

Framework for Upstream-Downstream Linkages of Land and Water Management in the Hindu Kush Himalaya (HKH) Region



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This series is based on the work of the Himalayan Adaptation, Water and Resilience (HI-AWARE) consortium under the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA) with financial support from the UK Government's Department for International Development and the International Development Research Centre, Ottawa, Canada. CARIAA aims to build the resilience of vulnerable populations and their livelihoods in three climate change hot spots in Africa and Asia. The programme supports collaborative research to inform adaptation policy and practice.

HI-AWARE aims to enhance the adaptive capacities and climate resilience of the poor and vulnerable women, men, and children living in the mountains and flood plains of the Indus, Ganges, and Brahmaputra river basins. It seeks to do this through the development of robust evidence to inform people-centred and gender-inclusive climate change adaptation policies and practices for improving livelihoods.

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Feedback is welcomed as a means to strengthen these works: some may later be revised for peer-reviewed publication.

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Framework for Upstream-Downstream Linkages of Land and Water Management in the Hindu Kush Himalaya (HKH) Region

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Himalayan Adaptation, Water and Resilience (HI-AWARE) Research

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Acronyms and Abbreviations

CC	Climate Change
CLZ	Climatic Landscape Zone
CARIAA	Collaborative Adaptation Research Initiative in Africa and Asia
DI	Deliverable
DEM	Digital Elevation Model
DFID	Department for International Development, United Kingdom
DGHM	Department of Geoinformatics, Hydrology and Modelling
DIST	Decision Information Support Tool
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
GCM	General Climate Model
GESI	Gender Equality and Social Inclusion
GIS	Geographic Information System
GL30	Globe Land 30 Project
GLOF	Glacial Lake Outburst Flood
HD	Human Dimension
HRU	Hydrological Response Units
HWSD	Harmonized World Soil Database
HI-AWARE	Himalayan Adaptation, Water and Resilience (HI-AWARE) Research
IDRC	International Development Research Centre, Ottawa, Canada
ILMS	Integrated Land Management System
ICIMOD	International Centre for Integrated Mountain Development
ILWRM	Integrated Land and Water Resources Management
ISA	Integrated System Analysis
JAMS	Jena Adaptable Modelling System
LULC	Land Use and Land Cover
LPJmL	Lund-Potsdam-Jena managed Land
MBT	Main Boundary Thrust
MCT	Main Central Thrust
MFT	Main Frontal Thrust
MTI	Ministry of Trade and Industry of Bhutan
NCA	Nested Catchment Approach
NE	Natural Environment
NER	North-Eastern Regions of India
NGCC	National Geomatics Centre of China
PD	Public Domain
RCM	Regional Climate Model
SCOC	Strengths, Challenges, Opportunities Challenges

SOAR	Strengths, Opportunities, Aspirations & Results
SOPA	Strength, Opportunities & Positive Action
SRTM	Shuttle Radar Topography Mission
SWOT	Strength, Weaknesses, Opportunities, and Threats
UDL	Upstream-downstream Linkages
WS	Workshop
WEAP	Water Evaluation and Planning
WFDEI	Watch Forcing Data ERA-Interim

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Summary

This paper develops a conceptual and generic framework design for the study of upstream-downstream linkages (UDL) in the Hindu Kush Himalaya (HKH) region. The framework application will define changing upstream-downstream linkages (UDL) and likely impacts on downstream regions. The results of such applications will be useful for policy makers, planners, decision makers, and researchers. It also addresses actors involved in Integrated Land and Water Resources Management (ILWRM) challenged by changing UDL processes, triggered by broader environmental changes such as climate change and human activities. This framework document defines the upstream downstream relationship. It describes the issues related to UDL mainly around land use and land cover (LULC) changes, erosion and sedimentation, climate change and infrastructure, which affect the availability of water in downstream areas.

Designed as a generic concept the framework proposes a structured methodology to identify, analyse, and evaluate UDL processes and to initiate respective integrated system analysis (ISA) studies with respect to sustainable ILWRM and impact mitigation. Depending on the scale at which the framework is applied to the ISA, it will focus on local, national, or transnational conditions and process dynamics respectively.

River basins in the HKH region have some common features, for example, topographic basin components, climate landscape zones (CLZ), and irrigation-based agriculture. Any activities and processes in upstream areas might have a direct influence on the downstream environment. The relationship occurs at different locations and scales, and the magnitude and nature of problems and related effects change between the local micro catchment scale and the regional macro river basin scale. Therefore, UDL in such river systems have a multi-scale reference.

Worldwide there are 261 international watersheds, which affect about 40% of the world's population. In the case of transboundary river basins, a better understanding of such relationships can help minimize risk (disaster) as well as maximize benefits (for example, irrigation, navigation, and socio-economic development).

In addition, it is also important to reduce conflict among countries, which may arise on account of the use of water resources in upstream and downstream areas. For that reason, assessment of UDL requires a multi-scale framework with interdisciplinary methodologies from the natural sciences, engineering, and socio-economic analysis, and geoinformatics. These methodologies will feed their findings into a decision information support tool (DIST) for data management, decision support, and information dissemination.

The generic framework design accounts for these methodological requirements when defining, assessing, and analysing multi-scale UDL processes. It applies a stepwise methodological approach comprising: **Step 1:** definition of the UDL system with respect to scale and outcome; **Step 2:** quantification of the present UDL system status and change detection; **Step 3:** modelling an analysis of the present system status; and **Step 4:** 'what-if?' scenario modelling, development, and evaluation of alternative ILWRM options.

A framework implementation structure has been developed and elaborated in tabular form. It was applied to four UDL system subjects: (1) Changing LULC with respect to water resources; (2) Impact of erosion and sedimentation in downstream areas; (3) Climate change and hydrological regimes; and (4) Infrastructures and downstream water availability.

Ultimately, a priority ranking for the framework application is recommended that stresses the importance of field studies for the methodological implementation. By applying this framework, the issues around UDL can be quantified. The resulting improved understanding will be instrumental for sustainable water resources planning and management.

1. Purpose

The purpose of this document is to develop a conceptual and generic framework design for the study of upstream-downstream linkages (UDL) in the Hindu Kush Himalaya (HKH) region. Worldwide there are 261 international watersheds, which affect about 40% of the world's population (Wolf 1998). In the case of transboundary river basins, a better understanding of such relationships can help minimize risk (disaster) as well as maximize benefits (e.g. irrigation, navigation, socio-economic development) and enhance cooperation among upstream and downstream countries.

In addition, it is also important to reduce conflict among countries, which may arise on account of the use of water resources in upstream and downstream areas.

It addresses decision makers, planners, researchers, and other actors involved in Integrated Land and Water Resources Management (ILWRM) and challenged by UDL phenomena, triggered by climate change (CC) or human activities respectively.

This framework document should be read in conjunction with a review document (Nepal, Pandey, Shrestha & Mukherji 2018). The document defines the upstream downstream relationship, and describes the issues related to UDL mainly around the following impacts:

- LULC changes on water resources;
- Erosion and sedimentation in downstream areas;
- Climate change on downstream water availability; and
- Infrastructure development on water availability in downstream areas.

Nepal et al., (2018) and Nepal, Flügel, & Shrestha (2014a) provided a detailed review of literature of such UDL processes, to which the reader is referred.

Designed as a generic concept, the framework proposes a structured methodology guiding the reader to identify changing UDL systems and to define respective integrated system analysis (ISA) studies to assess, analyse, and evaluate such systems with a view to sustainable ILWRM and impact mitigation.

Analysing and evaluating UDL processes in the HKH is a multi-scale challenge. Applications of the generic framework, therefore, will include micro-scale ($A \leq 10^3 \text{ km}^2$) and meso-scale ($A > 10^3\text{-}5 \times 10^4 \text{ km}^2$) river catchments as well as macro-scale river basins ($A > 5 \times 10^4 \text{ km}^2$). Even so, depending on the scale to which the framework applies, the respective ISA will focus more on local, national, or transnational conditions and scale-related process dynamics.

The authors appreciate the diversity and complexity of changing UDL systems within the HKH and understand that the identification and analysis of UDL impacts is an interactive and collaborative approach involving researchers, key stakeholder groups, planners, and water resources managers.

Consequently, the generic framework is to be taken as a 'living document' allowing for regular updates by know-how obtained from multi-scale applications of the framework in the HKH.

2. Objectives

The overall objective of the framework is to guide actors involved in ILWRM within the HKH region to define the scope and scale of UDL processes within national and international catchments and river basins and to compile respective framework study initiatives. In this regard, the framework realizes the following methodological objectives:

1. To develop a generic design to apply to UDL processes triggered by climate change, e.g., changing runoff dynamics and sediment load, or by human activities, e.g., changing LULC or reservoir infrastructures.
2. To formulate an adaptable, multi-scale methodology to assess and analyse scale-related UDL processes within the Natural Environment (NE) and its Human Dimension (HD), and to develop scenario-based, respective ILWRM response options.
3. To apply the generic framework in four multi-scale UDL systems common in the HKH region with likely impacts from changing UDL process dynamics.



Figure 1: The Hindu Kush Himalaya region and 10 major river basins

Note: The figure also shows the Gandaki river basin, which is the study area of HI-AWARE.

3. UDL Framework

The designed framework concept is for application in the HKH region shown on the map in Figure 1. The high altitude areas of the Himalaya region are the source of 10 river basins - Amu darya, Tarim, Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtse, and Yellow river. The basins of these rivers are inhabited by 1.9 billion people and the flow in these rivers connects upstream and downstream areas in the basins (Wester, Mishra, Mukherji and Shrestha, 2018).

Out of the 10 major river systems in this region, the Indus, Ganges, and Brahmaputra river basins are of vital importance to Pakistan, India, Nepal, Tibet/China, Bhutan, and Bangladesh. The river basins are described in brief in a literature review by Nepal et al., (2018).

This framework is focuses on these Himalaya river basins within the HKH region. However, since the concept and methodological approach is generic, it may be applied to other mountainous regions of the world as well.

Stretching about 3,500 km from the North-west to the South-east, the HKH region differs in climate, geology, soils, hydrological river dynamics, and population, but for the generic framework design, some common river system features may be identified as follows.

3.1. Common Basin Features

River basins in the HKH region have common features relating to their natural environment like topographic basin components and climate landscape zones (CLZ). With respect to the Human Dimension, they share issues like irrigation development and hydropower potential. The generic framework design accounts for these and other common features when assessing and analysing multi-scale UDL process dynamics.

