Preliminary analysis of hydroclimate and streamflow modelling in the Koshi Basin

Climate, hydrology, ecology and institutional setting

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Executive summary

The Sustainable Development Investment Portfolio (SDIP) is an Australian government initiative with the goal of increasing water, food and energy security in South Asia, targeting the poorest and most vulnerable, particularly women and girls. A key target sector is water resource management. Within the SDIP, preliminary research by CSIRO has focussed on understanding the biophysical, cultural and policy environments of the Koshi Basin in China, Nepal and India.

Part of this research examined the institutional context within which water resource management operates, using a series of semi-structured interviews. Respondents considered hydropower development as an opportunity, while on the other hand discussing the disparity of interests, values, and discourses as a challenge. The interviews suggest that within the governance context of the Koshi Basin, there is no recognised institutional framework for modelling to serve as a neutral platform to explore transboundary cooperation. There is no current institution that is considered impartial or unbiased. This limits the capacity to apply learnings on flood risk mitigation, agricultural productivity, or to avoid the cascading impacts of water resource decisions.

Since there exists no neutral platform to imagine future development scenarios, CSIRO began the process of developing an Integrated Assessment Framework (IAF) that would support policymakers consider future development scenarios. The IAF would support understanding how cumulative impacts on livelihood outcomes are possible under different future water resource development scenarios and under what circumstances these impacts may be disproportionately benefiting or disadvantaging poorest households and in particular women and girls.

This preliminary report describes the biophysical background around the Koshi Basin’s climate, hydrology, ecology and institutional setting. In-situ station observations and CMIP5 climate projections showed that temperatures were increasing and projections indicate these will likely increase in future (0.045°C/year historic). Using hydrological modelling, this study estimated that snow contributes around 7.3% of the annual streamflow at the Chatara gauge (near Nepal border), with ice melt contributing a further 2.7% (see limitations in the report). Most runoff is generated in the southern slopes of the Himalayas between 2000mASL and 3000mASL.

This report presents methods to understand how possible future water resource development scenarios might differ. The methods of streamflow characterisation and conceptualisation of streamflow to ecology relationships, help to interpret changes to streamflow between scenarios, and understand the potential impacts of different scenarios on the river ecology and livelihoods of riparian communities.

This is a preliminary analysis, focussing on the hydroclimate and streamflow modelling in the Koshi Basin. It is not complete; for example, it does not discuss all biophysical aspects (groundwater, geomorphology, sedimentation), it skims the surface on institutional arrangements and omits discussion on livelihood strategies of people in the Basin. However, it is expected that the broad modelling capacity described can support the dialogue between experts and stakeholders in China, Nepal, India and the broader international academic community, and in doing so contribute to the development of future analyses that would improve on this work.
1 Introduction

David J Penton, Luis E Neumann, Nicola Grigg and Tira Foran

Across the globe, planners and decision-makers aim to improve the living standards of their growing populations. The role and interaction of water, food and energy have drawn particular attention. By 2030, the United Nations projects that half of the world will not have access to clean drinking water, either because of physical water scarcity, or because of economic water scarcity (WWAP 2012). Parday et al. (2014) estimates that agricultural output needs to increase by around 70 per cent from 2010 to 2050 to meet the predicted growth in consumption caused by changes in demographics and improved lifestyles. Across the developed world energy needs are also increasing, with the largest growth in energy requirements projected to come from India where the International Energy Agency (IEA) estimates that $2.8 trillion USD in investment is needed by 2040 to meet India’s energy requirements (IEA 2015). Achieving improvements in living standards and meeting sustainable development goals requires careful planning of new infrastructure and improving the efficiency of existing practices.

However, there are limits to the available water and land resources that might support improvements to living standards. For example, the benefits from water resources must be shared between purposes such as domestic water supplies, food and fibre production, energy production, industry, fishery and tourism. The complexity of sharing the benefits from resources across different domains has led to extensive research across the water-food-energy nexus. Advances from this research has led to broader appreciation of technical and non-technical challenges to effective planning.

The Sustainable Development Investment Portfolio (SDIP) is an Australian government initiative with the goal of increasing water, food and energy security in South Asia, targeting the poorest and most vulnerable, particularly women and girls. A key target sector is water resources management. Within the SDIP, preliminary research and development by CSIRO has focussed on understanding the biophysical, cultural and national and transboundary policy environments of the Koshi Basin in China, Nepal and India.

1.1 The Koshi Basin study area

Planning decisions are made at a range of scales, for example trade is considered at a global scale, electricity is considered at a regional scale and sanitation is often considered at a local scale. For regional water planning, catchment or river basin scale is appropriate because it reflects the connectivity of the system i.e. how changes upstream impact downstream. The study area for this work is the Koshi Basin covering China, Nepal and India. There are two commonly used definitions of the Koshi Basin, which we shall describe as

- the Greater Koshi Basin taking into account the catchment of the Bagmati and Kamala sub-catchments, and
- the Nepal Koshi Basin taking into account the catchments upstream of the Koshi River at the border with India (see Figure 1).
Figure 1 The Arun originates in China and joins with six other large rivers, Tamor, Dudhkoshi, Tamakoshi, Sunkoshi (left branch), Bhotekoshi (not shown) and Indrawati to form the Sapta Koshi (known in Nepal as the Koshi Basin). The Koshi River then departs Nepal in a braided system (described as the Kosi Megafan) where it is joined by the Kamla and Bagmati rivers before it joins the River Ganges near Kursela.
The Greater Koshi Basin covers just under 70,000 square kilometres of land, spans a length of 730 kilometres and covers some of the poorest parts of India and Nepal. The Basin is home to approximately 50 million people, with the majority of the Basin’s population in lowland areas, reliant on the floodplains and water from the Koshi River for their livelihoods.

The region is prone to natural hazards, particularly floods, long dry seasons, landslides and debris flow. Heavy sedimentation in river flows caused by erosion, and rivers changing their course are also cause for concern. Electrification rates in the area are low (72% for rural Nepal according to IEA, 2015) and subject to daily load-shedding. The Koshi Basin contains areas of significant biodiversity including the UNESCO World Heritage Site – the Sagarmatha National Park in eastern Nepal and the Koshi Tappu Wildlife Reserve, a wetland of international significance also in Nepal.

1.2 Institutional context of water resource modelling

The institutional context for this research includes dynamics at domestic and transboundary levels. The domestic institutional context within India, Nepal and China includes high state interest in hydropower development but also high degrees of contestation (Dixit and Gyawali 2010, Alley 2012, Alley 2014, Choudhury 2014).

Nepal has many small enterprises hoping to develop small to medium hydropower schemes, but are struggling to transition from concept stage to bankable propositions. Since the World Bank abandoned plans to develop the Arun III hydropower project, planning of large schemes has fallen out of favour. Note, that in Nepal large run-of-river hydropower schemes are not necessarily opposed, as a result of generous benefit sharing provisions which some developers have offered (Lord 2016). However, there is more caution within state and civil society in Nepal about benefits and costs of large storage dams and the role of hydropower development to national development (Gyawali 2009, Dixit and Gyawali 2010).

Existing international agreements around water are relatively narrowly focussed (e.g. focussing on governance of particular water infrastructure schemes, and bilateral as opposed to multilateral). In October 2014, a power trade agreement between India and Nepal which aims to enable export-oriented hydropower schemes was signed.

The Koshi and Ganga basins have no existing official framework or organisation for cooperation. An eventual boom in hydropower development could result in unbalanced development unless governance processes represent the interests of people whose livelihoods depend on sustained access to water and sustained ecosystem services (Alley 2014, King and Smith 2016). However, evidence exists of semi-formal and informal initiatives around transboundary cooperation and dialogue, involving research as well as non-state organisations (see Chapter 6).
1.3 Integrated Assessment Framework

The focus of this research is to provide a preliminary understanding of the available water resource in the Koshi Basin, and how that knowledge might be able to support decision making by its governments. Recognising the potential for cascading impacts of water resource decisions, we are motivated by the following question:

What cumulative impacts on livelihood outcomes are possible under different future water resource development scenarios? Under what circumstances are impacts disproportionately benefiting or disadvantaging poorest households or women and girls?

In this context, cumulative impacts may be positive and negative, with benefits and costs distributed across different socio-economic groups. While future water resource development scenarios are designed at a regional planning scale, the outcomes will be experienced at district/household scale.

An Integrated Assessment Framework (IAF) can support the collation, interpretation and sharing of information to inform these questions. An IAF would include

a. collated datasets with known provenance, accuracies and limitations
b. Models built for particular purposes with acceptable performance
c. methods to link hydrological and ecological knowledge, and quantitative analysis of livelihoods
d. methods to link qualitative basin development scenarios to social-ecological responses and changes in livelihood strategies
e. datasets and results for baseline and alternative scenarios
f. research reports and papers describing the technical details and state of the art.

Furthermore, embedding the information gathering and assessment in effective multi-stakeholder engagement and participatory learning processes would ensure a diverse range of stakeholders are included, contribute to, and have greater awareness of the knowledge base upon which decisions are made.

The approach supports decision-making methodologies such as the Decision Tree Framework (Ray and Brown 2015) by explaining the current range of uncertainty of biophysical inputs, and frameworks like the SUMHA (Sustainable Management of Hydrological Alterations) framework for an integrated approach to the setting and governance of flow alterations to manage social-ecological impacts (Pahl-Wostl et al. 2013).

This preliminary report provides a background to the climate and how it is changing in Chapter 2. In Chapter 3, the major factors of the Himalayan water balance are estimated using hydrological models. Methods for characterising streamflow are presented in Chapter 4, and an overview of how such analysis can be used to assess changes to streamflow.
Chapter 5 introduces work to understand how the changes to streamflow might influence the ecology of the Koshi Basin. Chapter 6 presents perspectives from a range of state and non-state policy actors on the role of expert knowledge (including modelling) in Koshi and Ganga basin water governance.
Climate characterisation and change

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2.1 Local climate characteristics

Rainfall varies substantially across the Koshi Basin (Figure 2). The central Himalayan region has a two-step topography, with a parallel arrangement of mountain ranges: the Siwalik Range (Sub-Himalayas) in the south, the Mahabharat Range (Lesser Himalayas), and the Greater Himalayas in the north (see Figure 3). This topography significantly influences the precipitation pattern, as described by Shrestha et al. (2012).

In the Koshi region, the monsoonal weather systems predominantly travel from the Bay of Bengal northwards delivering precipitation on the southern slopes of the Mahabharat Range and the Himalayas. Diodato (2010) reported annual rainfall at stations in Nepal of the order of 1200 mm/year (5th percentile), 2100 mm/year (mean) and 3200 mm/year (95th percentile) at rainfall stations below 1000mASL, down to annual rainfall of 200 mm/year (5th percentile), 1200 mm/year (mean) and 1900 mm/year (95th percentile) above 4000mASL.

