following criteria (A to E), and it is therefore considered to be facing an extremely high risk of extinction in the wild:

A. Reduction in population size based on any of the following:

1. An observed, estimated, inferred or suspected population size reduction of ≥ 90% over the last 10 years or three generations, whichever is the longer, where the causes of the reduction are clearly reversible AND understood AND ceased, based on (and specifying) any of the following:

(a) direct observation

(b) an index of abundance appropriate to the taxon

(c) a decline in area of occupancy, extent of occurrence and/or quality of habitat

(d) actual or potential levels of exploitation

(e) the effects of introduced taxa, hybridization, pathogens, pollutants, competitors or parasites.

2. An observed, estimated, inferred or suspected population size reduction of ≥ 80% over the last 10 years or three generations, whichever is the longer, where the reduction or its causes

may not have ceased OR may not be understood OR may not be reversible, based on (and specifying) any of (a) to (e) under A1.

3. A population size reduction of ≥ 80%, projected or suspected to be met within the next 10 years or three generations, whichever is the longer (up to a maximum of 100 years), based on (and specifying) any of (b) to (e) under A1.

4. An observed, estimated, inferred, projected or suspected population size reduction of ≥ 80% over any 10 year or three generation period, whichever is longer (up to a maximum of 100 years in the future), where the time period must include both the past and the future, and where the reduction or its causes may not have ceased OR may not be understood OR may not be reversible, based on (and specifying) any of (a) to (e) under A1.

B. Geographic range in the form of either B1 (extent of occurrence) OR B2 (area of occupancy) OR both:

1. Extent of occurrence estimated to be less than 100 km2, and estimates indicating at least two of a-c:

a. Severely fragmented or known to exist at only a single location.

b. Continuing decline, observed, inferred or projected, in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) area, extent and/or quality of habitat

(iv) number of locations or subpopulations

(v) number of mature individuals.

c. Extreme fluctuations in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) number of locations or subpopulations

(iv) number of mature individuals.

2. Area of occupancy estimated to be less than 10 km2, and estimates indicating at least two of a-c:

a. Severely fragmented or known to exist at only a single location.

b. Continuing decline, observed, inferred or projected, in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) area, extent and/or quality of habitat

(iv) number of locations or subpopulations

(v) number of mature individuals.

c. Extreme fluctuations in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) number of locations or subpopulations

(iv) number of mature individuals.

C. Population size estimated to number fewer than 250 mature individuals and either:

1. An estimated continuing decline of at least 25% within three years or one generation, whichever is longer, (up to a maximum of 100 years in the future) OR

2. A continuing decline, observed, projected, or inferred, in numbers of mature individuals AND at least one of the following (a-b):

(a) Population structure in the form of one of the following:

(i) no subpopulation estimated to contain more than 50 mature individuals, OR

(ii) at least 90% of mature individuals in one subpopulation.

(b) Extreme fluctuations in number of mature individuals.

D. Population size estimated to number fewer than 50 mature individuals.

E. Quantitative analysis showing the probability of extinction in the wild is at least 50% within 10 years or three generations, whichever is the longer (up to a maximum of 100 years).

2. ENDANGERED (EN)

A taxon is Endangered when the best available evidence indicates that it meets any of the following criteria (A to E), and it is therefore considered to be facing a very high risk of extinction in the wild:

A. Reduction in population size based on any of the following:

1. An observed, estimated, inferred or suspected population size reduction of ≥ 70% over the last 10 years or three generations, whichever is the longer, where the causes of the reduction are clearly reversible AND understood AND ceased, based on (and specifying) any of the following:

(a) direct observation

(b) an index of abundance appropriate to the taxon

(c) a decline in area of occupancy, extent of occurrence and/or quality of habitat

(d) actual or potential levels of exploitation

(e) the effects of introduced taxa, hybridization, pathogens, pollutants, competitors or parasites.

2. An observed, estimated, inferred or suspected population size reduction of ≥ 50% over the last 10 years or three generations, whichever is the longer, where the reduction or its causes may not have ceased OR may not be understood OR may not be reversible, based on (and specifying) any of (a) to (e) under A1.

3. A population size reduction of ≥nbsp;50%, projected or suspected to be met within the next 10 years or three generations, whichever is the longer (up to a maximum of 100 years), based on (and specifying) any of (b) to (e) under A1.

4. An observed, estimated, inferred, projected or suspected population size reduction of ≥ 50% over any 10 year or three generation period, whichever is longer (up to a maximum of 100 years in the future), where the time period must include both the past and the future, and where the reduction or its causes may not have ceased OR may not be understood OR may not be reversible, based on (and specifying) any of (a) to (e) under A1.

B. Geographic range in the form of either B1 (extent of occurrence) OR B2 (area of occupancy) OR both:

1. Extent of occurrence estimated to be less than 5000 km2, and estimates indicating at least two of a-c:

a. Severely fragmented or known to exist at no more than five locations.

b. Continuing decline, observed, inferred or projected, in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) area, extent and/or quality of habitat

(iv) number of locations or subpopulations

(v) number of mature individuals.

c. Extreme fluctuations in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) number of locations or subpopulations

(iv) number of mature individuals.