3.1.1. Basin Component Structure

The basins of the Indus, Ganges, and Brahmaputra have a common, threefold-component structure, schematically

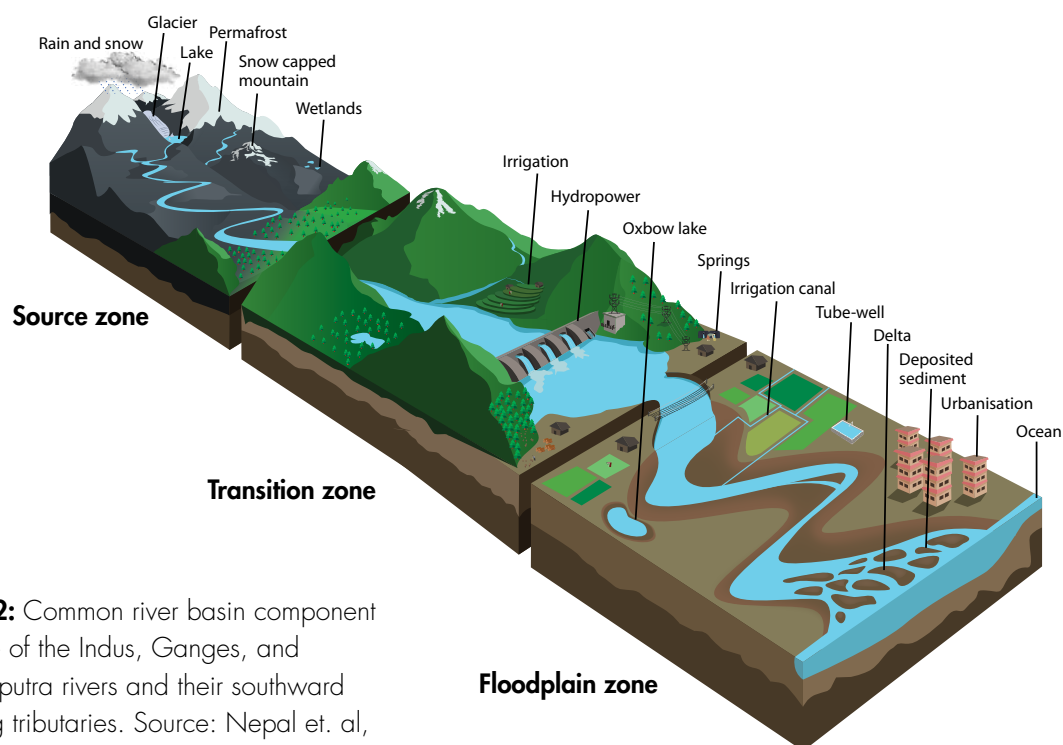


Figure 2: Common river basin component structure of the Indus, Ganges, and Brahmaputra rivers and their southward draining tributaries. Source: Nepal et. al, 2018

shown in Figure 2. This also applies to their southward flowing tributaries like the Gandaki River (Figure 1), except that they join the ocean via their respective main rivers, e.g. the Ganges River.

With respect to the UDL framework design, Figure 2 reveals:

- Runoff and sediment input, generated in the glaciated headwater source zone and lesser Himalayas, passes through the mountain environment and transition zone to the adjacent floodplain. Flooding and sedimentation of the densely populated floodplain is a natural process and ILWRM aims to control these dynamics to reduce vulnerability and to sustain irrigation development.
- Meanwhile the source zone and the upper part of the transition zone have a high socio-economic potential for hydropower generation and agriculture. The population in the mountains experience water stress during the dry season on hill slope locations.
- For thousands of years, river flow out of the transition zone has been providing the water supply for large-scale irrigation agriculture, sustaining the livelihood of millions of people on the densely populated flood plain.

3.1.2. Climatic Landscape Zones (CLZ)

Another generic feature of river basins in the HKH, and of relevance to a UDL process analysis, is the existence of climatic landscape zones (CLZ). They determine the climate and the LULC within respective topographic altitude ranges. An example of such a CLZ is shown in Figure 3 for the Gandaki River basin, a tributary of the Ganges River in China, India, and Nepal.

For catchments in the central part of the Himalaya between Sikkim in India, the Nepal section of the Himalayas, and Uttarakhand again in India, the topography will also include the Siwalik Hills, a promontory of the Himalayas. It should be noted that whenever the generic CLZ approach is applied, it has to be adjusted to reflect the

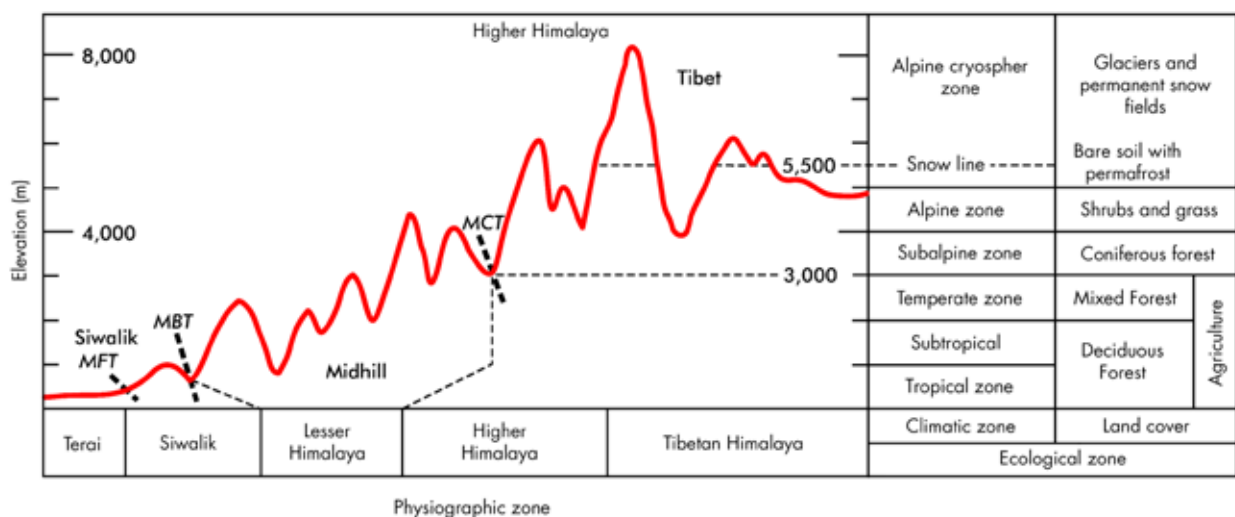


Figure 3: Climatic landscape zones (CLZ) and their altitude ranges for the Gandaki River (Source: Nepal et al. 2017)

physiographic reality of the river system under UDL study.

Figure 3 enhances the generic information for the framework design obtained from Figure 2 as follows:

- The 'source zone' subdivides into the Higher Himalaya and the adjacent Tibetan Plateau in the alpine and cryosphere zones with glaciers, snowcover, and permafrost with little or no vegetation.

- In this CLZ, rising temperatures from climate change trigger increasing snow and glacier melt, shrinking glacial area and permafrost, fostering runoff generation and slope instability with incremental sediment input to the stream network respectively.
- The 'transition zone' comprises the subtropical, temperate, and subalpine zone of the Lesser Himalayas, with forest and agriculture as the dominant LULC. Changing LULC such as deforestation and extending agriculture mainly occur in these zones impacting the basins' UDL dynamics.
- The densely populated 'floodplain zone' is in the tropical zone and subject to flooding and sedimentation. In the past centuries, the tropical forest has almost completely been replaced by irrigated agriculture. Due to the UDL dynamics described above, a changing climate and LULC, or infrastructures in the stream network are likely to affect the water supply to millions of people in this CLZ.

3.1.3. UDL System Features in the HKH

The information revealed in Figures 2 and 3 enables us to classify some common UDL system features in Himalaya river basins and to allocate them to respective CLZs. This will provide further generic understanding to define micro, meso, and macro-scale UDL systems and their process dynamics:

1. Snow and glacier melt in the cryosphere and alpine zone together with summer monsoon rainfall generate an annual runoff dynamic from the basins' headwater regions in the Higher and Lesser Himalayas. Depending on the concurrence of both components and the nature of annual hydrographs, the runoff may inundate the adjacent floodplain.
2. Snow and glacier melt water is stored in glacial lakes behind core moraine deposits in the cryosphere. Flash floods of disastrous magnitude may occur in downstream areas, either as glacier lake outburst floods (GLOFs) or from heavy monsoon storms in the Lesser Himalaya.
3. A vast amount of sediment is generated by natural denudation processes in the cryosphere as a result of the continuous uplift of the Himalaya mountain chain and enters the stream network system. Landslides in the Higher and Lesser Himalayas are another significant sediment input source, which may have been triggered by various circumstances, i.e., geo-tectonic activities, road construction, and riverbank erosion on steep slopes.
4. Sediment transport is discontinuous and, with receding flow, sediment gets deposited on broader valley floors, from where it is taken up again during flood events. Eventually, the reground sediment load reaches the downstream floodplain zone, where it is deposited during inundation periods.
5. The population in the HKH region is one of the poorest in the world and the situation might be exacerbated by environmental changes and water stress in the mountains, and also due to the high population density and people's vulnerability to flooding in the plains.
6. Changing LULC from forest to agriculture has been part of traditional slash-and-burn practices (*jhum* or *khoria*) as in the North-Eastern states of India - Arunachal Pradesh, Meghalaya, Mizoram, and Nagaland. It may also be a response to population growth, which demands more agricultural land for food production. On the other hand, urban settlements extend continuously at the expense of farmland in their surrounding hinterland.
7. In the HKH region, the potential for hydropower is high but not fully developed so far. The planning of additional reservoirs receives increasing critical attention and resistance from environmentalists nowadays because of their UDL impacts on the downstream environment and socio-economy.
8. Climate change has been affecting the HKH region through temperature rises in the past decades, and different climate models confirm measured trends. On the other hand, this does not apply in the same distinctness to observed and modelled precipitation, which has greater uncertainty.

3.2. Methodological Approach

UDL systems in river basins may have multi-scale dimensions. Their study requires an interdisciplinary approach comprising methodologies from the natural sciences, engineering, and socio-economic studies as well as geoinformatics applied within the ISA.

The UDL framework, therefore, needs to be generic and applicable to micro, meso, and macro-scale applications. Its methodological components must be flexible enough to adapt to the UDL scale identified and to account for the relevant processes identified in the natural environment and its human dimension.

A central component of each UDL study is a common Decision Information Support Tool (DIST) for data management, planning support, and information dissemination (Nepal, et al., 2014a). Such a DIST should be readily available for use in UDL studies, but it is not a part of this document. Reference in this regard is given to Kralisch, Zander & Flügel (2013).

Following the outline just presented, a stepwise UDL framework as shown in Figure 4 is proposed; it is explored in subsequent paragraphs.