Figure 2 Composite of best available information on precipitation in the Nepal area. The Nepal area is useful for display purposes because it has the highest resolution input data. Interpolated station data are used for the area under 3000mASL (Pai et al. 2014 for India and Neumann et al. 2016 for Nepal). WATCH reanalysis (Weedon et al. 2014) is used where land based observations are limited and a physical model of atmospherics is required to limit the extrapolation of rainfall with elevation.
Rainfall in Nepal occurs mostly (80%) during the monsoon period from June to September (Nayava 1974, Aryal 2011). For the rainiest month (July), Diodato et al. (2010) found that precipitation varies from ~100 mm over the Tibetan Plateau to ~500 mm in the southern part of Nepal, up to ~900 mm towards the pre-Himalayan range. During this period rainfall events with high intensity occur, sometimes causing landslides and floods. The soils often become completely saturated leading to a high proportion of rainfall becoming runoff.

Several studies have investigated the relationship between elevation and precipitation in the Himalayas (e.g. Dhar & Rakhecha 1981, Bookhagen & Burbank 2006, Shrestha et al. 2012). In general, precipitation increases with elevation, as moist air lifted along the slope cools and expands, decreasing its water-holding capacity and causing precipitation. However, as the air continues to rise, its water content drops. As a result, above certain elevations, precipitation decreases due to the reduced water content. Distinct rain shadows occur behind the Mahabharat Range, and also on the Tibetan Plateau.

Maximum temperatures in Kathmandu during summer, April to September, average at 28-29°C (MFD 2016). During January, the coldest month, the average maximum temperature is 19°C. The minimum temperatures fluctuate from 2.4°C in January through to 20°C in July. Kathmandu’s climate is indicative of the climate at 1400m (see Figure 4). According to Kattel et al. (2013), the temperature linearly decreases with elevation at observation sites in Nepal according to a lapse rate. The exact lapse rate varies seasonally, and for minimum and maximum temperatures. Kattel et al. (2013) reported the lapse rates as being between 4.1 and 6.8 °C per kilometre of elevation. Figure 4 shows long term average temperatures.
spatially. The north-south gradient within the Koshi Basin is mainly a factor of topography. The regional north-south gradient are a function of changes in latitude.

Evaporation occurs mainly during the pre-monsoon, or early monsoon period (March – August) – the northern hemisphere summer – when temperatures are warmer. As shown in Figure 5, actual evapotranspiration estimates using MODIS suggest evaporation rates are as low as 400 mm/year in the flat Terai areas. Actual evapotranspiration increases towards the north, reaching as much as 1000 mm/year in some areas. By comparing Figure 2 and Figure 5, it is also clear that there is a relationship between high evaporation and high rainfall.

Figure 4 Climatology mean of daily maximum temperature (top left), daily mean temperature (middle left) and daily minimum temperature (bottom left) in the Nepal area derived from station data using ANUSPLIN (Hutchinson 1989) for the period 1970-2009. The plot in the right is the climatology mean of daily mean temperature across the South Asia from Aphrodite for the period 1980 to 1999.
Figure 5 Estimated annual actual evapotranspiration 2000–2012 from MODIS satellite observations (Mu et al. 2011). Areas above 3000mASL are greyed out because there are no in-situ measurements to compare with satellite modelling (i.e. we cannot evaluate the performance of the product, but expect low evapotranspiration).

2.2 Changes of climate in the past decades

As part of the Integrated Assessment Framework, gridded daily rainfall and monthly temperature data sets were generated from historical station data provided by the Department of Hydrology and Meteorology (DHM), Nepal. Rainfall for 269 stations was run through automated quality assurance scripts and months with identified errors removed (e.g. periods of no data). DHM revisited stations to improve the precision of station metadata, and ensure elevation data was correct. The gridded daily rainfall data sets were generated using the ESDIIM approach (Song et al. 2014); for more information see Section 3.3.1. Monthly temperature surfaces were generated from historical station data using the ANUSPLIN approach of (Hutchinson 1989).

Previous work by Shrestha et al. (1999) identified trends in temperatures of 5 physiographic regions of Nepal: Terai, Siwalk, Middle Mountains, Himalaya and Trans-Himalaya (from south to north). For each region he observed an upward trend from 1971-94 of between 0.009 °C/year and 0.075 °C/year with statistical significance. Using the derived ANUCLIM surfaces, Figure 6 shows the warming trend from 1970 to 2009. Averaged across the Koshi region, the increasing rate of daily mean temperature, daily minimum temperature and daily maximum temperature are 0.045°C/year, 0.032 °C/year and 0.057 °C/year respectively. A higher rate of increasing temperature is observed at the north high altitude region.
Figure 6 Changes of mean temperature (Tmean), maximum temperature (Tmax), minimum temperature (Tmin) and annual precipitation (P) for the period 1970 to 2009. The unit of temperature change is °C/10 years, while it is mm/10 years for precipitation change.

2.3 Climate change projections

According to the most recent set of climate model projections for the Koshi Basin, trends in rising temperature are projected to continue, the models also project increases to potential evapotranspiration, and there is no clear picture as to changes in precipitation.

The range of future climate change was derived from the CMIP5 database (http://cmip-pcmdi.llnl.gov/cmip5/), which involves transient climate experiments from more than 20 climate modelling groups around the world. All the 42 CMIP5 GCMs with both historical and future outputs available are used (the same as that adopted by IPCC AR5). For the projections, the high emission Representative Concentration Pathways RCP8.5 is considered, which represents radiative forcing of +8.5 W/m² in the year 2100 relative to pre-industrial values (Moss et al. 2010, Taylor et al. 2010) and reflects the current trajectory.

The changes of the temperature, potential evapotranspiration and precipitation in the Koshi Basin are estimated according to their difference between the baseline period (1976-2005) and the future period (2046-2075), where the potential evapotranspiration for each GCM grid was estimated from the solar radiation, maximum and minimum temperatures, and actual vapour pressure data using Morton’s wet environment or equilibrium evaporation formulation (Morton, 1983). Since the spatial resolution varies between the GCMs, the climate factors for each GCM grid were resampled to an identical spatial resolution of 0.5° × 0.5° using the nearest neighbour approach. Based on the results, the 10th, 50th and 90th
percentile for each $0.5^\circ \times 0.5^\circ$ cell were obtained to show the range of projected climate change in the Koshi Basin (Figure 7).

It is found that there is strong agreement between the GCMs in the temperature projections. Averaged across the Greater Koshi Basin, the median projection for RCP8.5 is an increase in daily mean temperature of 2.7 $^\circ$C by 2046–2075 relative to the period 1976–2005, with a 10–90$^{th}$ percentile range of 2.2 to 3.8 $^\circ$C. The projected increase in daily minimum temperature is slightly higher and the projected increase in daily maximum temperature is slightly lower than the projected increase in daily mean temperature (figures not presented here).

Seasonally, the projected temperature increase is slightly higher in winter (DJF) than summer (JJA). Spatially, the projected temperature increase is noticeably higher in the north (high altitude regions) than in the south. There is also general agreement between the GCMs in the potential evaporation projections. The projected increase in potential evaporation is driven mainly by the increase in temperature. Averaged across the Greater Koshi Basin, the median projection for RCP8.5 is an increase in mean annual potential evaporation of 4.8% by 2046–2075 relative to 1976-2005, with a 10–90$^{th}$ of 1.8 to 7.3%. There is much greater uncertainty in the projected precipitation change. Nevertheless, a higher proportion of GCMs project an increase in precipitation. The median increase of precipitation averaging across the region is around 9.6%, with the 10$^{th}$-90$^{th}$ percentile of -5.6% to 29%.
Figure 7 Projected change of temperature (°C), potential evapotranspiration (%) and precipitation (%) across the Koshi Basin for the period 2046 to 2075 against 1976 to 2005.
3 Water balance of Nepal Koshi Basin

Luis E Neumann, Michaela M Dolk and David J Penton

One of the components of the IAF is a set of hydrological models to understand the availability of water resources and different components of the water balance in the Koshi Basin. This set of hydrological models provide a set of baselines for water resources. Using scenarios, this set of models can then be used to evaluate changes to streamflow due to development (e.g. hydropower development), or changes to climate. These changes to streamflow can then be used to evaluate cumulative impacts and to characterize streamflow and changes due to different development options (Chapter 4), and how these changes might influence the ecology of the Koshi Basin (Chapter 5).

In the following section, the model used in this study is described, followed by the methodologies applied to derive the required input data sets. The model results for the calibration and validation period are described, followed by an evaluation of the locations where most of the runoff is generated and the different contributions of snow and ice to the total runoff.

3.1 Description of the GR4JSG model

The model used to simulate rainfall runoff and snow and glacial melt in this study is a variation of the GR4JSG model developed by Nepal et al. (2015, 2016), which in turn is based on GR4J (Perrin et al. 2003), with the snow and ice melt dynamics described using degree day factors (Hock 2003). A schematic of the model is show in Figure 8, with the original GR4J model shown on the left side and the additional snow and ice stores shown on the right side. For the lower section of the catchment, were snow and glaciers are not important, the snow and glacier processes are turned off.

The GR4J model developed by Perrin et al. (2003) is a daily lumped rainfall-runoff model with four parameters (x1, x2, x3 and x4). GR4J consists of two main stores: the production store, and the routing store as shown in the conceptual structure of Figure 8. The time series inputs to the model are rainfall depth (P) in mm/day and potential evapotranspiration (E) in mm/day. As shown in Figure 8, x1 controls the size of the production store (mm), x2 controls the flux to groundwater (mm/day), x3 controls the size of the routing store (mm) and x4 controls the recession of the unit hydrograph (days).
As shown in Figure 8, GR4JSG represents the snow and glacier processes using two conceptual stores for snow and ice. The precipitation may be in liquid (rainfall) or solid (snow) forms, depending on the temperature (see below). The snow store represents snow accumulation and melt, and the ice store represents glacier melt processes. Snow is accumulated in the snow store and is melted prior to the glacier melting.

In the conceptual model, snowmelt from the snow areas infiltrates the soil and enters the production store, and is treated afterwards as though it was rainfall. For glaciated areas (including snowmelt on top of glaciers), the runoff is assumed to be delivered at the glacier toe and is considered as streamflow and is therefore directly added to the GR4J routing store. Therefore, it is important to note that snowmelt from non-glaciated areas enters the production store and therefore some water from snowmelt is lost through subsequent evapotranspiration, as if it was rainfall. In this approach, not all snowmelt will become runoff at the catchment outlet as some melt will leave the catchment through evapotranspiration. The contributions from snowmelt and rainfall to the production store are tracked separately to allow the calculation of the amount of snowmelt contribution to runoff. This is different to the approach in other models which estimate the contribution from snowmelt to runoff using the total snowmelt divide by the total runoff.
The snow accumulation and the melt processes for both snowmelt and ice melt are dependent on the daily representative temperature Reptemp (°C), which is a proportion of daily maximum and minimum temperature:

\[
Reptemp = T_{fraction} \times TMax + (1 - T_{fraction}) \times Tmin
\]

where TMax and TMin are the respective maximum and minimum daily temperatures (°C). Therefore, the model does not use the average of the maximum and minimum temperature to represent the average daily temperature as in other models (e.g. Hock 2003, Nepal 2016), but introduces an extra parameter to better estimate the average daily temperature. Noting that in reality this parameter is a temperature factor that is bounded by the minimum and maximum temperatures. As such it does provide some valuable insights into possible observed temperature errors when it is calibrated and hits either minimum or maximum bounds.