2. Area of occupancy estimated to be less than 500 km2, and estimates indicating at least two of a-c:

a. Severely fragmented or known to exist at no more than five locations.

b. Continuing decline, observed, inferred or projected, in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) area, extent and/or quality of habitat

(iv) number of locations or subpopulations

(v) number of mature individuals.

c. Extreme fluctuations in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) number of locations or subpopulations

(iv) number of mature individuals.

C. Population size estimated to number fewer than 2500 mature individuals and either:

1. An estimated continuing decline of at least 20% within five years or two generations, whichever is longer, (up to a maximum of 100 years in the future) OR

2. A continuing decline, observed, projected, or inferred, in numbers of mature individuals AND at least one of the following (a-b):

(a) Population structure in the form of one of the following:

(i) no subpopulation estimated to contain more than 250 mature individuals, OR

(ii) at least 95% of mature individuals in one subpopulation.

(b) Extreme fluctuations in number of mature individuals.

D. Population size estimated to number fewer than 250 mature individuals.

E. Quantitative analysis showing the probability of extinction in the wild is at least 20% within 20 years or five generations, whichever is the longer (up to a maximum of 100 years).

3. VULNERABLE (VU)

A taxon is Vulnerable when the best available evidence indicates that it meets any of the following criteria (A to E), and it is therefore considered to be facing a high risk of extinction in the wild:

A. Reduction in population size based on any of the following:

1. An observed, estimated, inferred or suspected population size reduction of ≥ 50% over the last 10 years or three generations, whichever is the longer, where the causes of the reduction are: clearly reversible AND understood AND ceased, based on (and specifying) any of the following:

(a) direct observation

(b) an index of abundance appropriate to the taxon

(c) a decline in area of occupancy, extent of occurrence and/or quality of habitat

(d) actual or potential levels of exploitation

(e) the effects of introduced taxa, hybridization, pathogens, pollutants, competitors or parasites.

2. An observed, estimated, inferred or suspected population size reduction of ≥ 30% over the last 10 years or three generations, whichever is the longer, where the reduction or its causes may not have ceased OR may not be understood OR may not be reversible, based on (and specifying) any of (a) to (e) under A1.

3. A population size reduction of ≥ 30%, projected or suspected to be met within the next 10 years or three generations, whichever is the longer (up to a maximum of 100 years), based on (and specifying) any of (b) to (e) under A1.

4. An observed, estimated, inferred, projected or suspected population size reduction of ≥ 30% over any 10 year or three generation period, whichever is longer (up to a maximum of 100 years in the future), where the time period must include both the past and the future, and where the reduction or its causes may not have ceased OR may not be understood OR may not be reversible, based on (and specifying) any of (a) to (e) under A1.

B. Geographic range in the form of either B1 (extent of occurrence) OR B2 (area of occupancy) OR both:

1. Extent of occurrence estimated to be less than 20,000 km2, and estimates indicating at least two of a-c:

a. Severely fragmented or known to exist at no more than 10 locations.

b. Continuing decline, observed, inferred or projected, in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) area, extent and/or quality of habitat

(iv) number of locations or subpopulations

(v) number of mature individuals.

c. Extreme fluctuations in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) number of locations or subpopulations

(iv) number of mature individuals.

2. Area of occupancy estimated to be less than 2000 km2, and estimates indicating at least two of a-c:

a. Severely fragmented or known to exist at no more than 10 locations.

b. Continuing decline, observed, inferred or projected, in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) area, extent and/or quality of habitat

(iv) number of locations or subpopulations

(v) number of mature individuals.

c. Extreme fluctuations in any of the following:

(i) extent of occurrence

(ii) area of occupancy

(iii) number of locations or subpopulations

(iv) number of mature individuals.

C. Population size estimated to number fewer than 10,000 mature individuals and either:

1. An estimated continuing decline of at least 10% within 10 years or three generations, whichever is longer, (up to a maximum of 100 years in the future) OR

2. A continuing decline, observed, projected, or inferred, in numbers of mature individuals AND at least one of the following (a-b):

(a) Population structure in the form of one of the following:

(i) no subpopulation estimated to contain more than 1000 mature individuals, OR

(ii) all mature individuals are in one subpopulation.

(b) Extreme fluctuations in number of mature individuals.