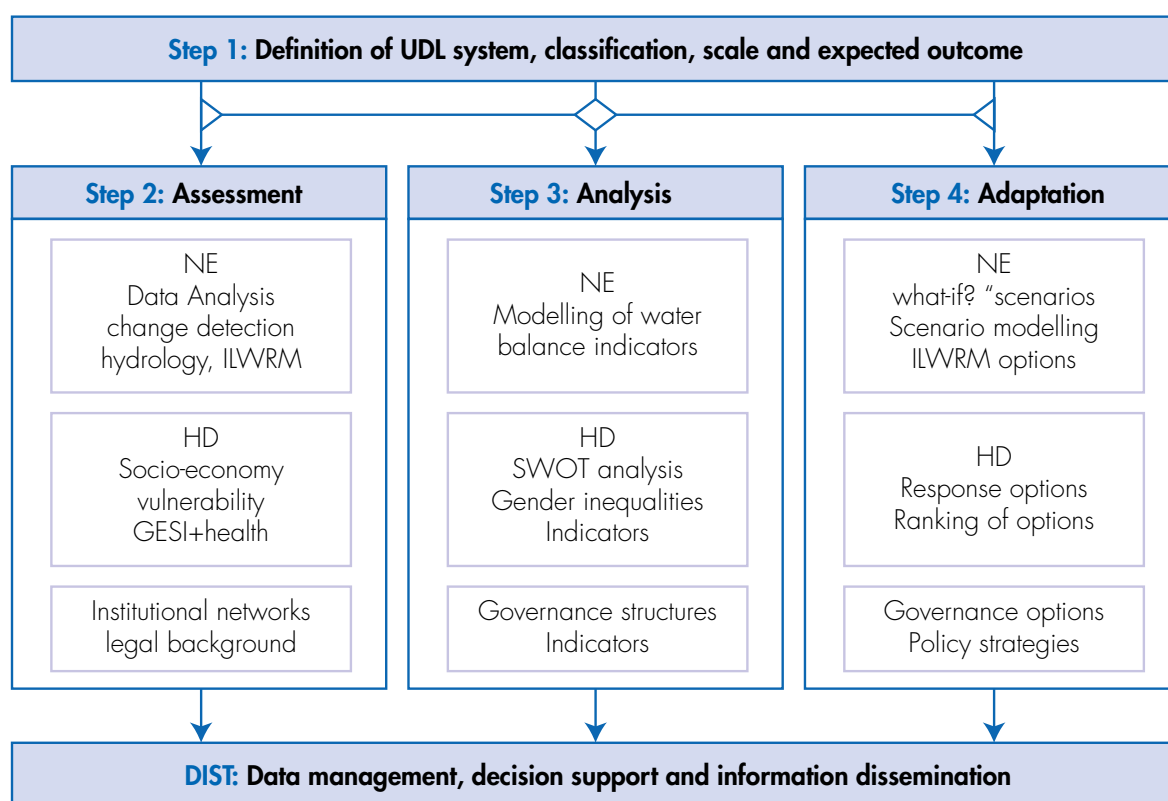


Figure 4: Stepwise framework guide for multi-scale UDL system definition, assessment, analysis, and adaptation

Note: NE = Natural Environment; HD = Human Dimension; GESI = Gender Equality and Social Inclusion; SWOT = Strengths, Weaknesses, Opportunities, Threats.

3.2.1. Definition of UDL System with Respect to Scale and Outcome

The precise definition of the UDL system to be studied is of paramount importance to the framework application and a detailed assessment and analysis. In defining the UDL system the generic component knowledge described in Figures 2 and 3 is relevant.

The definition of the UDL system must include the following elements:

- **Specification of UDL problems**, for analysis and evaluation by the framework application. Their priority ranking with relation to the NE and HD of the system will steer the subsequent framework application regarding ILWRM, and ecological or socio-economical interpretations.
- **Regional classification**, which describes the geographical reference to which the UDL system belongs. For example, the Brahmaputra River basin is part of the Himalaya and the Gandaki River basin is a tributary of the Ganges River.
- **Scale of analysis**, specified by naming the respective region like HKH, Himalaya, or main river basin like the Gandaki River catchment. For meso and macro-scale UDL systems, complementary representative, smaller scale tributary catchments should be included to allow for a detailed process analysis.
- **Expected outcome**, of the UDL analysis, which is related to problem priority ranking but needs precise specification. The latter must match, firstly, the scale of analysis and, secondly, the resolution of the input data, which define the application of the results of the analysis. Findings from representative tributary studies need regionalization up to the scale of the UDL system.

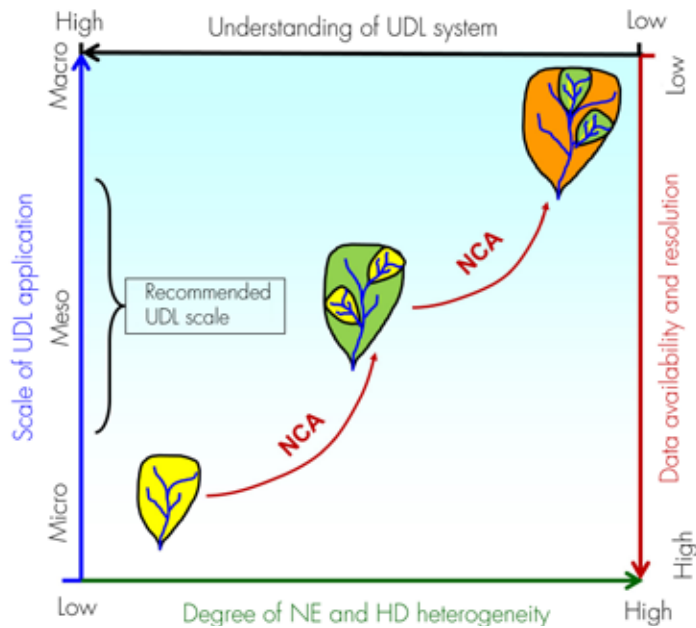
From the passages above it is obvious that the thematic subject of an UDL system analysis and the respective scale of a study are strongly interlinked. A general rule is that the complexity of UDL systems and the associated data volume to be analysed increase substantially with scale. There is a clear constraint of data processing with increasing scale, as data availability as well as resolution decreases with increasing scale.

This interdependence is schematically shown in Figure 5 and described as follows:

- While the heterogeneity of the NE and its HD increases with scale, data availability and resolution have a reverse trend. The current understanding of UDL system dynamics is reverse to the degree of its NE and HD heterogeneity. It is low in macro-scale UDL systems with a high degree of heterogeneity and high in micro-scale UDL systems with a low degree of NE and HD heterogeneity.
- Micro-scale UDL systems have a low degree of NE and HD heterogeneity and require data with a high spatial and temporal resolution. They provide a vast amount of detailed process knowledge, but its regionalization is still a challenge.
- Meso-scale UDL systems have a moderate degree of NE and HD heterogeneity. Sufficient data with moderate temporal and spatial resolution are available such as daily data-time series, satellite images, DEM data, socio-economic information, and end-user networks.
- Macro-scale UDL systems have a high degree of HD and NE heterogeneity and are analysed by means of data with low temporal and spatial resolution. Because of constraints regarding data availability, computing power, and software capabilities, they require the transfer of a meso-scale system understanding by means of the nested catchment approach (NCA).

In **conclusion**, Figure 5 suggests for the definition of UDL systems:

1. Identify and define UDL systems in such a way that they relate to scales with sufficient data availability. Some UDL system subjects may best be studied on a micro-scale like the impact of infrastructures. Others, like the impact of climate change, need a meso or even macro-scale UDL system dimension to yield realizable analysis results.



2. A meso and macro-scale UDL systems analysis needs to integrate knowledge available from lower scale studies by means of the NCA to the river components and CLZ shown in Figure 2 and 3, in which the UDL changes are expected to affect the system.

3. Because of NE and HD heterogeneity as well as constraints in data availability, computer power, and software capability, the scale definition of UDL systems should aim predominantly for the scale range shown in Figure 5.

Figure 5: Interdependence between UDL system scale and data availability in the HKH
Note: NCA = Nested Catchment Approach

3.2.2. Assessment

The overall objective of this component is to assess and quantify the UDL system environment by means of observations and measurements of NE and HD features that relate to the UDL definition. As shown in Figure 4 an assessment includes these components: (1) NE assessment, (2) HD assessment, and (3) institutional networks, described below. Field campaigns for ground truth validation are an important component of this assessment of the NE and HD. They must include all basin CLZs likely to be affected by UDL changes.

The assessment describes, quantifies, and evaluates the present UDL system. It identifies trends of changing environment features including climate, LULC, and water resources availability and also socio-economy, vulnerability, and institutional and end-user networks.

3.2.2.1. Natural Environment (NE)

The majority of UDL systems addresses the impacts of the changing climate, LULC, and sediment loads. They may also look at the effects of infrastructure on the hydrological dynamics of the river systems with respect to the availability and quality of water resources in downstream regions. Consequently, an NE assessment may be subdivided into an analysis of the following datasets:

- Times series of available discharge data from gauging stations within the UDL system provided by national hydrological services.
- Measured climate station data provided by national meteorological services.
- Modelled climate data provided by various distributors like the Watch Forcing Data ERA-Interim (WFDEI) dataset and further adapted for the Himalaya region by Lutz et al. (2016) as part of the Hi-AWARE programme.
- LULC classifications derived from satellite remote sensing and offered from different providers like the Globeland30 (GL30) project from the National Geomatics Center of China (NGCC).
- Digital Elevation Model (DEM) derived from, for instance, the Shuttle Radar Topography Mission (SRTM).
- Optical satellite images for the classification of landslides and road cuts as major contributors of sediment.

- Assessment of present ILWRM in place and identification of present and future water allocation deficits by using tools such as the Lund-Potsdam-Jena managed Land (LPJmL) model and the Water Evaluation and Planning (WEAP) tool.

The resolution of the data in time and space depends on the scale defined for the UDL system.

Measured and modelled data must pass a thorough data quality check comprising homogeneity, consistency, and plausibility. Data that has passed this check each analysed, **first** to describe the status of the hydrological and climate system and **second** to identify and quantify trends of changes by means of respective indicators. In order to carry out the future assessment of changes such as a future hydrological regime, a calibrated and validated hydrological model is required.

Field campaigns are of essential importance to validate the UDL system definition as well as the assessment of the different system features of the NE and its HD. Such field verifications are very effective at smaller scales and provide system understanding to be applied for larger ones.

LULC classifications provided by the different sources do not always supply the classification needed for the UDL subject and the hydrological modelling. They need adaptations by means of overlay analysis done in a Geographic Information System (GIS) and application of the CLZ concept of Figure 3 to the DEM of the river system.

The result of such an analysis is shown for the Beki River catchment, India in Figure 6. This LULC classification scheme is recommended for the LULC assessment of other river catchments and basins of the HKH as well. However, studies related to crop water requirement will apply a classification based on the water use of rainfed and irrigated crops.