In any given day where precipitation occurs, if the representative temperature is below a specified threshold, accumulation temperature \( T_{accum\_Threshold} \), all rainfall is considered to fall as snow, and if the temperature is above the threshold, all precipitation is assumed to be rain:

\[
\text{SnowProportion} = \begin{cases} 
1, & \text{Reptemp} \leq T_{accum\_Threshold} \\
0, & \text{Reptemp} > T_{accum\_Threshold}
\end{cases}
\]

Both snowmelt and ice melt are calculated using a modified version of the degree day factor of Hock (2003). Melt is assumed to occur when the representative daily temperature (Reptemp) is higher than the specified melt temperature threshold MeltThreshold (°C). If Reptemp is smaller than the MeltThreshold, no melt occurs, as given by the equations below:

\[
\text{Snowmelt} = \begin{cases} 
DDF_{snow} \times (\text{Reptemp} - \text{MeltThreshold}), & \text{Reptemp} > \text{MeltThreshold} \\
0, & \text{Reptemp} \leq \text{MeltThreshold}
\end{cases}
\]

\[
\text{Icemelt} = \begin{cases} 
DDF_{ice} \times (\text{Reptemp} - \text{MeltThreshold}), & \text{Reptemp} > \text{MeltThreshold} \\
0, & \text{Reptemp} \leq \text{MeltThreshold}
\end{cases}
\]

Where DDFice (mm.°C-1.day-1) is the degree day factor for ice melt and DDFsnow (mm.°C-1.day-1) is the degree day factor for snow. The 9 parameters of the model and their recommended value ranges are given in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Recommended GR4JSG model parameter value limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>X1 (mm)</td>
</tr>
<tr>
<td>X2 (mm)</td>
</tr>
<tr>
<td>X3 (mm)</td>
</tr>
<tr>
<td>X4 (days)</td>
</tr>
<tr>
<td>DDFsnow (mm.°C-1.day-1)</td>
</tr>
<tr>
<td>DDFice (mm.°C-1.day-1)</td>
</tr>
</tbody>
</table>
A simple spatially explicit conceptual model with only 9 parameters and minimal time series input requirements reduces the uncertainty around estimation of model parameters and is appropriate given the level of uncertainty in model inputs. However, these simplifications also introduce some limitations.

One limitation of the conceptual model is that the snow does not convert into glacial ice and consequently the conceptual model does not represent glacier mass balance processes. In reality, glacier areas shrink and expand due to melting and ice accumulation. In the model the glaciers are assumed to have a constant area and therefore act as an infinite supply of water. Since the gradual process of changes in glacier area at a catchment level occur at a decadal scale, the assumption of constant area is unlikely to affect the model results for short simulation periods – i.e. periods of a couple of decades (Jóhannesson et al. 1989, Pelto and Hedlund 2001) as the glaciers do not disappear during the simulation period and therefore the assumption of glaciers acting as an infinite supply of water is reasonable.

Due to the limited data availability for glacier changes across the catchment and the fact that the streamflow alone has limited signal to constrain the ice degree day factor (Nepal et al. 2016), the model makes no distinction between covered and uncovered glaciers and assumes the ice degree day factor to be equal to the snow degree day factor. Consequently the conceptual model makes no distinction between the different types of glacial cover.

Nepal et al. (2016) also highlighted some other potential limitations, namely i) the model sensitivity to initial conditions, ii) parameters collapsing to boundaries of GR4J’s parameter range and iii) a possible interplay of GR4J parameters such as x2 with the degree-day factors. In this study, the impact of initial conditions is minimized by the use of at least two years of model warm up. Parameters collapsing to boundaries may suggest issues with input data that may require further investigation. Interplay of parameters is minimised by using a two stage calibration process with snow and ice stores calibrated prior to runoff stores.

### 3.2 Conceptual representation of the catchments

The GR4JSG model is used within the Source modelling framework (Welsh et. al.). Source conceptualises a catchment as a combination of functional units (Argent et al. 2009). A functional unit is a conceptual portion of a catchment that functions in a similar way for hydrological processes, and which may be defined by different climate, land use, soil type or runoff processes. Functional units can be modelled by different models. In this conceptualisation two different models are used. For areas where snow does not occur GR4J is used and for areas where snow occurs and there is runoff or melt GR4JSG. In areas of high elevation where no runoff occurs the functional units are configured as nil runoff.
One of the characteristics of mountainous regions is the significant variation in temperature due to elevation. Valéry (2010) demonstrated that model performance in simulating high altitude catchments can be improved by accounting for the changes in temperature with altitude. As discussed previously, temperature can also vary with altitude and the use of elevation bands allows the model to take this variation into account. As shown in Figure 9, each catchment in this study was split into elevation bands up to 600m and then at 200-m intervals for an altitude up to 6000 m, followed by larger bands as shown in Figure 9 and in Table 2. At high altitudes, larger bands were used due to the lower variability in temperature and rainfall. Each elevation band having different forcing data based on its location and elevation. In addition to the elevation and location, catchments were categorized as glaciated or non-glaciated, with the glacier defined based on ICIMOD’s glacier extents obtained from Landsat imagery (Bajracharya et al. 2011). Ice stores were modelled in areas which were glaciated.

Table 2 Functional units used in the model and their elevation boundaries (NG= non glaciated, GL = glaciated)

<table>
<thead>
<tr>
<th>Functional Unit</th>
<th>Lower Bound (mAHD)</th>
<th>Upper Bound (mAHD)</th>
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<tr>
<td>NG1</td>
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</tr>
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<td>NG2</td>
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</tr>
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</tr>
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<td>2000</td>
</tr>
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</tr>
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</tr>
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</tr>
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</tr>
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</tr>
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</tr>
<tr>
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<td>4400</td>
</tr>
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</tr>
<tr>
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<td>4800</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>5600</td>
</tr>
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</tr>
<tr>
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</tr>
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<td>NG29</td>
<td>6001</td>
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</tr>
<tr>
<td>NG30</td>
<td>6501</td>
<td>7000</td>
</tr>
<tr>
<td>NG31</td>
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<table>
<thead>
<tr>
<th>Functional Unit</th>
<th>Lower Bound (mAHD)</th>
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</thead>
<tbody>
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<td>GL17</td>
<td>3601</td>
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<tr>
<td>GL21</td>
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<td>GL27</td>
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<td>GL28</td>
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<td>GL29</td>
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<td>GL30</td>
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</tr>
<tr>
<td>GL31</td>
<td>7001</td>
<td>9000</td>
</tr>
</tbody>
</table>
The combination of elevation bands at 200-m intervals and glacier areas resulted in 44 different functional units (FUs).

### 3.3 The hydrological model’s input data

The GR4JSG model requires time series of daily precipitation, daily minimum and maximum temperatures and potential evapotranspiration (PET). In order to calibrate and validate the model, daily time series of streamflow and snow cover are also required.

The main source of data for this study is Nepal’s Department of Hydrology and Meteorology (DHM), which operates a network of rainfall (Figure 11) and climatological stations (Figure 10) and a series of streamflow gauges as show in Figure 17. As can be seen in Figure 10 and Figure 11, most stations are located in low to mid-altitudes, with no data available in high altitude areas or in the Tibetan plateau. Data used for modelling these regions is a mixture of satellite based data and interpolated data as described in the following sections.
3.3.1 Precipitation

As most stations are located in mid to low altitudes, this study investigated different options to estimate rainfall in Nepal. Several papers compare available precipitation products, e.g. Andermann et al. (2012), Krakauer et al. (2013) and Diodato et al. (2010) and Dhari et al. (2016). Andermann et al. (2012) suggest that Aphrodite is the most accurate representation of precipitation in Nepal, but that it underestimates precipitation when compared to observed rainfall at ground stations. Additionally, the Aphrodite data finishes in 2007, which significantly limits the period for model analysis.

This study blended two data set products to provide precipitation inputs to the GR4SJ model. For elevations up to 3000m the ESDIIM data set was used and for higher elevations the WATCH data set was used. The ESDIIM data set is generated based on a Bayesian Hierarchical Modelling (BHM) approach that considers the spatial and temporal distribution of rainfall (Song et al., 2014). The data model of the BHM uses three components to describe the transformed rainfall at each rain gauge location; the long-term average daily rainfall at each location, a spatially and temporally correlated anomaly and a local error component that describes unexplained components including measurement error. The parameterised hierarchical model can then be used to interpolate between gauge locations and estimate sub-catchment rainfall. However the uncertainty in the ESDIIM estimates increases significantly away from observed stations particularly where elevations are significantly different. The average cross validation error in ESDIIM is estimated to be approximately 20%. In Nepal there are few good quality observations above 3000m ASL. On this basis it was decided not to use ESDIIM above 3000m ASL.
The WATCH data set is based on a reanalysis approach (Weedon et al. 2014) and is consequently less dependent on in-situ observed data. Dhari et al. (2016) has shown that for the HKH that WATCH performance is best out of a range of comparable products. We have considered that the uncertainty in WATCH is better than the uncertainty in extrapolated ESDIIM data sets for elevations above 3000m. Figure 12 shows the precipitation for each functional unit in the model. The spatial representation of a functional unit can cover multiple rainfall grid cells, in which case the precipitation for that functional unit is the areal weighted precipitation of each grid cell. We chose not to correct input precipitation for elevation because we did not have any evidence this would reduce the model’s uncertainty.

Figure 11 Location of rainfall gauges operated by the Government of Nepal’s Department of Hydrology and Meteorology (DHM). DHM revisited the location of rainfall gauges to increase the precision of elevation estimates and improve the accuracy of gridded rainfall products. Locations where new metadata was collected is shown in blue (progress as at 27 June 2016).
In the Arun catchment, several spurious precipitation peaks were observed in the winter months (i.e. snow events of a size that would cover most of the Tibetan Plateau). These events were not visible in satellite imagery and station data. Consequently the WATCH data was adjusted by replacing the 99th percentile rainfall data with the median. The same issue was not observed in other catchments.