D. Population very small or restricted in the form of either of the following:

1. Population size estimated to number fewer than 1000 mature individuals.

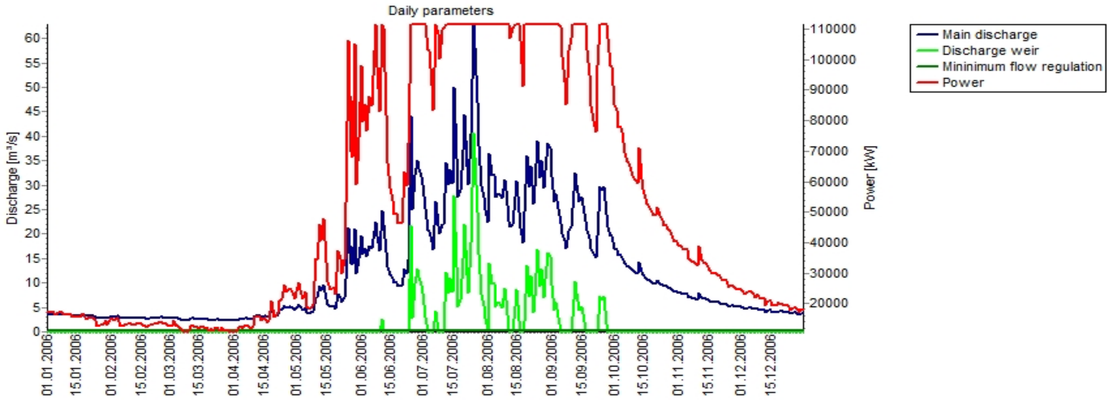
2. Population with a very restricted area of occupancy (typically less than 20 km2) or number of locations (typically five or fewer) such that it is prone to the effects of human activities or stochastic events within a very short time period in an uncertain future, and is thus capable of becoming Critically Endangered or even Extinct in a very short time period.

E. Quantitative analysis showing the probability of extinction in the wild is at least 10% within 100 years.

Annex 2:

Species	Common name	IUCN category	catchment
Schizothorax richardsonii	Snow trout	vulnerable	Pho Chhu, Wang Chhu, Punatsang Chhu
Schizothorax progastus	Dinnawah trout	Least concern	Wang Chhu, Punatsang Chhu
Crossocheilius latius	Minor carp	Least concern	Punatsang Chhu
Garra gotyla	Stone roller	Least concern	Punatsang Chhu
Garra lamta	Stone sucker	Least concern	Punatsang Chhu
Psilorhynchus homaloptera	Torrent stone carp	Least concern	Punatsang Chhu
Pseudecheneis sulcata	Sucker catfish	Least concern	Wang Chhu, Punatsang Chhu
Parachiloglanis hodgarti	Torrent catfish	Least concern	Punatsang Chhu
Parachiloglanis sp.	Torrent catfish	Data deficient	Pho Chhu
Glyptothorax sp.		Data deficient	Punatsang Chhu
Neolissochilus hexagonolepis	Chocolate Mahseer	Near threatened	Punatsang Chhu
Tor putitora	Golden Mahseer	endangered	Punatsang Chhu
Salmo trutta	Brown trout	Non native	Paro Chhu, Pho Chhu, Wang Chhu

Annex 3: CASiMiR Hydropower sample output



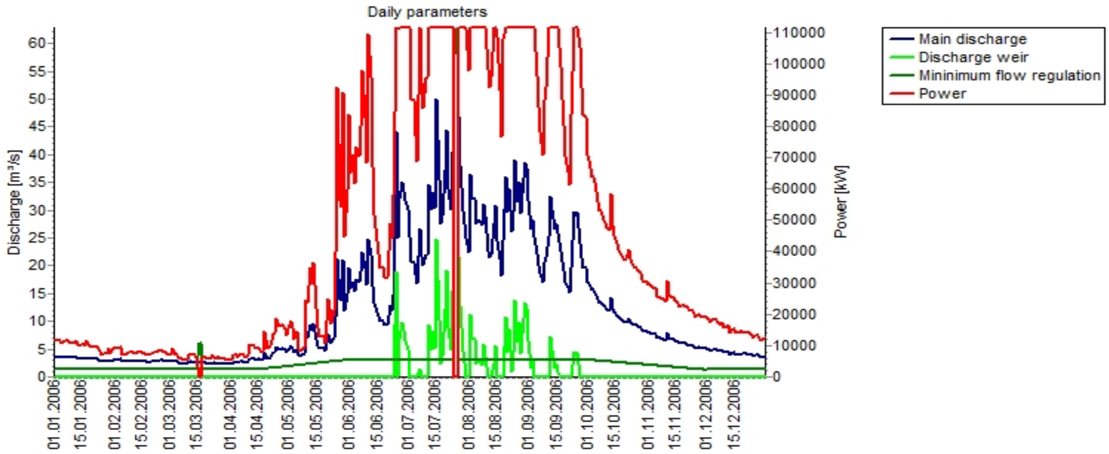
Scenario 0

Annual energy production	449849.39 MWh
Financial return (5.00 Cent/kWh):	22492469.69 Euro

	Mean parameters	Maximum	Minimum
Power	51352.67 kW	111489.91 kW	10795.86 kW
Efficiency	85.00 %	85.00 %	85.00 %
Main discharge	12.26 m³/s	62.86 m³/s	2.34 m³/s
Usable discharge	12.06 m³/s	62.66 m³/s	2.14 m³/s
Head	605.00 m	605.00 m	605.00 m
Daily energy	1232464.09 kWh	2675757.94 kWh	259100.54 kWh
Turbine flow	10.18 m³/s	22.10 m³/s	2.14 m³/s
Discharge weir	1.88 m³/s	40.56 m³/s	0.00 m³/s