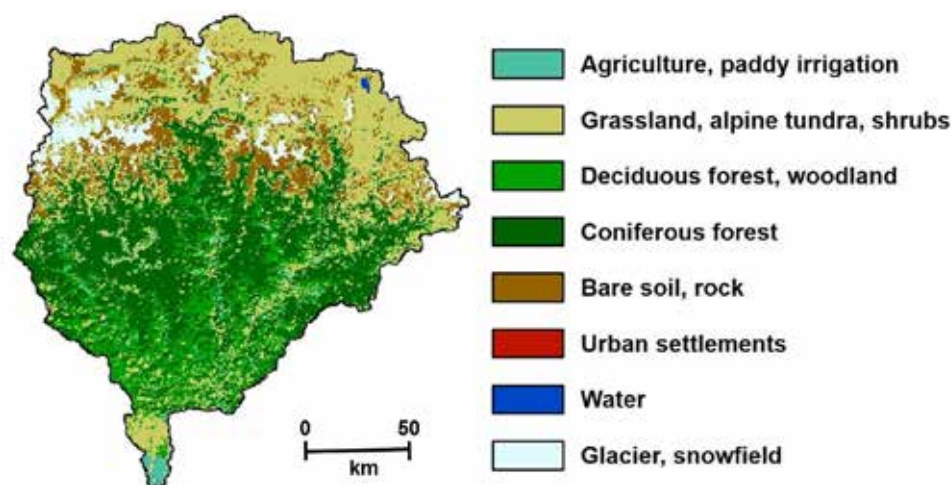


Figure 6: LULC classification for the Beki River catchment adjusted by applying the CLZ concept to the GL30 and SRTM-DEM data

3.2.2.2. Human Dimension (HD)

The aim of an HD assessment is to characterize and quantify the components of the human dimension related to a UDL system, especially those that are likely affected by changing UDL dynamics quantified by an assessment of the natural environment.

An HD assessment may be divided into the following components:

- Mapping of key socio-economic factors, socio-economic development, and community water-resource management within the UDL system and in particular downstream, where the impacts of UDL changes are expected.

- Vulnerability mapping of local and regional socio-economic factors that are of relevance for the expected UDL system changes. Also those that will likely endanger livelihood, property, infrastructure, and health from flooding, riverbank erosion, drought, GLOFs, and water stress during the dry season.
- Determining ongoing and historical trends and shifts between traditional livelihood and land use, settlement and migration, human health, and vulnerability in both mountain and low-land environments to provide a context for outline forecasting.
- Identifying policy relevant needs relating to improved human health, livelihoods, poverty alleviation, the establishment of Gender Equality and Social Inclusion (GESI), and human security.

Again, field campaigns are essential to carry out an institutional analysis and identify end-user networks and key stakeholders.

3.2.2.3. Institutional Networks

An institutional network assessment is part of the governance analysis. It will identify key stakeholder and end-user networks at the level of the UDL system and in particular in downstream regions likely to be affected by the UDL system changes.

Water allocation is dependent on water availability and its legal background is made up of laws, contractual regulations, and international treaties. This background needs to be explored, classified, and quantified with respect to its scale of application.

3.2.3. Analysis

This component involves applying the information and findings that have emerged from the NE and HD system assessments described above. Its overall objectives are threefold: (1) designing a model of the present NE of the UDL system, for example of the hydrological dynamics of rainfall runoff and the regeneration of water resources; (2) carrying out a SWOT (Strength, Weaknesses, Opportunities, and Threats) analysis of UDL-relevant HD components; and (3) analysing and classifying existing governance structures.

Results are classified by means of indicators, and the analysis components have been described in Figure 4.

3.2.3.1. Modelling the NE

The objective of this component is to set up and apply a model to reflect the measured reality of the UDL system on the temporal and spatial scale of the input data provided by the NE assessment. The most common modelling task is the rainfall-runoff modelling of a UDL river system, but other models such as water quality, melt runoff, inundation, ground water, sediment transport might be required as well, depending on the UDL subject to be analysed.

Careful attention must be paid to the selection of the best-suited model considering the following selection criteria related to the scale and definition of the UDL analysis:

1. Is the model appropriate for application on the scale defined for the UDL analysis?
2. Do the process dynamics simulated by the model fully match with the processes relevant for a UDL system analysis?
3. Does the distribution concept applied by the model suit the regionalization required by the scale of the defined UDL system?
4. Can the model work with the temporal and spatial resolution of the input data provided by the NE assessment?
5. Can the model provide the expected output defined for the UDL system analysis?

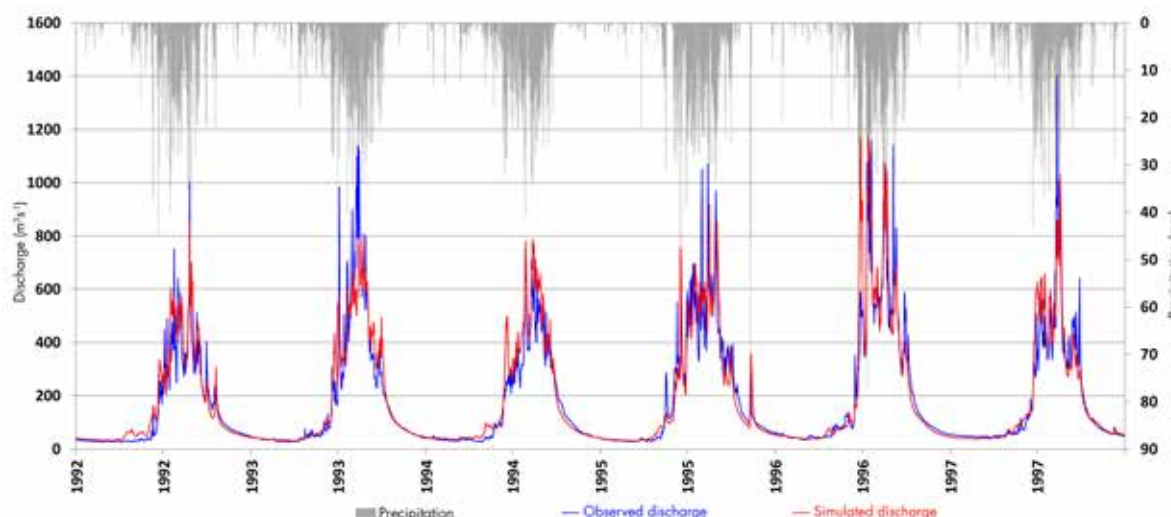


Figure 7: Result of a rainfall runoff simulation for the Dudh Koshi River in Nepal by applying the J2000 model. (Source: Nepal, et al., 2014b)

Apart from the criteria listed above, the resources of project time and funding, and computational facilities are additional criteria to be considered when choosing the appropriate model for the analysis of the defined UDL system.

Then modelling of the present UDL system status may proceed by carrying out the following steps:

1. Pre-processing of the input data and set-up of the model system.
2. Defining modelling strategies, and division of input data into model adaptation, calibration, and validation phases.
3. Parameter optimization, sensitivity analysis, classification of fit between modelled and measured data time series, and model evaluation with respect to the ability of the model to reflect measured realities such as discharge data.
4. Ultimately, indicators are defined to evaluate the model results with respect to the defined output of the UDL analysis.

The result of such a model exercise is presented in Figure 7 for the Dudh Koshi River in Nepal showing the ability of the hydrological model to represent hydrograph dynamics.

3.2.3.2. SWOT Analysis of the HD

An HD analysis focuses on the likely consequences of expected changes in UDL. It will develop further understanding of the socio-economic and social realities of the UDL system likely being affected by the UDL changes.

This is realized by means of a comprehensive SWOT analysis of present:

- socio-economic key components such as irrigation-based agriculture or hydropower;
- social inequalities, and an analysis of the role that social inequity plays in adaption mechanisms;
- traditional roles of women and men in water resources management with respect to water quantity, quality, accessibility, resource allocation, and use; and
- inherent capacities to adapt present water management in response to a likely change in water resources availability and/or quality.

There are alternatives to SWOT analysis as well, such as SOAR (Strengths, Opportunities, Aspirations & Results), SOPA (Strengths, Opportunities & Positive Action), SCOC (Strengths, Challenges, Opportunities Challenges) which can be used depending upon the specific situation of the UDL system. However for the purpose of this framework, only the SWOT analysis approach is described.

This component will also initiate the integration process by identifying interdisciplinary indicators, setting out the present ILWRM status of the components from the NE and its HD, and characterizing their ability to quantify UDL system changes, vulnerability, adaptation capacity, and relevance to response options.

3.2.3.3. Governance

Analysis in this component will focus on those regions of the defined UDL system that likely will be affected by UDL changes. It comprises (1) the effectiveness of governance such as institutional and regulatory frameworks, and (2) decision-making structures relevant to public water supply, agriculture, hydropower, human health, and the environment.

3.2.4. Adaptation

The adaptation component applies the findings from the NE and HD system analysis and develops alternative adaptation strategies to mitigate UDL system changes. The overall objectives are threefold (see Figure 4):

1. Model 'what-if?' change scenarios and execute quantification of impacts on the UDL system in respective ILWRM options,
2. Conduct a participatory evaluation and rank alternative adaptation options, and
3. Propose policy strategies to adapt institutional and regulatory structures to support the implementation of adaptation strategies.

3.2.4.1. Modelling of 'What-if?' Scenarios and ILWRM Response Options

Observed and modelled trends of system change are compiled into a set of alternative 'what-if?' change scenarios and respective input data time series are prepared for input into the validated model. As an example of 'what-if?' climate-change scenarios climate model projections or trend-modified observed data may be applied as climate forcing, for a hydrological basin model.

The 'what-if?' scenario modelling exercises will yield respective change scenarios as input into the development of ILWRM response options addressing the defined subjects of the UDL system to be evaluated.

3.2.4.2. Response Option Ranking

The 'what-if?' scenario ILWRM response options are presented to the respective end-user and institution networks involved to implement adaptive ILWRM measures. Experts and stakeholder groups will further evaluate these options obtained by means of expert opinion such as the Delphi approach. This is an approach for achieving convergence of opinion concerning real-world knowledge solicited from experts within certain topic areas (Hsu and Sandford 2007). This approach ranks the options according to their potential for successful implementation.

It is an iterative process and implies continuous feedback discussions between all groups, which means experts, end-user networks, planners, and decision-makers involved.

3.2.4.3. Governance

The governance component evaluates whether the existing institutional and regulatory network, the legal background, and the policy strategies in place are sufficient to support the implementation of the priority-ranked ILWRM response options. Based on this evaluation relevant improvements and governance adaptations are proposed.

3.3. Framework Guide

With reference to the methodological steps shown in Figure 4, the methodology component structure of the UDL framework is summarized in a tabular guide shown in Table 1. It is restricted to the general component structure of the UDL framework in Figure 4 explained earlier and may be applied to compile a UDL system study for a particular UDL subject and system scale.