### 3.3.2 Potential Evapotranspiration (PET)

There is limited data available to calculate potential evapotranspiration (PET) across the Koshi Basin, as not many stations recorded variables such as humidity and wind speeds which are required by several methods used to calculate PET. Daily PET was estimated across all catchments using two different methods depending on available data, and the annual estimates are shown in in Figure 13. For the Arun catchment in the absence of observed data for wind speeds and humidity, the Hargreaves method (Hargreaves and Samani 1982) was applied as it only requires daily minimum and maximum temperatures and solar radiation (which is estimated based on latitude).

For all catchments based in Nepal we used PET values derived by Nepal (2012) using the Penman-Monteith approach as described by Allen et al. (1998) The Penman-Monteith approach uses daily mean temperature, wind speed, relative humidity and solar radiation to provide estimates of PET. Nepal (2012) developed PET estimates for both the Tamor and Dudh Koshi catchments using the stations of Okhaldhunga and Tapplejun, respectively. Only two stations were used as most other stations in Nepal do not recorded the required variable such as wind speed and relative humidity. The values derived by Nepal (2012) for
the Dudh Koshi were applied to the Dudh Koshi and all basins to the west (Indrawati/Melamchi, Likhu, Indrati), while the values derived for the Tamor are used in the Tamor catchment only. For elevations different than the stations for which PET was derived, the PET was corrected using a lapse rate of -0.0005 mm/1000 m as in Nepal (2012).

![Figure 13 Estimations of annual PET used in the model](image)

### 3.3.3 Snow cover

The snow parameters were calibrated against satellite observations of snow extent to constrain the model to realistic values. The remote sensing of snow is built upon the Normalised Snow Difference Index (NDSI) devised by Dozier (1989) who worked towards defining the spectral signature of snow through LANDSAT imagery. The MODIS snow cover products utilise the NDSI algorithm (Hall, Riggs et al. 1995) to produce daily and 8 day composite products at 500 m resolution (Hall, Riggs et al. 2002). Currently available snow cover products from MODIS struggle to give accurate results due to the extensive cloud cover and shadowed areas. The most notable of attempts to improve the characterisation of snow by post-processing the MODIS outputs are the 8-day products described by Gurung et al. (2011).

However in some mountainous topography, especially in areas such as the Dudh Koshi, artefacts of cloud cover persist (see Figure 15). For this reason, we applied a two state Hidden Markov Model (HMM) to smooth the daily output of snow cover for each pixel in the catchment (see Figure 14). In this instance snow cover is observed at discrete, equally spaced intervals by the MODIS sensor. The actual state of an area, snow covered or not, is
hidden and it can only be observed through what the MODIS satellite records. Here the HMM can utilise previous observations at a single pixel to estimate the probability of transitioning between the two states in the model (snow or no snow). Thus this HMM aims to estimate the likelihood of the observed MODIS snow cover values representing the actual snow extent. When applied to the MODIS signal it acts as a filter for unlikely transitions. Because there were more cases where clouds were misclassified as snow below 3000mASL than cases where snow was likely, snow was masked out below 3000mASL. Any area classified as glacier was assumed to be snow-covered for the purpose of comparison (in both GR4JSG output and snow extent).

The revised product had a lesser snow extent than Gurung et al. (2011). There were occasions when each product performed better or worse when compared to a sample of Landsat images.

![Diagram of Hidden Markov Model]

**Figure 14** The Hidden Markov Model contains two states (Snow and Earth). We fitted the transition and emission probabilities by applying the Baum-Welch algorithm (referenced as Baum, et al. 1970) to the observed sequence of MODIS outputs (values of 25 for snow and <=25 for other classifications), which were assumed to be noisy. Then we calculated the most consistent set of states (ground/snow) using the Viterbi algorithm (Viterbi, 1967) and the state probability matrices.
Figure 15 The image above shows classifications when Landsat was not obscured (with various artefacts): a) Landsat imagery for 2013-11-11, b) MOD10A1 for 2013-11-27, c) MYD10A1 for 2013-11-27, d) Landsat imagery for 2013-11-27, e) Gurung et al. (2011) classification, and f) HMM filtered snow extent.
An important, and not always well understood, feature of the smoothing spline analyses is that the source data values are smoothed in the final fitted surfaces. The degree of data smoothing is set automatically to minimise the predictive error of the fitted surfaces, as measured by the generalised cross validation (Hutchinson and Xu, 2016). This aims to provide a surface that is representative of the climate values across the whole region, not just at the data points, for which there maybe remaining errors and data omissions. During the temperature analyses two runs of the SPLINE program of ANUSPLIN were performed to remove a small number of outliers with very large studentised residuals, leading to the removal of around 50 maximum temperature data values and around 80 minimum temperature values across all years and months (around 0.02% of all values). The model errors show minor variation over the year, with largest predictive errors in winter. Overall the error values compare well with values obtained elsewhere (Hutchinson et al. 2009).

Table 3 Summary statistics of the maximum and minimum temperature analyses for Nepal. The values are the average values across all years for each month. All error estimates in °C

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of data points</th>
<th>Maximum temperature</th>
<th>Minimum temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Root mean square predictive error</td>
<td>Mean absolute predictive error</td>
</tr>
<tr>
<td>Jan</td>
<td>59</td>
<td>1.43</td>
<td>1.16</td>
</tr>
<tr>
<td>Feb</td>
<td>60</td>
<td>1.22</td>
<td>1.1</td>
</tr>
<tr>
<td>Mar</td>
<td>61</td>
<td>1.34</td>
<td>1.06</td>
</tr>
<tr>
<td>Apr</td>
<td>61</td>
<td>1.38</td>
<td>1.09</td>
</tr>
<tr>
<td>May</td>
<td>62</td>
<td>1.39</td>
<td>1.09</td>
</tr>
<tr>
<td>Jun</td>
<td>62</td>
<td>1.36</td>
<td>1.1</td>
</tr>
<tr>
<td>Jul</td>
<td>62</td>
<td>1.35</td>
<td>1.09</td>
</tr>
<tr>
<td>Aug</td>
<td>62</td>
<td>1.36</td>
<td>1.07</td>
</tr>
<tr>
<td>Sep</td>
<td>62</td>
<td>1.32</td>
<td>1.06</td>
</tr>
<tr>
<td>Oct</td>
<td>60</td>
<td>1.38</td>
<td>1.1</td>
</tr>
<tr>
<td>Nov</td>
<td>61</td>
<td>1.45</td>
<td>1.18</td>
</tr>
<tr>
<td>Dec</td>
<td>60</td>
<td>1.5</td>
<td>1.22</td>
</tr>
</tbody>
</table>

The surfaces were disaggregated from monthly to daily using linear interpolation. The temperature in Nepal generally decreases with elevation, with higher temperatures in the Terai and river valleys, and lower temperatures toward the northern regions, as shown in Figure 16.
Owing to a lack of sufficient data in the Tibetan plateau, the ANUSPLIN product only covers Nepal. Consequently we used WATCH (Weedon et al. 2014) data in this region. The two products are similar for Nepal; for maximum temperature, ANUSPLIN is on average 0.73°C warmer (standard deviation 1.4°C) than WATCH, when the 53 WATCH cells that overlap by at least 50% are compared to the ANUSPLIN surface (using the mean of 1250-2500 coincident ANUSPLIN cells). For the four cells closest to the Tibetan Plateau in Koshi, the ANUSPLIN surface is 1.4°C cooler.

When WATCH was compared against two observed stations in the northern region it was found to be on average 4 degrees too cold. We subsequently bias correct this surface by 4 degrees to better match observations. A constant temperature lapse rate of -0.8°C/km was applied to account for the different functional unit elevation compared with the WATCH grid cells elevation. In absence of in-situ measurements, this value allowed the model to behave sensibly and would represent a dry atmosphere.

3.4 Procedure for calibrating the hydrological model

The models were calibrated using a two-step approach, with the first step focusing on the snow dynamics, and the second on the streamflow. The snow calibration was based on using a leave-one-out cross-validation (LOOCV) approach, in which one catchment is “left-out” and the modelled snow cover is calibrated for all of the remaining catchments. The procedure is then repeated several times such that each catchment is “left-out” once. The snow calibration period was 2002-2009.

The streamflow calibration was based on a split sample approach. The calibration and validation periods were chosen to be relatively long to test the models in different climatic condition and to drier and wetter years whenever possible, to ensure the model can perform across both periods. If
the model is calibrated on excessively drier or wetter periods, it may not perform well in wetter or drier periods, respectively (Vaze et al. 2010).

### 3.4.1 Snow calibration

The first step used the snow cover time series from the HMM model to calibrate the parameters controlling the snow cover, namely the degree day factor for snow ($DDF_{\text{snow}}$), the accumulation temperature threshold ($T_{\text{accumThreshold}}$), the melt temperature threshold ($MeltThreshold$) and the fraction of minimum and maximum temperature ($T_{\text{fraction}}$). As the glaciers are considered time-invariant, the $DDF_{\text{ice}}$ has no influence on the snow extent as the glaciers are always present and counted as snow covered. The objective function used in the model calibration was a combination of daily NSE and bias (Viney et al. 2009)

\[ F = NSE - 5 \ln(1 + Bias) \]

\[ Bias = \frac{\sum(y - m)}{\sum(y)} \]

\[ NSE = \frac{\sum(y - m)^2}{\sum(y - \bar{y})^2} \]

Where \( F \) is the objective function, \( y \) are the observations, \( \bar{y} \) is the average of the observations and \( m \) is the modelled values. A NSE value of 1 corresponds to a perfect match of modelled discharge to the observed data, while a value of zero indicates that the model predictions are as good as the mean of the observed data. If the values of NSE are negative, it indicates that observed mean is a better predictor than the model.

The conceptual snow processes, and the parameters used to control those processes, are designed to be invariant to the individual catchments. A regional calibration was chosen to inform the parameters with the greatest available information, and also to avoid over-training to uncertainty inherent in the input data. The snow parameters were calibrated regionally for Indrawati, Tama Koshi, Likhu, Dudh Koshi and Tamor, using a leave-one-out cross-validation (LOOCV) approach. Each catchment was given equal weighting in the calibration. Based on the results of the LOOCV procedure, the best set of calibrated snow parameters was selected, and applied to all catchments (including Arun). Once the snow calibration is completed and the temperature values governing melt are set, we set $DDF_{\text{ice}}$ equal to $DDF_{\text{snow}}$ and evaluated the total glacier melt against values reported in Kaab et al. (2012), which estimated the change in glacier in Nepal to be about -0.19 to -0.42 m/yr, with values up to 0.67 m/yr in parts of the Himalayas. The values of $DDF_{\text{ice}}$ were subsequently reduced until the total glacier change was within the limits reported in Kaab et al. (2012).
Figure 17 Locations of streamflow gauges in the Koshi Basin (Nepal) where data was available. For selected gauges, a bar graph represents the record length from 1960 to 2006 (white represents data, grey represents no-data)
3.4.2 Flow calibration

Once the model was calibrated for snow areas and glacial melt, a second calibration using NSE as the objective function was performed for the parameters that do not influence the snow cover or ice melt, namely x1 (production store), x2 (flux to groundwater), x3 (routing store) and x4 (recession of the unit hydrograph).