Volume of discharge	
Annual discharge	386724672.00 m³
Usable discharge	380417472.00 m³
Discharge weir	59401728.00 m³
Turbines	321015744.00 m³

Energy utilization ratio 70.56 %



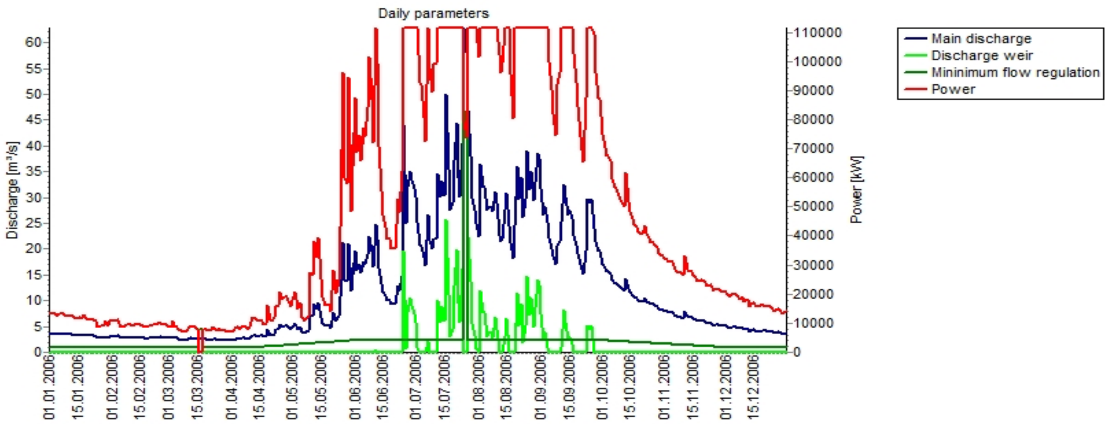
Scenario 1

Annual energy production	381389.95 MWh
Financial return (5.00 Cent/kWh):	19069497.26 Euro

	Mean parameters	Maximum	Minimum
Power	43537.66 kW	111489.91 kW	0.00 kW
Efficiency	85.00 %	85.00 %	85.00 %
Main discharge	12.26 m³/s	62.86 m³/s	2.34 m³/s
Usable discharge	9.78 m³/s	46.95 m³/s	0.00 m³/s
Head	605.00 m	605.00 m	605.00 m
Daily energy	1044903.96 kWh	2675757.94 kWh	0.00 kWh
Turbine flow	8.63 m³/s	22.10 m³/s	0.00 m³/s
Discharge weir	1.15 m³/s	24.85 m³/s	0.00 m³/s

Volume of discharge	
Annual discharge	386724672.00 m³
Usable discharge	308352960.00 m³
Discharge weir	36190368.00 m³
Turbines	272162592.00 m³

Energy utilization ratio 59.82 %



Scenario 2

Annual energy production	402797.58 MWh
Financial return (5.00 Cent/kWh):	20139879.14 Euro

	Mean parameters	Maximum	Minimum
Power	45981.46 kW	111489.91 kW	0.00 kW
Efficiency	85.00 %	85.00 %	85.00 %
Main discharge	12.26 m³/s	62.86 m³/s	2.34 m³/s
Usable discharge	10.40 m³/s	47.73 m³/s	0.00 m³/s
Head	605.00 m	605.00 m	605.00 m
Daily energy	1103555.02 kWh	2675757.94 kWh	0.00 kWh
Turbine flow	9.11 m³/s	22.10 m³/s	0.00 m³/s
Discharge weir	1.28 m³/s	25.63 m³/s	0.00 m³/s

Volume of discharge	
Annual discharge	386724672.00 m³
Usable discharge	327905366.40 m³
Discharge weir	40466131.20 m³
Turbines	287439235.20 m³

Energy utilization ratio 63.18 %

Annex 4: Socio-economic data collection guideline

Section A: General Information

Name of interviewer/team leader in charge: ____

Name of project and river: ____

Date of assessment: ____

*General data on socio-economic aspects**

*(*Section A: 1 form per river reach)*

Household income characteristics (national level)	USD per year
Average household income	
Average rural household income	
Household expenditures on nutrition	

Proposed source: National/District/Local authorities; national statistics

(Remark: Derive numbers from national statistics)

Socio-economic characteristics (project area level)	
Number of households	(number)
Population in affected area	(number)
Average rural household income	(USD/year)
Average household income	(USD/year)
Household expenditures on nutrition	(USD/year)

Proposed source: National/District/Local authorities; national statistics

(Remark: Estimation of the average household incomes and estimated shares of expenditures on nutrition in the project area is required (e.g. Dzonkhag level or more detailed if available)

Affected area*	Area
Direct (Area on diverted stretch); area of valley	(ha)
Indirect (upstream)	(ha)
Indirect (downstream)	(ha)

**according to project planning documents*

Remark: Get this information from the planning documents/maps or alternatively from other maps.