Table 1: Framework guide for multi-scale application of the UDL framework

Step	Component	Description of framework activities
1	UDL definition	Define UDL system, specify scale, expected changes and impacts: <ul style="list-style-type: none"> Specify and describe the UDL system in the context of the HKH region; Specify basin component and CLZ where likely changes are dominant; and Specify expected ILWRM impacts, scale, and dominant CLZ.
2	NE assessment	Describe, analyse, and evaluate NE features related to the UDL system: <ul style="list-style-type: none"> Collect data with resolution adjusted to the defined UDL scale; Check and analyse data for quantification of present system status; Identify system changes, and quantify and evaluate trends; and Quantify hydrological system and identify ILWRM in place.
	HD assessment	Describe, analyse, and evaluate HD features related to expected UDL changes: <ul style="list-style-type: none"> Identify socio-economic components likely affected in their CLZ; Classify vulnerability of socio-economic and social components; and Identify social inequities, gender roles and health, and how they will be affected by expected UDL changes.
	Networks	Identify institutional and end-user structures and legal background for ILWRM and water allocation in place
3	NE modelling	Design a model of present status of UDL river system: <ul style="list-style-type: none"> Identify what is to be modelled; Select appropriate model; Prepare input data and setup model; Modelling, parameter optimization, validation, and model evaluation; Analyse and evaluate modelled water balance; and Define indicators to quantify hydrological system status.
	SWOT analysis	Carry out SWOT analysis to improve understanding of impacts of the UDL system changes on <ul style="list-style-type: none"> Key socio-economic components; Social inequalities and their role in the adaption mechanisms; and Traditional gender roles and capacities to adapt to UDL changes.
	governance	Specify effectiveness of governance with respect to <ul style="list-style-type: none"> Institutional and regulatory frameworks; and Decision-making structures relevant for public water supply, agriculture, hydropower, human health, and the environment.

4	NE 'what-if?' scenarios and ILWRM options	Develop mitigating ILWRM strategies by <ul style="list-style-type: none"> • Compiling and modelling of 'what-if?' scenarios of UDL system changes; and • Development of alternative ILWRM response options for mitigation.
	HD response option ranking	Evaluate the ILWRM response options by <ul style="list-style-type: none"> • Experts assessment and ranking; and • Delphi processes for ranking by end-user networks.
	Governance	Evaluate the governance in place to <ul style="list-style-type: none"> • Support the implementation of the ranked ILWRM response options; and • Identify deficits to propose governance improvements.

3.4. Framework Project Structure

The UDL framework structure shown in Figure 4 and conceptualized in Table 1 is best implemented by means of interdisciplinary UDL projects. The generic structure of such a project is shown in Figure 8 and described as follows:

1. Definition of the UDL system and its expected priority-ranked changes are the base for a regional scale for a UDL change analysis.
2. This UDL definition is discussed and eventually modified at a first workshop (WS1) attended by all groups involved in the analysis.
3. Feedback from WS1 initiates step 2 of the framework. It is essential that during the system assessment continuous feedback takes place between the different components to ensure interdisciplinary cooperation.
4. Deliverables (DI) from the system assessment in step 2 are evaluated in a second workshop (WS2) attended by project members and key end-users.
5. Feedback from WS2 then initiates step 3 of the framework, which is producing a model of the UDL system. Feedback is important to support interdisciplinary understanding of the methodological approaches and to generate the synergy required for this component.
6. Deliverables from step 3 are reported in workshop WS3, attended by project partners, key stakeholders, and representatives of end-user organizations.
7. Feedback from WS3 guides the framework activities in the final analysis - step 4 of the framework project. Representatives from institutions and end-user organizations, who likely will be affected by the expected UDL system changes, are involved in the evaluation and ranking of the proposed response options. Governance institutions, decision and policy makers in turn will be integrated in the governance analysis.
8. The results of the adaptive framework component are presented in workshop WS4 to representatives of key stakeholders, end-user and institutional networks, ILWRM managers, decision and policy makers as well as representatives of communities involved.
9. All outcomes produced by step 2 through step 4 must be put into the project DIST, and made available to all involved in the framework project study.

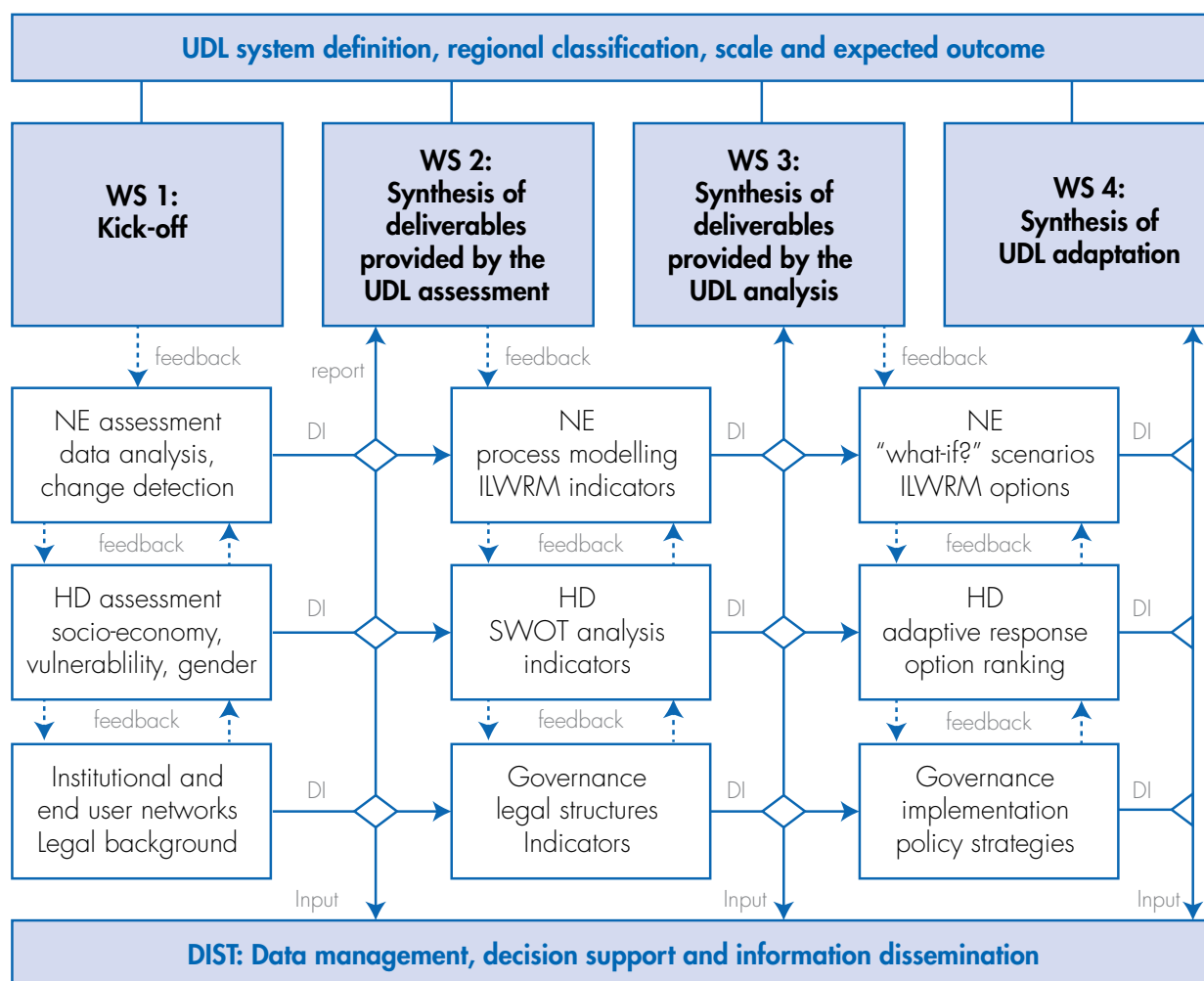


Figure 8: Design of a multi-scale UDL analysis project applying the framework guide methodology

Note: WS = Workshop, DI = Deliverable



4. Common UDL Scenarios in the HKH Region

As a practical application of the framework, four UDL system scenarios that are common in the Himalayas have been discussed in detail in a literature review provided by Nepal et al. (2014a, 2018). The framework will be applied to each of them in the following sections. It should be noted, though, that in reality each UDL system has an individual setup of river system features that cannot be reflected by a generic framework design.

To guide the application of the framework listed in Table 1, some general remarks are given for each framework step in each of the four scenarios.

4.1. Impacts of Changing LULC on Water Resources

Changing LULC is an ongoing process throughout the HKH region, and comprises:

- Firstly, the transfer of forested land into agriculture, either as a component of traditional slash-and-burn agriculture or a response to increasing population density, raising the need for more food production.
- Secondly, forest degradation by exploiting forests for firewood through pruning and removing smaller brushwood undergrowth.
- Thirdly, the continuous transfer of farmland, wetlands, or fallow land in the hinterland of cities into urban settlement.

As schematically shown in Figure 9 each LULC, such as forest, agricultural fields, wetlands, and settlements, is acting in a specific way within the hydrological cycle, when transferring the precipitation input individually to

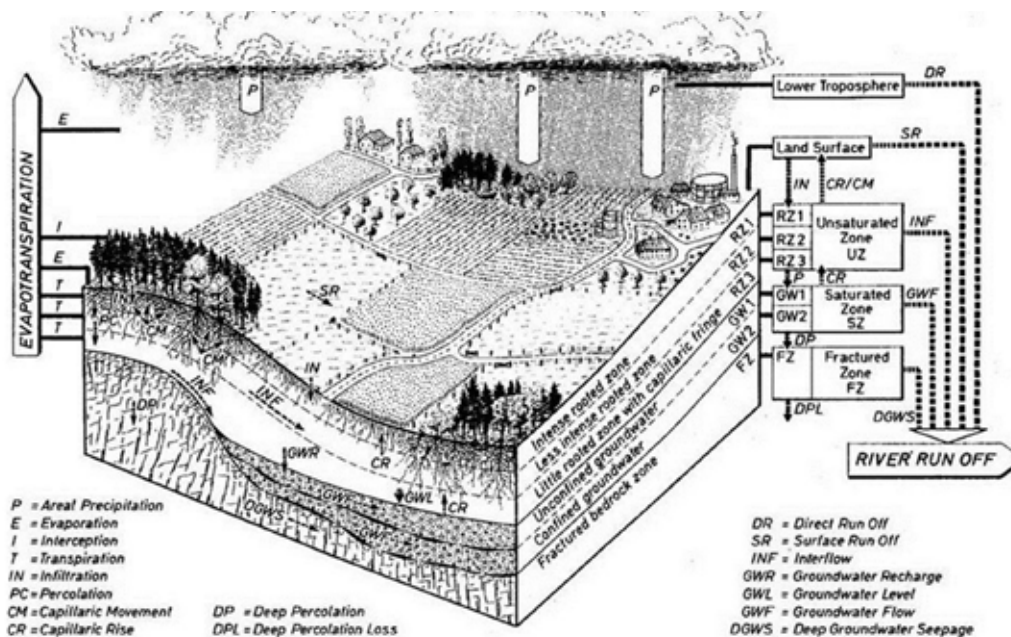


Figure 9: Schematic presentation of the hydrological process dynamics active in various LULC situations that transfer precipitation input into output components - evapotranspiration, and sub-surface and surface runoff (Source: Flügel, 1996)

evapotranspiration and the different surface and sub-surface runoff components. Changing LULC within such a system is modifying the input-output transfer dynamics and will affect the runoff generation of the system as a whole.