Headwater catchments

The models for all the for all the headwater catchments (Arun, Indrawati/Melanchi, Tama Koshi, Likhu, Dudh Koshi and Tamor were calibrated using a split-sample approach, where some of the available data is used to calibrate the model, and a second period (the validation period) not used in the calibration is used to evaluate the model. For the streamflow calibration, different time periods were used for different gauges depending on the availability of data, as some gauges have relatively shorter records available as shown in Figure 17 (validation periods were generally chosen to enable comparison with other published results).

Downstream catchments

As the Sun Koshi is located downstream of all the other catchments, and therefore receives streamflow from all the upstream (headwater) catchments, it was calibrated last using a different approach. To reduce the influence of errors from the calibration of the upstream catchments, during calibration all inflows into the Sun Koshi were replaced with observed inflows from gauge data, with any missing data infilled with modelled flows. The Sun Koshi streamflow was then calibrated to streamflow from 3 gauges within the catchment (gauges 606, 681 and 690). Each of these intermediate nodes was given equal weighting in the calibration procedure. The calibrated parameters were then applied to the remaining portion of the catchment, downstream of the intermediate nodes. The Chatara gauge was used for validation.

3.5 Results of the application of the hydrological model

3.5.1 Snow cover

The results of the LOOCV procedure used for calibration of the snow parameters are presented in Table 4 and Table 5 and Figure 18. Overall, calibrations of snow extent for most catchments provide reasonably satisfactory results with most catchments having bias < 20% and positive NSE scores.

Whilst the NSE scores for most catchments would be considered poor when calibrating a hydrological model for streamflow, the overall range of the GR4JSG modelled snow extent is similar to the HMM snow extent range and the timing of the GR4JSG modelled snow extent peaks is generally aligned with the HMM snow extent peaks for all catchments Figure 18, with NSE scores affected by the general noise of the data as discussed previously. Arun is an exception, with peaks in GR4JSG modelled Arun snow extent substantially higher than those estimated based on the HMM. This is largely due to WATCH overestimating precipitation when compared to two observed stations, especially during the winter season. It is on average 3 times larger than observed. Due to a significant lack of data there is no defensible way of correcting this problem. A
positive NSE was unable to be achieved for the Arun, even if the snow parameters were calibrated for the Arun on its own.

The timing of the GR4JSG modelled snow extent peaks is generally aligned with the HMM snow extent peaks for all other catchments. However, in the warmer months, there are large discrepancies between the GR4JSG and HMM snow extents, with GR4JSG generally underestimating snow extent relative to HMM. Noting that this is a period that cloud cover dominates and consequently HMM estimates are quite poor. It is thus difficult to rationalise whether this is an error in the GR4JSJ model or in HMM estimates.

As Likhu performed poorly for all calibrations with large biases and negative NSE scores, partly because the Likhu HMM time series of snow cover is particularly noisy the snow parameter values from the calibration when Likhu was “left-out” for application to all catchments (including Likhu and Arun). Moreover the snow cover are an order of magnitude smaller than the other catchments. The snow validation statistics for the Arun for 2002-2009 using these parameters were bias 9.59% and NSE -2.71. Analysis of cloud-free MODIS imagery revealed inaccuracies in the snow cover estimated by the HMM.

Table 4 Performance statistics from the LOOCV procedure used for regional calibration of snow parameters. The calibration period was 2002-2009. The values on the diagonal (shaded) are the validation statistics for each catchment that was ‘left-out’. Based on the results, the parameter values calibrated when Likhu was ‘left-out’ were selected for application to all catchments

<table>
<thead>
<tr>
<th>Catchment left out</th>
<th>Dudh Koshi</th>
<th>Indrawati</th>
<th>Likhu</th>
<th>Tama Koshi</th>
<th>Tamor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias (%)</td>
<td>NSE</td>
<td></td>
<td>Bias (%)</td>
<td>NSE</td>
</tr>
<tr>
<td>DudhKoshi</td>
<td>-20.15</td>
<td>0.17</td>
<td></td>
<td>-46.34</td>
<td>-0.31</td>
</tr>
<tr>
<td>Indrawati</td>
<td>9.56</td>
<td>0.05</td>
<td></td>
<td>-51.29</td>
<td>-0.49</td>
</tr>
<tr>
<td>Likhu</td>
<td>7.70</td>
<td>0.12</td>
<td></td>
<td>-52.05</td>
<td>-0.52</td>
</tr>
<tr>
<td>TamaKoshi</td>
<td>13.54</td>
<td>-0.06</td>
<td></td>
<td>-48.32</td>
<td>-0.39</td>
</tr>
<tr>
<td>Tamor</td>
<td>11.39</td>
<td>-0.02</td>
<td></td>
<td>-50.47</td>
<td>-0.45</td>
</tr>
</tbody>
</table>

Table 5 Calibrated snow parameter values from the LOOCV procedure. The parameter values calibrated when Likhu was ‘left-out’ were applied to all catchments

<table>
<thead>
<tr>
<th>Catchment left out</th>
<th>DDFsnow (mm.°C⁻¹.day⁻¹)</th>
<th>MeltThreshold (°C)</th>
<th>TaccumThreshold (°C)</th>
<th>Tfraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>DudhKoshi</td>
<td>4.51</td>
<td>0.97</td>
<td>2.97</td>
<td>0.83</td>
</tr>
<tr>
<td>Indrawati</td>
<td>3.42</td>
<td>-0.95</td>
<td>2.97</td>
<td>0.74</td>
</tr>
<tr>
<td>Likhu</td>
<td>3.29</td>
<td>-0.78</td>
<td>2.96</td>
<td>0.78</td>
</tr>
<tr>
<td>TamaKoshi</td>
<td>2.16</td>
<td>-2.12</td>
<td>3.00</td>
<td>0.65</td>
</tr>
<tr>
<td>Tamor</td>
<td>4.47</td>
<td>-0.36</td>
<td>2.99</td>
<td>0.77</td>
</tr>
</tbody>
</table>
Preliminary analysis of hydroclimate and streamflow modelling in the Koshi Basin

3.5.2 Streamflow

The streamflow performance statistics for each of the catchments are presented in Table 6, with the hydrographs for the different catchments shown in Figure 19. Overall, the model performed reasonably well during the calibration period, with daily NSE values for headwater catchments ranging from 0.62 to 0.88 and absolute biases less than 10%. In general, there is good agreement between magnitude of the peak flows and the timing of modelled and gauged streamflows, as shown in Figure 20. The exception was the Arun catchment where the initial calibration using NSE
only resulted in poor recessions during autumn. To improve the modelling of the recessions in autumn, the Arun was recalibrated using a combination of NSE and logNSE, with equal weights for both objective functions. The issues that arose in the Arun is likely to be caused by the relatively course rainfall provide by the WATCH data.

The performance of modelled streamflow at the nodes at which the SunKoshi streamflow parameters were calibrated, Gauge 681 (downstream of the Indrawati / Melamchi, TamaKoshi, Likhu and DudhKoshi catchments) is reasonably good, compared with the performance at and 690 (downstream of the Tamor catchment), where there are relatively large biases. We believe the large biases are as a result of gauging errors as the gauge is just 40km downstream of the 684 gauge which is more consistent through calibration and validation. For most catchments (except Likhu), good performance was also maintained in the validation periods, with the exception of Gauge 690 which still has relatively large bias although improved in relation to the calibration period.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Calibration Period</th>
<th>Calibration Bias (%)</th>
<th>NSE</th>
<th>Validation Period</th>
<th>Validation Bias (%)</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arun</td>
<td>1989-1996</td>
<td>-8.4</td>
<td>0.64</td>
<td>2000-2009</td>
<td>-4.5</td>
<td>0.70</td>
</tr>
<tr>
<td>Dudh Koshi</td>
<td>1986-1996</td>
<td>-5.3</td>
<td>0.80</td>
<td>2000-2009</td>
<td>-11.5</td>
<td>0.72</td>
</tr>
<tr>
<td>Indrawati / Melamchi</td>
<td>1986-1996</td>
<td>-0.7</td>
<td>0.88</td>
<td>2000-2009</td>
<td>13.9</td>
<td>0.79</td>
</tr>
<tr>
<td>Likhu</td>
<td>1994-2008</td>
<td>-5.8</td>
<td>0.63</td>
<td>1986-1991</td>
<td>9.5</td>
<td>0.69</td>
</tr>
<tr>
<td>Tamakoshi</td>
<td>1995-2009</td>
<td>-0.7</td>
<td>0.77</td>
<td>1986-1994</td>
<td>-15.8</td>
<td>0.82</td>
</tr>
<tr>
<td>Tamor</td>
<td>2001-2004</td>
<td>-2.4</td>
<td>0.85</td>
<td>2005-2009</td>
<td>6.8</td>
<td>0.83</td>
</tr>
<tr>
<td>Sun Koshi (Chatara)</td>
<td></td>
<td></td>
<td></td>
<td>1996-2003</td>
<td>9.8</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2005-2009</td>
<td>15.1</td>
<td>0.80</td>
</tr>
<tr>
<td>Sun Koshi Gauge 681</td>
<td>1996-2003</td>
<td>16.5</td>
<td>0.86</td>
<td>2005-2009</td>
<td>-0.9</td>
<td>0.91</td>
</tr>
<tr>
<td>Tamor Gauge 690</td>
<td>1996-2003</td>
<td>-38.7</td>
<td>0.62</td>
<td>2005-2009</td>
<td>-23.0</td>
<td>0.74</td>
</tr>
</tbody>
</table>

The calibration and validation results shown in Table 6 were also compared to published results of other studies, as shown in Table 7, Table 8 and Table 9. For the Tamor catchment, the model show similar performance to an application of GR4JSG and GR4JSG by Nepal et al. (2016) which used a different set of input data, and a much better performance in terms of NSE than an application of SWAT (IWMI 2013) for the same period. Although for different periods, the performance is also similar to the results from SRM (Panday et al. 2014, shorter calibration) and J2000 (Nepal 2012, longer calibration. In addition to the different input data used by Nepal et al. (2016), the results in that study maybe show a different bias due to the unconstrained ice melt in that study, which may provide more melt for runoff.
Figure 19 Modelled and gauged streamflow at catchment outlets for calibration and validation periods. Sun Koshi streamflow is modelled using modelled inflows from upstream catchments
A similar set of results is shown in Table 8 for the Dudh Koshi catchment, with the version of GR4JSG used in this study showing a slightly poorer performance to Nepal et al. (2015). The results in this study showed similar performance when compared to SRM and GR4J (Pokhrel et al. 2014), although in this study we used a much longer period for validation and calibration. In similar fashion to the results for the Tamor catchment, the reduction in performance in this study when compared to Nepal et al. (2015) is likely to be a function of the different input data and the constraint on the ice melt.