Section B – Socio-Cultural Screening*

*(*Section B: 1 form per river reach)*

Name of interviewer/team leader in charge: ____

Name of project and river: ____

Date of assessment: ____

____

B 1: Socio-cultural screening

<u>QUESTION 1:</u> Are there any traces of human settlement, activity or use in the area or proximity of the dewatered reach?

☐ YES ☐ NO

<u>QUESTION 2:</u> Are there any traces of human settlement, activity or use in the area immediately below or within a 3-5 km radius of the dewatered reach?

☐ YES ☐ NO

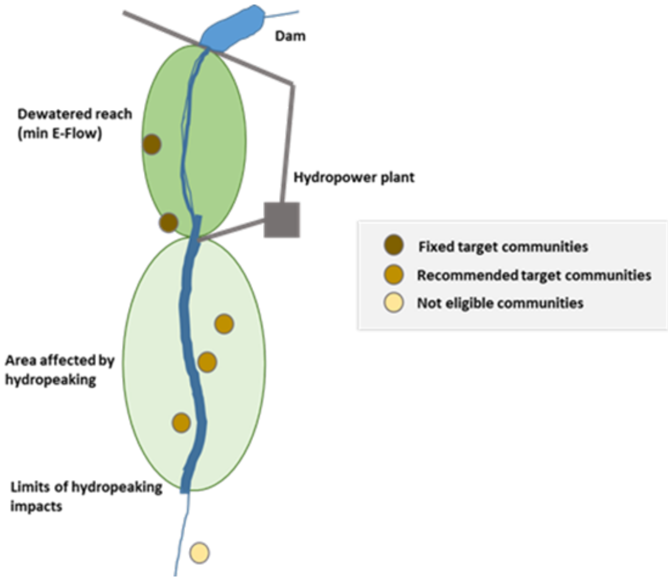
➔ *<u>If any of the answers is **yes** or remains **unclear**, continue with the socio-cultural-economic assessment (SECTION C). If both answers are "no", no socio-cultural-economic assessment is required for this reach.</u>*

<u>Remarks:</u>

B 2: Description of potentially affected villages and project area

Task:

- Identify villages, settlements and communities potentially affected
- Collect basic data on the village (size, population, main economic activities, maps etc.)



Background:

Villages or communities, which are the main target communities. However, villages further down the river may be also affected (e.g. by hydropeaking). If notable settlements are found within this area additional studies may be required, but are not subject of this guideline.

Name of settlement	Number of households	Main economic activities	Distance to river reach in km

Section C – Socio-Cultural Assessment*

*(*to be completed if Section B requires in-depth assessment)*

Name of interviewer/team leader in charge: ____

Name of project and river: ____

Date of assessment: ____

____

C.1.: Describe socio-economic environment with specific focus on the river

Due to the large variation of possible activities and social meanings of rivers, an on-site assessment including interviews and discussions with local stakeholders needs to be carried out.

The tasks are to be accomplished by an expert/group of experts of NEC by

- visiting the river reach and target communities potentially for visual inspection (**Photo documentation**)
- Carry out **interviews or stakeholder workshops** in the villages to discuss the role of the river
- Collecting of available data on river uses and importance in the target area (maps, historic pictures, oral history, village chronicles etc.)
-

Target group for interviews:

- People living in the target area
- People using the river in any kind
- Village/settlement authorities

There is no fixed number for interviewees. It is recommended to interview at least the community representative and conduct a workshop within the settlement to discuss the guiding questions.

Guiding interview questions

The interviews should give answer to guiding questions listed on the next page

Photo documentation and field visit

The assessment team should visit the communities and the river reach and document all visible signs of human activity around the river (people doing something at or in the river, small architecture or man-made infrastructures, tourism activities, pastures, rice paddies etc.).

These activities should contribute to be able to fill out a comprehensive and correct assessment of the checklist on the next page

C.1.1. Interview guideline for semi-structured interviews in communities

Describe along the questions how the rural communities link to the river. Try to be as specific as possible (e.g. location of temples, number of water pumps for extraction of water, period of the year when river resources are used).

C1.) Which role does the river and its landscape play within the community? How important is the river for the community?

C2.) In which way do you use the river or its resources (water, fish, collection/harvesting, washing of clothes, swimming, drinking water for livestock etc.)?

C3.) Are there important spiritual places in or along the river? Which ones?

C4.) Are there any events taking place near or next to the river?

C5.) Do you know any further people/communities who use the river or for whom the river is of particular importance?