Such impacts of changing LULC must reach a significant magnitude with reference to the scale of the UDL system, before they can be identified from measured or modelled runoff time series data. Therefore, UDL systems of this kind are studied preferably in micro-scale or small meso-scale river systems.

4.1.1. Remarks on the UDL Definition

When defining the scale of the UDL system to study impacts of changing LULC on water resources the following factors must receive consideration:

1. The process of a changing LULC is a continuous one. It is not captured well by remote-sensing based LULC classification available for the macro-scale of the Himalayas. Such methods of classification have not provided satisfactory results to date, particularly at a local scale.
2. Transfer of forest to agriculture – and reverse recession, if fields are abandoned again after a couple of years – is largely limited to the subtropical, temperate, and subalpine zones (Figure 3). In total it is quite small, when compared to the macro-scale of the Indus, Ganges, and Brahmaputra river basins.
3. River basin models can only capture changing hydrological dynamics related to changing LULC, if the areas concerned are of a magnitude that relates to the scale of analysis. Otherwise, the impacts are masked by the bias between measured and modelled runoff data.

In conclusion, it is recommended to focus on such river systems where the areas of LULC changes are significant compared to the scale of the UDL system. The latter should range between micro and smaller meso-scales.

4.1.2. Remarks for the Assessment

The crucial assessment component is the classification of LULC and its changes at least within the past 30 years. The NE assessment requires substantial fieldwork and field campaigns in all CLZs of the UDL system as a prerequisite for this framework component.

The defined UDL system scale and the scale of LULC changes require the use of higher resolution satellite LULC classifications with at least 30 m spatial resolution. The LULC satellite classification shown in Figure 6 is recommended for the first approach.

LULC change detection that needs to be done for the analysis, faces the following challenges:

- Forest types as shown in Figure 3 are difficult to classify.
- It is not always possible to distinguish on satellite images between vegetated farm fields, grassland, or forest areas.
- Ploughed farm fields are often classified as ‘bare soil and rock’ instead of ‘agriculture’.

The hydrological model appropriate for this analysis must

- firstly apply a process-based distribution of model entities like the Hydrological Response Unit (HRU) concept in the modelling system, and
- secondly, be capable of simulating all hydrological processes related to the LULC of the catchment as shown in Figure 9.

To run the model, observed or modelled hydro-meteorological time series must be available that covers the time period set by the LULC change classification, e.g. 30 years. Historical climate datasets for the Indus, Ganges, and Brahmaputra river basins generated by Lutz et al. (2016) as a part of the Hi-AWARE project might be useful for such an assessment.

As the meteorological infrastructure is not always sufficient and time series data often are inconsistent, the application of modelled climate-input data is a recommended alternative. This data, however, needs to be bias corrected with respect to temperature and precipitation. The historical dataset by Lutz et al. (2016), referred to in the previous paragraph is bias corrected and may be useful for many different purposes. The data may need further correction for a specific geographic area.

The delineation of model entities requires additional GIS data layers like soils and a DEM. Both are available from public domain (PD) sources such as the Harmonized World Soil Database (HWSD). Soils provided by the HWSD need to be adapted to the CLZ with respect to texture and permafrost.

4.1.3. Remarks for the Analysis

Careful parameterization of the LULC-related model parameters is required to simulate forest-related processes of evapotranspiration and runoff generation as accurately as possible for the detection of LULC-related runoff change.

Crop rotation and irrigation management must be studied from farmers, to be considered in the model input data and development of LULC parameterization. Models such as the LPJmL might be useful. It has been successfully applied for irrigation water demand for crop-specific seasonal estimates in South Asia as part of the HI-AWARE project (Biemans, Siderius, Mishra, & Ahmad 2016).

4.1.4. Remarks for the Adaptation

If the identified LULC changes are not summing up to a significant portion of their respective end-users of CLZ, surveys become increasingly important to support indistinct model signals.

4.1.5. The UDL Framework Application

Adjusted to the LULC related UDL analysis, the respective framework components are listed in Table 2.

Table 2: Framework application for UDL impact analysis of a changing LULC

Step	Component	Description of framework activities
1	UDL definition	<p>Define changing LULC-UDL system at micro or small meso scale catchment level, specify expected changes and likely impacts of runoff and water resources:</p> <ul style="list-style-type: none"> Describe relevance of UDL system with reference to higher regional scale within the HKH region; Specify basin component and CLZ where likely changes are dominant; and Specify expected ILWRM impacts, scale, and dominant CLZ.
2	NE assessment	<p>Describe, analyse, and evaluate NE features related to the UDL system:</p> <ul style="list-style-type: none"> Hydro-meteorological input data of daily time steps from measured and modelled climate data; Check data and correct bias to quantify present system status; Identify system changes, quantify and evaluate runoff and LULC trends; and Quantify hydrological system and identify ILWRM in place by means of field campaigns.
	HD assessment	<p>Describe, analyse, and evaluate HD features related to expected UDL changes:</p> <ul style="list-style-type: none"> Identify socio-economic components likely affected in their CLZ; Classify vulnerability of socio-economic and social components; and Identify social inequities, gender roles, and health, and how they will be affected by expected UDL changes.
	Networks	<p>Identify institutional and end-user structures and legal background for ILWRM and water allocation in place.</p>



3	NE Modelling	Develop model of present status of UDL river system: <ul style="list-style-type: none"> • Select appropriate model with special emphasis on LULC related processes; • Prepare input data and setup model; • Execute modelling, parameter optimization, validation, and model evaluation; • Analyse and evaluate modelled water balance; and • Define indicators to quantify hydrological system status
	SWOT Analysis	Carry out SWOT analysis to improve understanding of impacts of the UDL system changes on <ul style="list-style-type: none"> • Key socio-economic components; • Social inequalities and their role in the adaption mechanisms; and • Traditional gender roles and capacities to adapt to UDL changes.
	Governance	Specify effectiveness of governance with respect to <ul style="list-style-type: none"> • Institutional and regulatory frameworks related to LULC management; and • Decision-making structures relevant for public water supply, agriculture, hydropower, human health, and the environment.
4	NE 'what-if?' scenarios and ILWRM options	Development of adaptive ILWRM option by <ul style="list-style-type: none"> • Compiling and modelling of 'what-if?' scenarios of LULC system changes; and • Development of alternative ILWRM response options for mitigation.
	HD response option ranking	Evaluation of the ILWRM response options by <ul style="list-style-type: none"> • Experts' assessment and ranking; and • Delphi processes for ranking by end-user networks
	Governance	Evaluation of the governance in place to <ul style="list-style-type: none"> • Support the implementation of the ranked ILWRM response options; and • Identify deficits to propose governance improvements.

4.2. Impacts of Erosion and Sedimentation

The sediment load of a river system comprises coarse bed load and fine suspended load. Sedimentation always occurs if the river flow is not capable any more of carrying the sediment load delivered from upstream areas. This is the case if the river gradient is dropping after entering the floodplain and also when flow recedes. Sedimentation on the floodplain can be beneficial if the sediment is fine and fertile, but is destructive if sandy sediment is dropped on fertile farmland turning the latter into useless fallow land and thereby threatening the livelihoods of smallholders and farmers.

4.2.1. Remarks for the UDL Definition

The sources of the sediment load in the river are erosion and denudation, both summarized herein as erosion. Different kinds of erosion are dominant in different CLZs:

- Rockslides and solifluction in the permafrost regions of the higher alpine and the non-glaciated cryosphere zones.
- Landslides occur in all the other CLZs except for the tropical floodplain, triggered by
 1. geo-tectonic activities and river bank erosion at the foot slopes, both related to the continuous uplift of the small Himalaya mountain ridge;
 2. road construction cutting into the steep slopes;

3. degrading forest by firewood collection; and
 4. LULC change from forest cover to agriculture.
- Erosion of finer soil material from agricultural fields during flooding irrigation and heavy monsoon rainstorms in all CLZs.

Except for the solifluction processes, what all other kinds of erosion have in common is that they are discontinuous and are triggered by heavy monsoon-generated rainstorm events. They generate interflow (Figure 9) within the slopes that is wetting potential slipping layers within the weathered bedrock from which the material above slips downwards. Thin clay layers in the weathered bedrock below the slope debris support this process, as was the case in the landslide shown in Figure 10 that had occurred in Bhutan.

Landslides are a major source of sediment input into the stream network and their occurrence is hard to predict by deterministic process models. They provide vast amounts of sediment to the stream networks.

Figure 11 also reveals that the channel system of the stream network is acting as a temporary sink for sediment. This sediment is taken up again through a natural event, when flow increases during the summer monsoon, until the reground material eventually reaches the floodplain. There it either is deposited during floods or reaches the receiving main stream of the Indus, Ganges, or Brahmaputra respectively.



Figure 10: Landslides in the Lesser Himalaya of Bhutan



Figure 11: Sediment deposition in the floodplain areas of the Sun Koshi River in Nepal

4.2.2. Remarks for the Assessment

Sediment load in the narrow stream network of the Higher Himalayas is mainly bed load. This coarse material is reground down to the sand and silt fraction in the process of transportation to the floodplain, where the sediment load is mainly suspended load.

Quantification of the sediment load is mostly done by measurements at gauges near the floodplain, which quantify the suspended load through collected water samples. If discharge measurements are done simultaneously with sediment sampling, a correlation between discharge and sediment load may be expected. Such correlations were established in an unpublished study for the Brahmaputra River at the gauge station 'Pandur' near Guwahati ($r = 0.8028$), and for its tributaries the Baralia ($r = 0.85$) and Pagladia Rivers ($r = 0.93$) at their gauge station, the 'NH31-bridge'.

For change detection, aerial photography or satellite image analysis can establish trends of landslide development, but their quantification for sediment input to the stream network requires a DEM of fine resolution.

End-user consultations are an additional important method to identify vulnerability during flood periods and to quantify loss of farmland by sand deposition and riverbank erosion. The latter is a result of river braiding on the sediment cone of the river, when it enters the floodplain and drops part of its sediment load.

4.2.3. Remarks for the Analysis

Because of the constraints described for this UDL system, assessment-process based modelling of sediment load and sedimentation alternatively may be replaced by a conceptual model. The latter combines the trends of landslides established from the satellite classification with the statistical relationships between runoff and sediment load, and the frequency and magnitude of summer monsoon rainstorms.

The SWOT analysis will receive special attention, because the input provided by the conceptual sediment model is qualitative for the most part. Protection against floods and riverbank erosion is a major focus of such a SWOT analysis.

4.2.4. Remarks for the Adaptation

The development of 'what-if?' scenarios will be based on qualitative sediment input trends developed and analysed in the previous framework steps. If a relationship with the frequency and magnitude of summer monsoon rainstorms was established, then climate change impacts must be considered as well, and the same applies for a changing LULC.

The governance component has to consider the origin of the sediment load. In case it is from landslides not triggered by human activities, such as road construction and mining, the focus ought to be mainly on flood protection. In case LULC changes and road construction are the basic causes, land management policies must address this issue as well.