Other studies (Lutz et al. 2014, IWMI 2013) use the gauge 695 located at Chatara for calibration. In this study we have not used the gauge at Chatara. When we compared the streamflow at the gauge at Chatara to nearby gauges the total streamflow seemed inconsistent. The flow at Chatara should always be greater than the upstream gauges. However, in Figure 16, the top graph shows the difference in total monthly volumes between Chatara and the sum of the three gauges located immediately upstream of Chatara – gauges 606 (Simle), 681 (Hampchuwar at Sun Koshi), 690 (Mulghat).

We have more confidence in the upstream gauges because they are mostly consistent with the gauges further upstream. As shown in the bottom graph of Figure 16, the sum of the 3 gauges are mostly greater than the sum of the upstream gauges (604.5, 630, 660, 670, 647 and 684), as expected. This allowed for a sensible calibration of the downstream catchment area.
Figure 20 Comparison of monthly volumes at gauged stations. The top graph shows the difference between Chatara (gauge 695) and the sum of the 3 gauges immediately upstream (blue line), and the difference of the sum of the 3 gauges and the sum of all headwater catchment used in this study (red line). The bottom graph shows the flows at Chatara (blue line) and the sum of the 3 gauges (red line) minus the sum of all headwater catchment used in this study (red line).

The results of our model at the Chatara gauge and other studies are shown in Table 9. Other studies have calibrated larger catchment areas to the Chatara gauge so they have not resolved the internal inconsistencies in streamflow gauging. For reference, it is possible to calibrate GR4J to the Chatara gauge with a bias of -1.5% and a NSE of 0.91 (period 1998-2005), but the resulting parameter set required a groundwater exchange of almost -10 to account for the problems at the gauge.
When the model is evaluated against the Chatara gauge, the model overestimates the flow, which we would expect. Likewise, studies by Lutz et al. (2014) and IWMI et al. (2013) show a similar disparity. We recommend calibrating to gauges upstream of Chatara to avoid building parameter sets that are unjustified.

### Table 9 Streamflow calibration and validation performance statistics for this study and other studies at Chatara

<table>
<thead>
<tr>
<th>Model</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period</td>
<td>PBIAS</td>
</tr>
<tr>
<td>GR4JSG (this study) [Not calibrated to Chatara]</td>
<td>1996-2003</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWAT (IWMI 2013)</td>
<td>2001-2004</td>
<td>8.7</td>
</tr>
<tr>
<td>SPHY (Lutz et al. 2014)</td>
<td>1998-2007</td>
<td>7.9</td>
</tr>
<tr>
<td>SWAT (Bharati et al. 2012)</td>
<td>1996-2000</td>
<td>0.62</td>
</tr>
</tbody>
</table>

The other catchments in this study have a smaller set of models available for comparison, with one study for the Tama Koshi (Khadka et al. 2014) and two studies for the Arun, one by IWMI (2013) and one by Lutz et al. (2014). In the Tama Koshi, Khadka et al. used the SRM model for calibration in the period 2004-2008 (NSE=0.82, PBIAS = -2.1%) and for validation in 2001-2002 (NSE=0.86, PBIAS = 2%). We do not believe that two years is an adequate length to evaluate the model. However, if it were we would conclude that the values for the model in this study are inferior to those reported by Khadka et al. (2014).

In the Arun basin, Lutz et al. (2014) used a long period for calibration (1998-2007) but have not performed a validation on the gauge, and reported a NSE of 0.87 and PBIAs of -5.4 %. In our case, for a slightly different validation period (1989-1996), we have a similar bias but a poorer NSE. A similar comparison is possible to the model results using SWAT reported by IWMI (2003), as the periods for calibration and validation were the same as in this study. The results in IWMI (2003) were NSE of 0.81 and PBIAS of 5.8% for calibration and NSE of 0.61 and a very large PBIAS of -25.8% for validation. The GR4JSG model used in this study had relatively lower biases across both calibration and validation periods.

The calibrated streamflow parameter values are presented in Table 10. For most catchments, the value of x1 (production store) was slightly above the recommended value range. The high x2 value in TamaKoshi, Likhu and Dudh Koshi suggests that these catchment are importing water, possibly due to errors in rainfall (or gauging as discussed above). The x4 values are at the lower end of the recommended range, indicating a relatively fast hydrograph recession.
Table 10 Calibrated streamflow parameter values. Parameter values on the boundaries of the recommended value ranges (Table 1) are shown in red

<table>
<thead>
<tr>
<th>Catchment</th>
<th>x1 (mm)</th>
<th>x2 (mm)</th>
<th>x3 (mm)</th>
<th>x4 (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arun</td>
<td>1240.21</td>
<td>1.47</td>
<td>56.83</td>
<td>1.10</td>
</tr>
<tr>
<td>DudhKoshi</td>
<td>596.34</td>
<td>4.87</td>
<td>349.02</td>
<td>0.59</td>
</tr>
<tr>
<td>Indrawati/Melamchi</td>
<td>1777.23</td>
<td>0.36</td>
<td>360.70</td>
<td>0.63</td>
</tr>
<tr>
<td>Likhu</td>
<td>1801.81</td>
<td>5.00</td>
<td>298.96</td>
<td>1.15</td>
</tr>
<tr>
<td>TamaKoshi</td>
<td>423.24</td>
<td>4.62</td>
<td>498.07</td>
<td>1.12</td>
</tr>
<tr>
<td>Tamor</td>
<td>1648.47</td>
<td>1.62</td>
<td>284.83</td>
<td>0.50</td>
</tr>
<tr>
<td>SunKoshi</td>
<td>1845.20</td>
<td>-2.83</td>
<td>208.59</td>
<td>1.12</td>
</tr>
</tbody>
</table>

3.5.3 Water balance components

Given the satisfactory performance of the hydrological for most catchments, it is possible to use the model to estimate the contributions of different rivers to the total flow at Chatara, as well as the relative contributions from rainfall, ice melt and snow melt to the total runoff. Note, that neither a sensitivity nor uncertainty analysis has been conducted, so there may be other parameter sets with similar performance scores that might generate different estimates of the relative contributions.

The generation of runoff across the different catchments and areas of the Koshi Basin is highly variable as shown in Figure 21, with the majority of the runoff generation occurring in the southern slopes of the Himalayas between 2000mASL and 3000mASL, and lower generation in the upper catchments of the Himalayas and the Tibetan Plateau (Arun) and in the Terai areas. This pattern is generally consistent with the rainfall distribution shown in Figure 12.

The upper reaches of the Arun sit in the rain shadow of the Himalayas and therefore receive relatively lower precipitation (Figure 12) and thus generate less runoff per unit area. Despite this fact, the Arun’s large catchment area means it still contributes about 30% of Koshi’s stream-flow at Chatara, as shown in Figure 22. The south western catchments of the Dudh Koshi, Tama Koshi and Indrawati also make significant contributions to the total streamflow at Chatara.
Figure 21 Runoff is generated predominantly at elevations between 2000mASL and 4000mASL. The Sunkoshi sits in a rain shadow, so runoff generated below 2000mASL is less. At higher elevations, snow and glacial processes become more important and generate a higher amount of runoff.

Figure 22 The accumulated flow of the tributaries of the Koshi show a significant portion of water coming from the Arun catchments.

In the Koshi Basin, snow that has accumulated through the winter season starts melting from April/May as the temperatures increase, leading to an increase in contribution to streamflow during the summer months, June to September. This generation of meltwater is an important process in the hydrological cycle of the Koshi Basin, with the most important contribution from snowmelt and ice melt being above 6000mASL (see Figure 23). Using GR4JSG, we estimate...
meltwater contribution to annual streamflow in the Koshi Basin to be approximately 9.4%, with most of this occurring during the monsoon months (Figure 24).

Figure 23 Results from GR4JSG model indicate that snow melt processes form a significant proportion of the water balance from above 4000mASL in the east of Nepal (note the 4000mASL to 6000mASL is skewed by the Tibetan plateau which sits in the rain shadow of the Himalayas)

Published estimates of snowmelt contribution to annual discharge in the different subcatchments of the Koshi Basin vary greatly, from 7% (Bookhagen and Burbank 2010) to 30% (Panday et al. 2014) for the Tamor catchment; to 25% (Bookhagen and Burbank 2010) for the Arun and 18% (Khadka et al. 2014) for the Tama Koshi; to 29-34% from snow and ice melt for the Dudh Koshi (Nepal et al. 2014; Savéan et al. 2015; Nepal 2016). On the other hand, other estimates for the Koshi Basin by Andermann et al. (2012) are substantially lower with a snowmelt contribution to total streamflow of 5% and ice melt contribution at 2%. A similar estimate of contribution to runoff from ice melt of 2% using glacier mass balances is suggested for the Ganges basin (Kaab et al. 2012).

As noted by Pellicciotti et al. (2012) there is considerable uncertainty about the contribution of snowmelt and ice melt to streamflow in the Koshi Basin, and one of the possible causes of uncertainty is the internal inconsistencies between models used for hydrological component assessment. As an example, in the model used here early snowmelt contributes to soil moisture and is therefore subjected to evaporation, while in other models all snowmelt is counted as contribution to runoff. For example, precipitation underestimation may result in overestimation of melt contributions to streamflow (Pellicciotti et al. 2012), as increases in the degree day factor can lead to extra melt to compensate for reduced rainfall and therefore still allowing the model to be calibrated to streamflow. Finger et al. (2011) also showed that the use of streamflow only to calibrate a hydrological model can lead to poor estimates of snow cover and mass balances of glaciers. The approach adopted here of calibrating for snow cover to set the snowmelt pattern and
quantities followed by setting a degree day factor for ice to produce realistic glacier changes is aimed to minimize excess melt to compensate for deficiencies in rainfall and provide a more defensible estimate of the various contributions.

**Figure 24** Contributions of snow melt, ice melt and rainfall to runoff in the Koshi Basin catchments. The Sun Koshi runoff includes runoff generated by upstream catchments. Most runoff is contributed by rainfall, but substantial proportions of runoff are also contributed by meltwater.
4 Characterising streamflow as a method to explore change

Nicky Grigg, Danial Stratford, Elise Boudier, Michaela Dolk, Hongxing Zheng, Luis Neumann and Dave Penton

Livelihoods across the Koshi Basin are dependent on ecosystem goods and services (van Oort et al. 2015, Sharma et al. 2015, Bhatta et al. 2016). Aquatic ecosystems underpin many of these goods and services, and include fisheries, floodplain agriculture, fodder for livestock, flood control and ecotourism (e.g. Sharma et al. 2015, Rai et al. 2015). The flow characteristics of a river are collectively referred to as the flow regime. The flow regime is a key influence on riverine ecosystems. Any changes in the flow regime can result in ecosystem changes, and so impact on the livelihoods that depend on them. Flow characterisation refers to the analysis of a flow regime in order to identify its key features, and can provide an input to understanding those features that determine ecosystem outcomes. It is essential, therefore, that an IAF contains knowledge about the ecological flow regime.