(If the answer here is yes, the community/settlement should be visited as well it is located within the project area (and then be listed above as well)

	Ecosystem services	**Guiding questions** *(Please provide supplementing and concrete information for integration into future interview guidance, (e.g. specific use forms) (Collect all answers in this table (qualitative) and finally give a qualified estimate of relevance and likeliness of impacts*	**Local Relevance (none-low-medium-high)[9]**	**Likeliness of adverse impacts by river flow changes (none-low-medium-high)[10]**
1	**Provisioning services**			
C6	Food	Do you use the river for food production (fishing, algae collection etc.)?		
C7	Water	Do you use water from the river for your household/community? (Drinking water, water for cooking, flood irrigation systems, laundry, waste water etc.)		
C8	Raw materials	Do you use any natural materials from the river (Fiber, stone, sand, fuelwood collection etc.)?		
C9	Medicinal resources	Do you collect any medicinal resources from the river (e.g. plant, herbs, insects, mud etc.)?		
C10	Ornamental resources	Does the river provide any ornamental resources to you or your community? (e.g. harvesting of flowers, collection of stones etc.)		
2	**Regulation services**			
C11	Waste treatment/water purification	Do you use river water as drinking water, for sanitary purposes or waste water treatment?		
C12	Maintenance of soil fertility/nutrient cycling	Do you benefit from the nutrients provided by the river (e.g. flood irrigation systems)?		
C13	Biological control	Are there any river-based organisms relevant for pest control?		
3	**Habitat services**			

[9] *It is important to discuss/assess with the interviewees whether this activity is important for the community. Make a final statement with a local representative.*
[10] *It should be roughly assessed whether changes in the flow will affect this actitity (e.g. location of the water pump on a side river or main stretch, algae which would be no longer available)*

C14	Lifecycle maintenance (esp. Nursery services)	Does fishery a play a role in your household/community?		
4	**Cultural services**			
C15	Aesthetic information	Are there any temples, buildings, monuments in a riverine setting?		
C16	Opportunities for recreation and tourism	Is there river-bound tourism or recreation (present or potential) (kayaking, rafting, local recreation, swimming, children's playground)?		
C17	Inspiration for culture, art and design	How does the river link to your traditions? (Existence of river bound routines and traditions of daily live such meeting points, rituals, art work, stories, myths and legends referring to the river), Typical or traditional architecture (e.g. mills, watering-systems)		
C18	Spiritual experiences	Does the river play a spiritual role for your household/in your community? (e.g. holy river, holy spring, religious place, memorial sites, burial sites, river related festivities, pilgrimage sites, lamas, holy caves)		

Section D – Quantitative Assessment

*(*to be filled out for every reach based on a positive SE-screening)*

Name of interviewer/team leader in charge: _______________________________________

Name of project and river: ____

Date of assessment: ____

Quantitative assessment of socio-cultural services

Next to qualitative assessments, some quantitative data is needed for the economic valuation of selected ecosystem services.

Note: The questionnaire investigates estimates of quantitative data (eg. hectares, number of households, cost in USD per annum (pa.). In particular, with estimates of percentage shares of cost, **interviewers are advised to assist interviewees with own skill in estimating economic proportions.** Collected data of this section are to be entered into the "Criteria"-Table of the EVALUATION TOOL MODEL. The information here only refers to data relevant to be collected on site by interviews.

For this section, the following sources of information should be considered:

- Regional or local authorities
- Household interviews in dewatered reaches
- Tourism board

Quantitative data is required for the following ecosystem services (see also checklist in model):

- (ESS 11) Waste treatment / water purification
- (ESS 1) Food – Category: Fishing, other
- (ESS 2) Water – Category: Irrigation, transport, other
- (ESS 19) Opportunities for recreation and tourism - Dzongkhag-Level

NOTE: All this data refers to the project area and the target communities as specified above.

(ESS 11) Waste treatment / water purification

(Collect numbers based on project planning documents, responsible authorities and supplementing interviews)

ESS 11	Amount
Number households affected (existing)	(number)
Number of households (with planned sewage infrastructure)	(number)

Proposed source of information: national/regional/local authorities and interviews). Interviewers should specifically ask about the local sewage infrastructure.

(ESS 19) Opportunities for recreation and tourism - Dzongkhag-Level

ESS 19	Opportunities for recreation and tourism - Dzongkhag-Level
Estimated tourism spending on site	(USD/year)

Proposed source: National tourism board. Ask local communities about touristic activities in the areas (e.g. hiking trails, guesthouses, rafting or kayaking).

(ESS 1) Food – Category: Fishing, other

(Collect numbers based on household and village group interviews; give a qualified estimate based on interviews)

ESS 1	Food provision: Fishing, algae etc.
Number of existing households extracting food	(number)
Share of harvest used for nutrition	% of total
Share of harvest used for income	% of total

Proposed source: Household interviews in dewatered reaches. Here it is important to clarify with interviewees whether the river plays a substantial role for food collection or as an income source. Ask people how they use the harvest.

(ESS 2) Water – Category: Irrigation, transport, other

(Collect numbers based on household and village group interviews; give a qualified estimate based on interviews)

ESS 2	Water: Irrigation, transport

Number of existing households using river water	(number)
Share used for nutrition	% of total
Share used for income generation	% of total

Proposed source: Household interviews in dewatered reaches. This includes particularly use of the water from the river (irrigation, cooking). Clarify whether the water is used for subsistence or for commercial activities (e.g. selling on markets).