4.2.5. UDL framework Application

Adjusted to the sediment-related UDL analysis the respective framework components are listed in Table 3.

Table 3: Framework application for UDL impact analysis of changing erosion and sedimentation

Step	Component	Description of framework activities
1	UDL definition	<p>Define erosion and sedimentation of the UDL system at the micro-scale catchment level, specify expected changes and likely impacts on water quality and sedimentation:</p> <ul style="list-style-type: none"> Describe the UDL system with reference to higher regional scales within the HKH region; Specify basin component and CLZ expected changes that are dominant; and Specify expected ILWRM impacts, scale, and dominant CLZ.
2	NE assessment	<p>Describe, analyse, and evaluate NE features related to the UDL system:</p> <ul style="list-style-type: none"> Geological strata and geo-tectonic activity; Anthropogenic and natural causes of landslides; Measured sediment load data and their statistical relationship with runoff; and Aerial photography and satellite image classification of landslides. <p>Identify system changes, quantify and evaluate landslide dynamics by means of field campaigns.</p>
	HD assessment	<p>Describe, analyse, and evaluate HD features related to expected UDL changes:</p> <ul style="list-style-type: none"> Identify socio-economic components likely affected by landslides; Classify vulnerability of socio-economic and social components; and Quantify loss of farmland by sedimentation and riverbank erosion.
	Networks	Identify institutional and end-user structures involved



3	NE Modelling	<p>Conceptual model presents status of UDL river system:</p> <ul style="list-style-type: none"> • Develop conceptual model combining trends from satellite classifications with statistical relationships between sediment load and runoff; • Prepare input data and setup model; • Identify and quantify probability ranges of landslides and their location in respective CLZ; and • Define indicators to quantify erosion and sedimentation system status.
	SWOT Analysis	<p>Carry out SWOT analysis to improve understanding of impacts of the UDL system changes on</p> <ul style="list-style-type: none"> • key socio-economic components with focus on infrastructures and irrigation agriculture; • social inequalities and their role in the adaption mechanisms; and • traditional gender-based roles and capacities to adapt to UDL changes.
	Governance	<p>Specify effectiveness of governance with respect to</p> <ul style="list-style-type: none"> • institutional and regulatory frameworks related to LULC management; and • flood warning and farmer compensation.
4	NE 'what-if?' scenarios and ILWRM options	<p>Development of adaptive ILWRM option by</p> <ul style="list-style-type: none"> • compiling conceptual 'what-if?' scenarios of erosion and sedimentation; • identifying research needs to improve understanding of the UDL subject; and • developing alternative ILWRM response options for mitigation.
	HD response option ranking	<p>Evaluation of the ILWRM response options by</p> <ul style="list-style-type: none"> • experts' assessment and ranking; and • Delphi processes for ranking by end-user networks.
	Governance	<p>Evaluation of the governance in place to</p> <ul style="list-style-type: none"> • support the implementation of the ranked ILWRM response options; and • identify deficits to propose governance improvements and farmer compensation.

4.3. Impacts of Climate Change on Hydrological Regimes

Climate change is an accepted and obvious process in the HKH region. This subject has a priority status in ILWRM related UDL system analysis. Because rising temperatures and the intensity of rainstorms are associated with climate change, this subject also relates to the erosion and sedimentation UDL subject discussed previously. The advices given in Sections 4.1 and 4.2 apply to this UDL system as well.

Climate change related research in the HKH is manifold and has been discussed with respect to the UDL system in the literature review in Nepal et al., (2014a, 2018). For the macro-scale Brahmaputra river basin, the European Commission had funded a comprehensive and interdisciplinary climate-change study BRAHMATWINN between 2006 and 2009. The results from this project have been published extensively (for instance, Flügel 2011; Sharma and Flügel 2015), and that project structure provides a blueprint for similar UDL projects in the HKH region.

4.3.1. Remarks for the UDL Definition

Climate change is a global phenomenon. General Climate Models (GCMs) provide input data of climate projections for the macro-scale, which are downscaled by Regional Climate Models (RCMs) to particular regions like the Himalaya. Therefore, the expected outcome of a UDL system analysis related to climate change with respect to ILWRM and water resources availability is of national and international relevance as in the Indus, Ganges, and Brahmaputra river basins.

The availability of daily measured hydro-meteorological data as well as the environmental heterogeneity of these macro-scale river basins demands complementary smaller scale studies as well. The latter capture the differences of

the hydrological dynamics between the different basin components (Figure 2) and their respective CLZ (Figure 3). Applying the NCA as shown in Figure 5 is an appropriate strategy in this regard.

In conclusion, we recommend defining climate change related UDL systems on a macro-scale river basin level and, in addition, to apply the NCA to integrate process knowledge from meso-scale catchments.

4.3.2. Remarks for the Assessment

Measured hydro-meteorological station data must pass thorough data quality control before applying them to quantify the present basin status. Modelled climate data, like those from the ERA40-Interim project, need bias correction by considering local measurements before they can be used for analysis.

The system status must be presented for individual basin components (see Figure 2) applying the NCA to identify the magnitude of climate change with respect to the basin's heterogeneity. In the Brahmaputra River basin, the latter ranges from the semi-arid headwater region in Tibet to the subtropical and tropical floodplain in Assam, India.

For the present status of LULC and topography, the satellite image information specified in section 4.1.2. for the UDL analysis related to changing LULC is appropriate as well, and the LULC classification scheme shown in Figure 6 is applicable. It might need modification depending on the LULC reality within different basin components.

For the HD assessment, it is recommended to identify representative key stakeholder and end-user networks in the meso-scale catchments used by the NCA; otherwise the assessment might lose focus. The legal background will include national as well as international frameworks of regulations and treaties.

4.3.3. Remarks for the Analysis

The model selection criteria described in section 4.1.3. applies in this case as well. In addition, special attention must be given to the model's capability to handle the meso-scale NCA catchments as well as the macro-scale river basin at the same temporal and spatial scale. This capability depends on the applied distribution concept and the computing power and software available. Parallel computing as applied, for example, by the JAMS/J2000 model within the Integrated Land Management System (ILMS) can bring about this capability.

Glacial retreat is a well-known feature in the HKH region. The analysis of the hydrological regimes within the basin and their tendency to change is of importance in the headwater region of the basin.

The SWOT analysis carried out in the meso-scale NCA catchments needs regionalization to macro-scale. This is an easy task in the sparsely populated headwater regions of Tibet and the Higher Himalaya, but becomes more complex and challenging in the Lesser Himalaya and especially so in the floodplain. The role of indicators should receive special attention in this regard.

4.3.4. Remarks for the Adaptation

'What-if?' scenarios are compiled from RCM climate projections, and projected meteorological data-time series are applied as climate forcing in the validated hydrological river basin model. The design of adaptive ILWRM options, however, must differentiate between the different basin components shown in Figure 2.

The development of appropriate policy strategies to implement best-ranked ILWRM response options needs to consider national as well as international disputes and partly diverging political interests between riparian countries.

4.3.5. UDL Framework Application

Adjusted to the climate change related UDL analysis the respective framework components are listed in Table 4.

Table 4: Framework application for UDL impact analysis of climate change in macro-scale basins applying the NCA

Step	Component	Description of framework activities
1	UDL definition	<p>Define macro-scale UDL system for climate change analysis at the basin level and specify how to apply the NCA to achieve expected outcomes:</p> <ul style="list-style-type: none"> Describe UDL system reference within the context of the HKH region; Specify expected changes and the likely impacts of runoff and water resources with respect to basin components and CLZ; and Specify expected ILWRM impacts, scale, and dominant CLZ.
2	NE assessment	<p>Describe, analyse, and evaluate NE features related to the UDL system:</p> <ul style="list-style-type: none"> Hydro-meteorological input data of daily time steps from measured and modelled climate data; Data quality check and bias correction to quantify present system status; Identify system changes, and quantify and evaluate runoff; and Quantify hydrological system and identify ILWRM in place and validate by means of field campaigns.
	HD assessment	<p>Describe, analyse, and evaluate HD features related to expected UDL changes:</p> <ul style="list-style-type: none"> Identify socio-economic components likely affected in their basin components and CLZ; Classify vulnerability of socio-economic and social components; and Identify social inequities, gender roles, and health, and how they will be affected by expected UDL changes.
	Networks	Identify institutional and end-user structures and legal background for ILWRM and water allocation in place
3	NE modelling	<p>Model present status of UDL river system:</p> <ul style="list-style-type: none"> Select appropriate model with special emphasis on climate change related processes and capability to model meso and macro scale process dynamics; Prepare input data and setup model; Modelling, parameter optimization, validation, and model evaluation; Analyse and evaluate modelled water balance; and Define indicators to quantify hydrological system status.
	SWOT analysis	<p>Carry out SWOT analysis to improve understanding of impacts of the UDL system changes in the basin components on</p> <ul style="list-style-type: none"> Key socio-economic components; Social inequalities and their role in the adaption mechanisms; Traditional gender roles and capacities to adapt to UDL changes; and Regionalize results from the NCA meso-scale to the respective basin component.
	Governance	<p>Specify effectiveness of governance with respect to the</p> <ul style="list-style-type: none"> Institutional and regulatory frameworks related to ILWRM; Decision making structures relevant for public water supply, agriculture, hydropower, human health, and the environment; and Integration of international water treaties if the scale is appropriate.

4	NE 'what-if?' scenarios and ILWRM options	<p>Development of adaptive ILWRM option by</p> <ul style="list-style-type: none"> • Compiling and modelling of 'what-if?' scenarios of CC and apply validated model; and • Development of alternative ILWRM response options for mitigation.
	HD response option ranking	<p>Evaluation of the ILWRM response options by</p> <ul style="list-style-type: none"> • Experts' assessment and ranking; and • Delphi processes and option ranking by end-user networks.
	Governance	<p>Evaluation of the governance in place to</p> <ul style="list-style-type: none"> • Support the implementation of the ranked ILWRM response options within the international river basin; and • Identify deficits to propose governance improvements.



4.4. Impacts of Infrastructures on Downstream Water Availability

This is the most common UDL system analysis and applies to hydropower reservoirs and barrages across a river for diverting irrigation water, among others. If not part of a pre-feasibility study done in the planning phase of the infrastructure, the need for such an analysis arises when downstream users feel disadvantaged in their water allocation. In past decades, environmental concerns about such structures have increasingly gained attention as well.

In many cases, hydropower generation and irrigation-based agriculture are involved in controversial disputes. These concern the operation of the reservoir as well as the volume of water demanded for release to sustain irrigation-based agriculture. Details in this regard are discussed in the literature review (Nepal et al. 2014a, 2018)

4.4.1. Remarks for the UDL Definition

The scale of such UDL river systems in the HKH region varies between the lower meso-scales and the micro scales. The scale definition for the UDL system depends on the location of the infrastructure and the size of the downstream area concerned. In many cases, the micro to meso-scale is the recommendable scale for such a UDL analysis.