Bunn and Arthington (2002) identified the following principles of the ecological flow regime:

- Principle 1: the flow regime determines the physical habitat in stream (e.g. channel form, habitat complexity), which is a key determinant of biotic composition and diversity;
- Principle 2: Aquatic species have evolved life history strategies (e.g. spawning and recruitment) primarily in direct response to the natural flow regimes;
- Principle 3: Flow regime shapes both lateral and longitudinal connectivity (and so dispersal of migratory aquatic organisms) and access to otherwise disconnected floodplain habitats.
- Principles 4: Invasions by introduced species are more likely to succeed at the expense of local biota if introduced species are adapted to the modified flow regime.

It is common for river managers to cater for environmental flow needs by identifying minimum flow volumes, however the above four principles point to the importance of multiple components of the flow regime in order to sustain riverine ecosystems. There are flow variables that are useful for identifying important patterns or events that affect aquatic species and ecosystems. These include daily and seasonal flow patterns, flow velocity, timing of rising flows, altered water temperature (e.g. below dams and thermal power stations), frequency of wetland or floodplain inundation and the presence of water diversions or in-stream barriers. A series of daily flow measurements collected over several years can be used to characterise a range of these flow properties, identify and understand the range of hydrological habitats, and assess their likely changes under different development scenarios.

Several metrics and classification methods have been developed to assess ecologically-relevant characteristics of flow regimes. For example, Kennard et al. (2010) conducted an assessment of ecologically-relevant characteristics for hydrological regimes for Australian rivers using 120 flow metrics. Flow metrics summarise the statistical properties of the long-term flow data, and in particular they are useful for identifying changes to different aspects of the flow regime.
Assessments of this kind provide a strong evidence base for informing environmental flow requirements (Arthington et al. 2006), and are suited to frameworks for developing environmental flow guidelines (e.g. the Ecological Limits of Hydrologic Alternation (ELOHA) framework, Poff et al. 2010, Pahl-Wostl et al. 2013).

In the following sections, we demonstrate how the SDIP Koshi Basin modelling can be used to conduct analyses of flow metrics under different flow regimes.

### 4.1 Method and results of streamflow characterisation

Chapter 3 presents a hydrological model of the Koshi catchment that presents modelling daily flow at identified sites throughout the Koshi Basin. This can be used to project changes to the flow regime under different assumptions (e.g. climate change or development scenarios) by using different input data sets and model assumptions.

The modelling enables flow analysis comprising two components, illustrated in Figure 25:

1. Flow characterisation suitable for identifying and classifying different riverine habitats based on their flow attributes, so adding to current riverine ecosystem knowledge.
2. Flow alteration analysis for identifying sensitivities, vulnerabilities or significant changes that arise under different future scenarios or modelling assumptions.

![Figure 25 Steps for flow characterisation and flow alteration analysis](image)

The hydrological model generates daily time series of flow at the locations marked in Figure 26. These sites will be referred to as network points. We used the modelled flow time series to calculate a set of hydrological metrics for each flow location (Jin 2014), and used a clustering algorithm to identify classes of flow types. The choice of metrics reflects different components of the flow regime and hence affects the clustering, and it is a choice that will need to be reviewed and revisited in light of expert knowledge about which flow metrics are of most interest or relevance to ecosystems within the Koshi Basin. Here a subset of metrics (Table 11) was chosen simply to illustrate the potential for this approach, and more work is required to identify those flow metrics of most relevance in the Koshi Basin.
### Table 11 Flow metrics chosen for demonstration analysis. The metrics are drawn from Pusey et al. 2009 and Marsh et al. 2012

<table>
<thead>
<tr>
<th>Metric code</th>
<th>Unit of measurement</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA1</td>
<td>ML.day$^{-1}$</td>
<td>Mean daily flow</td>
</tr>
<tr>
<td>MA3</td>
<td>dimensionless</td>
<td>Coefficient of variation in daily flows</td>
</tr>
<tr>
<td>ML17</td>
<td>dimensionless</td>
<td>Baseflow index; that is ratio of base flow to total flow, averaged across all years. Baseflow is calculated using a filter according to Grayson et al. 1996.</td>
</tr>
<tr>
<td>MH14</td>
<td>dimensionless</td>
<td>Median of the highest annual daily flow divided by the mean annual daily flow averaged across all years</td>
</tr>
<tr>
<td>MH21</td>
<td>days</td>
<td>Mean of the high flow volume divided by the mean daily flow</td>
</tr>
<tr>
<td>FL1</td>
<td>year$^{-1}$</td>
<td>Low flood pulse count (&lt;75%); that is the number of annual occurrences during which the magnitude of flow remains below a lower threshold. Hydrologic pulses are defined as those periods within a year in which the flow drops below the 75th percentile (low pulse) of all daily values for the time period</td>
</tr>
<tr>
<td>DL2</td>
<td>ML.day$^{-1}$</td>
<td>Annual minima of 3-day means of daily discharge</td>
</tr>
<tr>
<td>MKTA1</td>
<td>month</td>
<td>Seasonality of mean daily flow</td>
</tr>
<tr>
<td>TH2</td>
<td>dimensionless</td>
<td>Variability in Julian date of annual maximum flow</td>
</tr>
<tr>
<td>RA1</td>
<td>ML.day$^{-1}$.day$^{-1}$</td>
<td>Rise rate; that is the mean rate of positive changes in flow from one day to the next</td>
</tr>
<tr>
<td>RA4</td>
<td>dimensionless</td>
<td>Variability in fall rate; that is the coefficient of variation in the mean rate of negative changes in flow from one day to the next</td>
</tr>
</tbody>
</table>

The metrics in Table 11 were calculated for the modelled time series for each network point. The metrics were used to form a classification based upon the differences and similarities of the metrics creating a dendrogram showing relationships between network points (Oksanen et al. 2015). The height of the branch points joining two network points indicates their level of similarity: a greater height indicates a greater dissimilarity.

The dendrogram is shown in Figure 27. The location of the network points is shown in Figure 26, and these are coloured according to the cluster identified in Figure 27. Currently these clusters are predominantly explained by differences in mean daily flow between network points, with network points of similar mean daily flow clustered alike. This clustering result is based on several underpinning assumptions, including the choice of metrics to include and the choice of clustering algorithm and associated parameters. These choices can be honed to better reflect flow characteristics of particular interest to river basin managers.

The primary benefit of classifying river reaches in this way is that it provides a basin-wide consistent approach for identifying different hydrological habitats in the absence of comprehensive ecological knowledge of every river reach. In doing so, basin-level patterns in hydrological habitat can be identified and inferences drawn about ecosystem flow requirements. Figure 27 shows that the clusters identified in dendrogram in Figure 26 are associated with high elevation sites, mid hills sites, Arun and Sun Koshi high flow sites and main trunk sites.
The above analysis was conducted on a ‘historical’ scenario, where the model was calibrated according to past observations and driven by historical climate inputs. The model can be configured to run alternative scenarios to assess impacts of climate change or development changes on the flow regime.

The flow metrics calculated for model time series create high-dimensional datasets. If there are 20 flow metrics of particular interest, ordination methods allow similarities and differences between network points to be readily visualised in two or three dimensions, rather than 20 dimensions. Ordination methods characterise similarity and dissimilarity of high-dimensional data points by positioning points in a lower-dimensional space so that relationships of interest between data points are maintained. Figure 28 demonstrates a conceptualisation of 2 dimensions of
environmental space within an ordination, and illustrates how such analysis can be interpreted to anticipate risks and opportunities for different species or ecosystems.

**Figure 28** Conceptualisation of an ordination space that illustrates how changes in environmental factors may affect different species differently. The filled ovals represent the dimensions of species’ environmental requirements and the unfilled ovals represent the dimensions of environmental space of a particular habitat under different climate scenarios. The environmental space of the current climate is depicted with the solid perimeter and the alternate future climate by the dashed perimeter. Under these hypothetical conditions, ‘Species A’ loses all its required environmental space, ‘Species B’ maintains environmental space within the altered conditions, while novel environmental space is created which favours the potential invasion of ‘Species C’

We have used a non-metric multidimensional scaling (nMDS) algorithm (Oksanen et al. 2015) to characterise the model results. An example is shown in Figure 29, and the points have been coloured according to the clusters identified in Figure 27. The nMDS plot confirms that the clustering is sensible, with network points in the same cluster occupying a similar region in the nMDS ordination space. Once alternative climate or development scenarios are developed it will be possible to repeat the ordination analysis and compare results to identify those network points that are most impacted under different scenarios (e.g. using a Procrustes analysis, Oksanen et al. 2015).
Figure 29 (Above) nMDS ordination plot for modelled network points, coloured by clusters identified in the dendrogram in Figure 27, confirming that network points in the same cluster occupy a similar region in nMDS ordination space.

4.2 Interpretation of streamflow characterisation

These are preliminary results, intended only to point to the methods that are available to glean more ecologically relevant insights from hydrological modelling. Further work is required to refine input knowledge and validate and check the results with local experts. Local experts are needed to link important ecosystem processes to attributes of the hydrograph that are relevant to valued freshwater ecosystem services, and to check and verify that any classification derived from the clustering analysis is consistent with on-ground observations, knowledge and experience. These checks are needed in order to have confidence in model conclusions.

Once baseline results are verified to be consistent with on-ground knowledge, the analysis of model scenarios with altered flow regimes is possible. Climate surfaces are being developed for the Koshi Basin and here we have outlined how alternative scenarios could be used to assess impacts on flow. Noting that any results of such scenario analysis needs to be interpreted in light of a sensitivity analysis of the hydrological model and flow characterisation calculation assumptions.

Flow classification and analysis does not provide definitive answers that prescribe what the flow regime of a river should be. Rather, it is one contribution to a body of evidence and a sound basis for deliberation on the multiple factors affecting river basin management decisions. There are many ways in which this deliberation can take place. Leading international practice recognises inevitable iteration and co-learning between hydrologists, ecologists, policy makers and other stakeholders in the development of environmental flow requirements. For example, the Sustainable Management of Hydrological Alterations (SUMHA) framework proposed by Pahl-Wostl
et al. (2013) builds upon the ELOHA framework to pay more attention to policy and management processes, Figure 30.