Annex 5: Socio-economic evaluation tool

VALUATION APPROACHES							
	TEEB Value			Mean	Verification - Bhutan - site specific		
	Min.	Mean	Max	Valuation	Remark	Valuation	
	Int. $/ha/yr	Int. $/ha/yr	Int. $/ha/yr	USD/yr		USD/yr	Int. $/ha/yr
PROVISIONING SERVICES							
1 Food	30	105	218	-		-	
Fishing					Income related		
2 Water	1'269	3'739	6'208	-		-	
Irrigation					Income related		
3 Raw materials							
4 Genetic resources							
5 Medicinal resources							
6 Ornamental resources							
REGULATING SERVICES							
7 Influence on air quality							
8 Climate regulation							
9 Moderation of extreme events							
10 Regulation of water flows							
11 Waste treatment / water purification	339	2'939	5'538	-	Annual (incl. avg. planned)	-	
12 Erosion prevention							
13 Maintenance of soil fertility /nutrient cycling							
14 Pollination							
15 Biological control							
HABITAT SERVICES							
16 Lifecycle maintenance (esp. nursery service)							
17 Maintenance of genetic diversity (gene pool prot.) - **Biodiversity conservation**		320		-	Global valuation	-	
CULTURAL SERVICES							
18 Aesthetic information							
19 Opportunities for recreation and tourism	339	1'487	3'041	-	Tourism spending		
20 Inspiration for culture, art and design							
21 Spiritual experience							
22 Information for cognitive development							
TOTAL				-		-	
Costanza 2013 - Total Rivers and Lakes - Mean USD/ha/yr		4'827		-			
Provisioning services		3'060		-			
Regulating services		863		-			
Habitat services		316		-			
Cultural services		588		-			

Item	Unit	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Inflation index		1.00	1.06	1.12	1.19	1.26	1.33	1.39	1.46	1.54	1.61	1.69	1.78	1.87	1.96	2.06	2.16	2.27	2.38	2.50	2.63
BTN/USD (PPP IMF WEO)		22.1	23.2	24.2	25.2	26.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1
BASELINE																					
Average flow	m³sec																				
Efficiency	%																				
Capacity		GWh																			
Capacity factor		96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%
Power production Baseline	GWh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tariffs																					
Estimated long term average price	USD-Cent/kWh																				
Growth of average tariff	inflation based		6%	6%	6%	5.6%	5.6%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
	BTN/MWh		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Average tariff	BTN/kWh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	USD-Cent/kWh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
REVENUES																					
TOTAL REVENUES	1,000 BTN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1,000 USD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reduction for EF-limitation																					
Revenues loss from EF		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
External effects from ESS																					
Valuation of																					
Provisioning services	avoided cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Regulating services	avoided cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Habitat services	avoided cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cultural services		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total ESS		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Economic Present Value at	5.5%	-																			
Avoided cost of ESS		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cost from EF regulation		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Net economic value		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

ENPV

Approach		mn. USD
Approach No.	2	-
TEEB 2015	1	-
Costanza 2013	2	-
Site specific	3	-

Table 1. 10

Dzongkhag Arrivals and Bed Nights

Dzongkhag	Tourist Arrivals 2013	2014	Bed Nights 2013	2014	Share 2014	Change Nights 2014
Paro	43'707	56'828	102'116	127'560	35.01%	24.92%
Thimphu	41'594	55'383	73'645	96'171	25.25%	30.59%
Punakha	30'127	43'003	42'525	58'319	14.58%	37.14%
Bumthang	11'762	12'327	29'399	30'663	10.08%	4.30%
Wangdue Phodrang	16'833	18'256	24'604	25'498	8.44%	3.63%
Trongsa	6'913	6'957	761	7'850	0.26%	931.54%
Chukha	4'574	4'826	4'799	5'082	1.65%	5.90%
Trashigang	225	2'272	4'228	4'498	1.45%	6.39%
Haa	2'811	2'801	3'532	3'629	1.21%	2.75%
Monggar	2'385	2'464	3'481	3'548	1.19%	1.92%
Gasa	401	480	271	2'998	0.09%	1006.27%
Samdrup Jongkhar	2'064	2'056	223	2'314	0.08%	937.67%
Trashi yangtse	937	672	1'129	860	0.39%	-23.83%
Zhemgang	165	205	420	541	0.14%	28.81%
Sarpang	155	179	210	480	0.07%	128.57%
Lhuentse	144	230	178	341	0.06%	91.57%
Pema Gatshel	84	96	132	142	0.05%	7.58%
Tsirang	13	8	16	8	0.01%	-50.00%
Dagana	8	18	12	20	0.00%	66.67%
Samtse	5	3	7	3	0.00%	-57.14%
TOTAL	164'907	209'064	291'688	370'525		27.03%