4.4.2. Remarks for the Assessment

The assessment involves intense fieldwork downstream of the infrastructure comprising

- mapping of key water users, their present and planned water withdrawals, and allocation, and
- environmental flow requirements to sustain the flora and fauna of the downstream system.

Hydrological modelling is only necessary if there is a substantial runoff contribution from the catchment below the infrastructure, until the first key end-user requires water allocation.

If the micro-scale is selected, a socio-economic assessment must be done in detail. It should focus on the seasonal demand of water as specified by key water users.

4.4.3. Remarks for the Analysis

For a micro-scale UDL analysis GIS based abstraction and water allocation modelling are replacing the hydrological process model. Input data for the GIS model are the releases from the infrastructure to the stretch of the river downstream, water allocation data supplied by end-user networks, and the environmental flow requirements set by legal regulations.

The SWOT analysis must include income from hydropower generation, socio-economic development, and related water demand. Governance analysis will focus on the regulations of hydropower generation, contracted water releases, the development of water demand with socio-economic development, and on the legal representation of environmental concerns.

4.4.4. Remarks for the Adaptation

‘What-if?’ scenarios will relate to possible adaptations of water releases to end-user and key stakeholder demands and are part of the GIS model.

ILWRM response options need to be explored together with representatives from the infrastructure management, end-user networks, and environment protection agencies.

4.4.5. UDL Framework Application

The framework components adjusted to the UDL analysis of the impacts of infrastructures are listed in Table 5.

Table 5: Framework application for UDL impact analysis of infrastructures on downstream water availability

Step	Component	Description of framework activities
1	UDL definition	<p>Define UDL system to analyse impacts of infrastructures on downstream water availability at the micro or small meso-scale catchment level, specify expected changes and likely impacts on downstream water allocation:</p> <ul style="list-style-type: none"> Describe UDL system within the higher scale river system; and Specify expected downstream ILWRM impacts.
2	NE assessment	<p>Quantify, analyse, and evaluate water allocation to end-users downstream of the infrastructure:</p> <ul style="list-style-type: none"> Collect data related to the operation of infrastructure; Collect meteorological input data from nearby stations; Perform data quality check and quantification of present system status; and Identify system changes and ILWRM in place by means of field campaigns.
	HD assessment	<p>Describe, analyse, and evaluate HD features related to expected UDL changes:</p> <ul style="list-style-type: none"> Identify socio-economic development trends and related water demand; Classify vulnerability of socio-economic and social components; and Identify social stress by present water allocation and expected UDL changes.
	Networks	Identify institutional and end-user structures and legal background for water releases and water allocation in place
3	NE modelling	<p>Develop a GIS model to describe the present status of the UDL system:</p> <ul style="list-style-type: none"> Analyse and evaluate modelled water balance; and Define indicators to quantify UDL system status.
	SWOT analysis	<p>Carry out SWOT analysis to improve understanding of impacts of the UDL system changes on</p> <ul style="list-style-type: none"> Key socio-economic components; and Capacities to adapt to UDL changes.
	Governance	<p>Specify effectiveness of governance with respect to</p> <ul style="list-style-type: none"> Regulatory frameworks related to infrastructure management; and Decision making structures relevant for public water supply, agriculture, hydropower, human health, and the environment.
4	NE 'what-if?' scenarios and ILWRM options	<p>Development of adaptive ILWRM options by</p> <ul style="list-style-type: none"> Compiling and modelling of 'what-if?' scenarios; and Development of alternative ILWRM response options for water resources.
	HD response option ranking	<p>Evaluation of the ILWRM response options by</p> <ul style="list-style-type: none"> Experts' analysis of SWOT options; and Delphi processes for ranking by end-users and infrastructure managers.
	Governance	<p>Evaluation of the governance in place to</p> <ul style="list-style-type: none"> Support the implementation of the ranked ILWRM response options; and Identify deficits to propose governance improvements.

5. Priority in Framework Applications

This paper's analysis of UDL has revealed that any priority ranking of framework applications must relate first to the scale of the UDL system in question and second, to the outcome of the system assessment described in subsection 3.2.2. Based on the literature review provided by Nepal et al. (2018) and the above-stated discussions relating to the four common UDL systems in the HKH region, we recommend the following priority ranking:

1. For larger meso- and macro-scale river systems, an UDL framework analysis of climate change should receive first priority for the following reasons:

- Ongoing climate change within the Hindu Kush Himalaya region is obvious from both measured and modelled temperature time series. Models reflect respective impacts on glacial melt and permafrost in the alpine zone and the cryosphere.
- Changes in glacial melting and permafrost modify the seasonal and annual discharge dynamics of rivers and affect ILWRM with respect to preventing flooding, affecting the availability and allocation of water resources, and considering environmental flow requirements.
- Although the impact of climate change on precipitation has a greater degree of uncertainty than temperature increases, research indicates that the magnitude and intensity of rainfall events are affected. Both are relevant to ILWRM and affect erosion processes as the resultant intensified overflow often triggers landslides.

LULC changes induced by climate change have not been reported in forested areas. Farmers, however, have adapted their crop management techniques to suit higher temperatures. Since changing LULC is difficult to prove and quantify on these scales, we recommend that LULC receive lower priority ranking in these framework applications.

2. In smaller meso- and micro-scale river systems, UDL framework applications that analyse the impacts of climate change and a changing LULC are ranked equally for the following reasons:

- River systems on both scales might suffer from the impacts of climate change — flash floods, for instance, can trigger UDL system changes.
- LULC changes attributable to adaptation efforts resulting in changed land use management can equally trigger UDL system changes due to resultant modifications to runoff components.

It is the task of the system assessment to identify whether climate change or LULC change play predominant roles in triggering changes in UDL at the particular scale. The framework application ranking must be based on this assessment.

The same applies to the UDL framework ranking regarding impact from sediment load, which requires complementary fieldwork as part of the assessment work.

3. Framework applications analysing UDL impacts triggered by infrastructure construction give high priority to those river systems that already have the respective infrastructure. This system assessment will clearly relate the causes of UDL system changes to the operation of infrastructure — the release of water from reservoirs, for example, or the channelling of water through irrigation water diversions from river barrage.

This system assessment and the accompanying validating field campaigns have been important prerequisites to defining the ranking of the four UDL framework applications. The assessment provides evidence of the controlling

processes that trigger the changing of the UDL system, including the melting of permafrost and glacier retreat, changing LULC and forest degradation, sediment input, and sedimentation or environmental flow requirement, and biodiversity.

The impacts of climate change can most likely be identified at all system scales, followed by the impacts of changing LULC and sediment input. The construction of infrastructure will become predominant impacts if they are already implemented in a river basin.

6. Conclusions

This paper presents a framework for policy makers, decision makers, planners, and researchers to identify and define changing upstream-downstream linkages (UDL) in the HKH – triggered by climate change, LULC changes, erosion and sedimentation, and implemented infrastructures, which affects water availability within the UDL system. The framework proposes a structured methodology to identify, analyse, and evaluate UDL processes, and to initiate respective integrated system analysis studies with respect to sustainable ILVRM and impact mitigation. Depending on the scale, the framework can be applied to local, national, or transnational conditions and process dynamics respectively.

The UDL relationship has a multi-scale reference, since it occurs at different locations and scales, and the magnitude and nature of problems and related effects change between the local, micro catchment scale and the regional, macro river basin scale. Accounting for this multi-scale dimension, this interdisciplinary framework applies methodologies from the natural sciences, engineering, socio-economic analysis, and geoinformatics, feeding their findings into a common decision information support tool. It is implemented by means of a step-wise methodological approach elaborated in a tabular design.

The framework was discussed for four UDL system subjects in the HKH: (1) Changing LULC effects on water resources; (2) Erosion and sedimentation on downstream areas; (3) Climate change on hydrological regimes; and (4) Infrastructure development and downstream water availability.

Ultimately, a priority ranking for the framework application is recommended for the methodological implementation.

Designed as a generic concept with a focus on the HKH region, the framework applies to landscape features, for example topographic basin components, climatic landscape zones, or irrigation-based agriculture that are common in mountains, and can therefore be applied to other mountainous regions globally as well.

7. References

- Biemans, H., Siderius, C., Mishra, A. & Ahmad, B. (2016). Crop-specific seasonal estimates of irrigation-water demand in South Asia. *Hydrology and Earth System Sciences*, 20(5), 1971–1982.
- Flügel, W.-A. (1996). Hydrological response units (HRU's) as modelling entities for hydrological river basin simulation and their methodological potential for modelling complex environmental process systems. Results from the Sieg catchment. *Erde*, 127, 43–62.
- Flügel, W.-A. (2011). Twinning European and South Asian river basins to enhance capacity and implement adaptive integrated water resources management approaches – Results from the EC-project BRAHMATWINN. *Advances in Science and Research*, 7, 1–9.
- Hsu, C. & Sandford, B. (2007). The delphi technique: making sense of consensus. *Practical Assessment, Research & Evaluation*, 12(10), 1–8.
- Kralisch, S., Zander, F. & Flügel, W.A. (2013). OBIS-a Data and Information Management System for the Okavango Basin. In J. Oldeland, C. Erb, M. Finckh, & N. Jürgens (Eds.), *Biodiversity and ecology* (p. Vol. 5, 213–220).
- Lutz, A.F., ter Maat, H.W., Biemans, H., Shrestha, A.B., Wester, P., Immerzeel, W.W., 2016. Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. *Int. J. Climatol.* 36, 1–18. <https://doi.org/10.1002/joc.4608>
- Nepal, S., Flügel, W. A., Krause, P., Fink, M., & Fischer, C. (2017). Assessment of spatial transferability of process-based hydrological model parameters in two neighbouring catchments in the Himalayan Region. *Hydrological Processes*, 31(16), 2812–2826.
- Nepal, S., Flügel, W.A. & Shrestha, A.B. (2014a). Upstream-downstream linkages of hydrological processes in the Himalaya region. *Ecological Processes*, 3(19), 1–16.
- Nepal, S., Krause, P., Flügel, W.A., Fink, M. & Fischer, C. (2014b). Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalaya region using the J2000 hydrological model. *Hydrological Processes*, 28(3), 1329–1344.
- Nepal, S., Pandey, A., Shrestha, A.B. & Mukherji, A. (2018) [forthcoming]. *Revisiting key questions regarding Upstream-Downstream linkages of land and water management in the Hindu Kush Himalaya region*. ICIMOD, Kathmandu.
- P. Wester, A. Mishra, A. Mukherji, A.B. Shrestha (Eds.) (forthcoming). *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Springer: Cham, Heidelberg, New York, Dordrecht, London.
- Sharma, N. & Flügel, W.A. (Eds.). (2015). *Applied geoinformatics for sustainable integrated land and water resources management (ILWRM) in the Brahmaputra River Basin*. Springer India.
- Wolf, A. (1998). Conflict and cooperation along international waterways. *Water Policy*, 1(2), 251–265.

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