Bhutan Tourism Monitor Annual Report 2013

Visitors by Activity

		2013	2014
Others	2'500	4.06%	
Traditional Medicine	9	0.01%	
Fly-Fishing	9	0.01%	
Rafting/Kayaking	181	0.29%	13.30%
Retreat an Meditation	204	0.33%	
Spa and Wellness	288	0.47%	
Mountain Biking/Motorcycling	332	0.54%	
Flora, Fauna and Avi-Fauna	845	1.37%	0.07%
Textiles	135	0.22%	
Day Hikes	2'018	3.28%	
Trekking	2'943	4.78%	0.04%
Festivals	8'363	13.60%	
Cultural Sightseeing	43'684	71.02%	
TOTAL	61'511		
Nature tourism	4'310	7.01%	13.41%

Tourism spending

			2013	pCap spending in USD	Total Bed Nights	Avg. Length of Stay	Daily
Tourists	International	173'349'245	44'252	3'917		8.5	461
	Regional	46'650'755	43'691	1'068		5	214
Total visitors		220'000'000	116'209		302'965		

Districts of Bhutan

Dzongkhag (District)	Capital	Area ha	Population 2005	Density	Dsongdey (Zone)	Dungkhag[3 (Sub-districts)	Gewog	Towns
Bumthang	Jakar	249'000	16'116	6.5	Southern	-	4	5
Chukha	Phuentsholing	199'100	74'387	37.4	Western	1	11	6
Dagana	Daga	127'600	18'222	14.3	Central	-	11	4
Gasa	Gasa	408'900	3'116	0.8	Central	-	4	1
Haa	Ha	131'900	11'648	8.8	Western	-	5	1
Lhuntse	Lhuntshi	288'100	15'395	5.3	Eastern	-	8	2
Mongar	Mongar	163'800	37'069	22.6	Eastern	-	16	4
Paro	Paro	169'300	36'433	21.5	Western	-	10	2
Pemagatshel	Pemagatsel	59300	13'864	23.4	Eastern	-	7	7
Punakha	Punakha	84500	17'715	21	Central	-	9	1
Samdrup Jongkhar	Samdrup Jongkhar	220'700	39'961	18.1	Eastern	3	11	5
Samtse	Samtse	172'500	60'100	34.8	Western	2	16	3
Sarpang	Geylegphug	204'800	41'549	20.3	Southern	2	15	3
Thimphu	Thimphu	161'700	98'676	61	Western	1	10	1
Trashigang	Tashigang	217'100	51'134	23.6	Eastern	3	16	6
Trashiyangste	Tashi Yangtse	145'900	17'740	12.2	Eastern	-	8	2
Trongsa	Tongsa	181'500	13'419	7.4	Southern	-	5	1
Tsirang	Damphu	63200	18'667	29.5	Central	-	12	1
Wangdue Phodrang	Wangdue Phodrang	418'100	31'135	7.4	Central	-	15	3
Zhemgang	Zhemgang	214'600	18'636	8.7	Southern	1	8	3
Bhutan	Thimphu	3'881'600	634'982	16.4		13	201	61

Bhutan

Subject Descriptor	Units	Scale	Country/Series-specific Notes	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Estimates Start After
Implied PPP conversion rate	National currency per current int		See notes for: Gross domestic	14.1	14.3	14.7	15.3	16.0	16.9	18.2	19.5	20.8	22.1	23.2	24.2	25.2	26.1	27.1	-
Inflation, average consumer prices	Index		Source: Central Bank	637	670	712	763	800	868	956	1'039	1'139	1'221	1'295	1'372	1'452	1'534	1'621	2013
Inflation, average consumer prices	Percent change		See notes for: Inflation, average consumer prices (Index).	4.9	5.2	6.3	7.1	4.8	8.6	10.1	8.6	9.6	7.2	6.1	6.0	5.8	5.6	5.6	2013
Population	Persons	Millions	Source: International Financial Institution	0.666	0.679	0.692	0.705	0.717	0.729	0.742	0.754	0.766	0.779	0.792	0.804	0.818	0.831	0.845	2011

International Monetary Fund, World Economic Outlook Database, October 2015

Country/Series-specific Notes

Bhutan: Implied PPP conversion rate (National currency per current international dollar)

See notes for:
Gross domestic product, current prices (National currency).

Bhutan: Inflation, average consumer prices (Index)

Source: Central Bank
Latest actual data: 2013. Latest quarterly data extend to Q3 2014.
Harmonized prices: No

Frequency of source data: Semi-annual 1980-2003. Quarterly from from 2003Q2

Base year: 1980
Primary domestic currency: Bhutanese ngultrum
Data last updated: 07/2015

Bhutan: Inflation, average consumer prices (Percent change)

See notes for:
Inflation, average consumer prices (Index).

Bhutan: Population (Persons)

Source: International Financial Institution (e.g. Eurostat, OECD, IFS, World Bank, WTO). World Development Indicators

Latest actual data: 2011
Primary domestic currency: Bhutanese ngultrum
Data last updated: 07/2015