![Figure 30 Framework proposed by Pahl-Wostl et al. (2013): the Sustainable Management of Hydrological Alterations (SUMHA) Framework. It includes analysis of the hydrology (blue), ecology (green) and governance and management systems (orange squares) in order to inform the policy and management processes (orange rounded squares)](image)

### 4.3 Conclusions

In conclusion, the preliminary flow analysis points to a capacity to classify and assess changes to flow regimes in the Koshi Basin. Combined with knowledge of flow-ecosystem requirements this form of analysis can provide a well-grounded basis for assessing environmental change associated with modification of the flow regime. The analysis does not give prescriptive answer of what a flow regime should be, but it provides information that informs deliberation on environmental flow requirements. It can also guide the choice of management units, as well as informing where to invest effort in further research or monitoring of impacts of flow changes. The analysis provides a transparent evidence base, founded upon ecologically important components of the flow regime, and a quantitative assessment of change in these components under different scenarios. It provides one line of evidence for identifying where the system is most vulnerable to change, and this can be used to inform assessment of trade-offs between scenarios or prioritise basin management objectives.
Chapter 4 introduces the idea of characterising streamflow and identifying flow patterns that are similar or unique. Life along the river is expected to have evolved and adapted to the history of streamflow. When considering the potential changes to river systems, such as the sustainable development of infrastructure, understanding the dependencies between streamflow and ecology is important. The SUMHA framework (Pahl-Wostl et al., 2013), introduced in Section 4.2, describes a step in this process as generating flow-ecology hypotheses. Developing these flow-ecology hypotheses is critical for conducting integrated assessments. This chapter introduces recent work by Doody et al. (2016) to investigate the state of knowledge of flow-ecology hypotheses in the Koshi Basin.

Given the number of threatened species in the Koshi Basin, experts suggest that it is critical that further quantitative and qualitative water specific research is undertaken.

5.1 Building streamflow-ecology conceptual models

In the Koshi Basin, much of the knowledge about links between streamflow and ecology are not readily available, they may be known only by particular experts, they may be in the grey literature, or there may be a knowledge gap. TM Doody (Doody et al. 2016), through a process of expert elicitation, workshops and literature reviews, created a number of conceptual models to capture the known links between river flow and specific ecological components such as birds, fish, buffalo, crocodiles/gharials, invertebrates, flora and the freshwater Ganges River Dolphin.

Figure 31 is an example of a streamflow-ecology conceptual model for Water Buffalo. In a fairly simple schematic Basnet and Dahal (2016) describe the current known requirements of Water Buffalo. For example, the Water Buffalo need to have suitable habitat, including waterholes. Hypothetically, if there were proponents of a sustainable development that might impact the flow regimes of locations with Water Buffalo (perhaps using methods from Chapter 4), then the conceptual model would indicate that one measure to protect Water Buffalos might be management or monitoring of water holes.
5.2 Current knowledge on linkages

Qualitative (Table 12) and quantitative (Table 13) relationships were extracted from the knowledge assembled by the experts.

Table 12 Quantitative relationships that have been identified through scientific studies in Nepal

<table>
<thead>
<tr>
<th>Ecological component</th>
<th>Threshold to flow (quantitative relationships)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td>Snow Trout (<em>Schizothorax</em> spp) require ability to migrate upstream to spawn in March to June at water temperatures between 14–21°C. Require clear water of depths 30–60 cm to lay eggs in gravel along stream bank.</td>
</tr>
<tr>
<td>Fish</td>
<td>Require (in general) a dissolved oxygen of between 5–7 mg L⁻¹.</td>
</tr>
<tr>
<td>Fish</td>
<td>Maximum water temperature of 28.16 (±0.19) °C and minimum water depth of 3.0–3.6 m, is unfavourable for most fishes.</td>
</tr>
<tr>
<td>Fish</td>
<td>Common carp (<em>Cyprinus carpio</em>) and grass carp (<em>Ctenopharyngodon idella</em>) require a water temperature between 10–25°C for reproduction.</td>
</tr>
<tr>
<td>Grassland bird</td>
<td>Swamp francolin (<em>Francolinus gularis</em>) prefers high density grass 2–3 m tall.</td>
</tr>
<tr>
<td>Grassland bird</td>
<td>Bengal florican (<em>Houbaropsis bengalensis</em>) males prefer moist, short, pure grassland 15–35 cm tall.</td>
</tr>
<tr>
<td>Grassland bird</td>
<td>Bengal florican (<em>Houbaropsis bengalensis</em>) females prefer moist grassland &gt;110 cm tall.</td>
</tr>
<tr>
<td>Water bird</td>
<td>Lesser Adjutant Stork (<em>Leptoptilos javanicus</em>) nests in tall trees generally &gt;30m high.</td>
</tr>
<tr>
<td>Buffalo</td>
<td>Requires alluvial tall grassland composed of 80% <em>Sacchrum</em> spp.</td>
</tr>
<tr>
<td>Buffalo</td>
<td>Need to wallow 6–8 hours a day to cool themselves.</td>
</tr>
<tr>
<td>Crocodile</td>
<td>Suitable substrate for basking – 62% sand/sand bar and 37% rocky substrate.</td>
</tr>
<tr>
<td>Crocodile</td>
<td>Requires shade by 14:00 in winter to manage thermoregulation.</td>
</tr>
<tr>
<td>Crocodile</td>
<td>Water depth – juveniles require 1–3 m depth, if 120–180 cm long, require 2–3 m but will use &gt;4 m water depth if available, adults require water depth &gt;4 m.</td>
</tr>
<tr>
<td>Dolphin</td>
<td>Water depth – adult/calf pairs require less than 2.2–2.4 m depth, sub-adults require &gt;3.8 m depth and adults require &gt;5 m.</td>
</tr>
<tr>
<td>Dolphin</td>
<td>Gillnets that go to 4.5 m depth are a threat to dolphin life.</td>
</tr>
<tr>
<td>Dolphin</td>
<td>Require channels with a cross-sectional area of &gt;700 m² to ensure forging opportunities.</td>
</tr>
</tbody>
</table>
Table 13 Qualitative relationships identified between river flow and ecological components in the Koshi Basin

<table>
<thead>
<tr>
<th>Ecological component</th>
<th>Relationship between ecology and river flow (qualitative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td>Mahseers (<em>Tor putitora</em> and <em>Tor tor</em>) and Katle (<em>Neolissochilus hexagonolepis</em>) require cool, clean river pools and lakes with oxygenated water interconnected with mid hill river streams, often in upper floodplain reaches. Temperatures are often less than 21°C</td>
</tr>
<tr>
<td>Fish</td>
<td>Reduction in longitudinal connectivity, increasing anoxia, increasing area of macrophyte biomass and increasing nutrients lead to alteration of fish community composition</td>
</tr>
<tr>
<td>Forest bird</td>
<td>Woodpeckers nest in tree cavities in forested riverine areas</td>
</tr>
<tr>
<td>Forest bird</td>
<td>Woodpeckers feed on water dependent arthropods and other insects</td>
</tr>
<tr>
<td>Grassland birds</td>
<td>Swamp Francolin (<em>Francolinus gularis</em>) feed on water-dependent tubers, invertebrates and small vertebrates</td>
</tr>
<tr>
<td>Grassland birds</td>
<td>Bengal Florican (<em>Houbaropsis bengalensis</em>) feed on aquatic plants (winter/spring) and invertebrates (summer)</td>
</tr>
<tr>
<td>Grassland birds</td>
<td>Indian Courser (<em>Cursorius coromandelicus</em>) requires a large expanse of water-dependent grassland</td>
</tr>
<tr>
<td>Water bird</td>
<td>Black-bellied Tern (<em>Sterna acuticauda</em>) require undisturbed fish rich wetlands</td>
</tr>
<tr>
<td>Water bird</td>
<td>Black-bellied Tern (<em>Sterna acuticauda</em>) breed along sandy river banks between March and June</td>
</tr>
<tr>
<td>Water bird</td>
<td>Black-bellied Tern (<em>Sterna acuticauda</em>) feed on fishes</td>
</tr>
<tr>
<td>Water bird</td>
<td>Lesser Adjutant Stork (<em>Leptoptilos javanicus</em>) nests in water dependent <em>Bombax ceiba</em> and <em>Adina cordifolia</em></td>
</tr>
<tr>
<td>Water bird</td>
<td>Lesser Adjutant Stork (<em>Leptoptilos javanicus</em>) feeds on water dependent snails, fishes and reptiles</td>
</tr>
<tr>
<td>Water bird</td>
<td>Common Merganser (<em>Mergus merganser</em>) inhabits medium to larger rivers and lakes</td>
</tr>
<tr>
<td>Water bird</td>
<td>Common Merganser (<em>Mergus merganser</em>) is an excellent swimmer but not able to live outside of waterbodies</td>
</tr>
<tr>
<td>Water bird</td>
<td>Common Merganser (<em>Mergus merganser</em>) live exclusively on fish</td>
</tr>
<tr>
<td>River bird</td>
<td>Little Forktail (<em>Enicurus scouleri</em>) prefer small to large rivers with cascading water, wet boulders to forage on and exists on an aquatic diet</td>
</tr>
<tr>
<td>River bird</td>
<td>Brown Dipper (<em>Cinclus pallasii</em>) prefer the channel centre of small to large rivers with cascading water and forage underwater for aquatic organisms. They also live on terrestrial water dependent organisms</td>
</tr>
<tr>
<td>River birds</td>
<td>Black-back and Slaty-back Forktails (<em>Enicurus immaculatus</em> and <em>E. schistaceus</em>) feed on channel margins of rivers and lakes</td>
</tr>
<tr>
<td>River bird</td>
<td>Spotted Forktail (<em>Enicurus maculatus</em>) prefers to forage in small, shaded streams with lots of leaf litter, feeds on riparian margins</td>
</tr>
<tr>
<td>River bird</td>
<td>Plumbeous Water Redstart (<em>Rhyacornis fuliginosa</em>) prefers small to large rivers to forage on a mixed aquatic-terrestrial diet, often found feeding on wet boulders</td>
</tr>
<tr>
<td>River bird</td>
<td>White-capped Water Redstart (<em>Chairmannornis leucocephalus</em>) prefers small to large rivers. Feeds on water dependent flying and ground prey, found on the outer rim of the riparian zone</td>
</tr>
<tr>
<td>River bird</td>
<td>Blue Whistling Thrush (<em>Myiophonus caeruleus</em>) prefers small to large rivers. Feeds on water dependent flying and ground prey, found on the outer rim of the riparian zone</td>
</tr>
<tr>
<td>River bird</td>
<td>Kingfisher species are directly dependent on river fish stock</td>
</tr>
<tr>
<td>Buffalo</td>
<td>Require mixed riverine forest in order to have shade and to exfoliate after wallowing</td>
</tr>
<tr>
<td>Buffalo</td>
<td>Require water dependent <em>Saccharum</em> spp for grazing</td>
</tr>
<tr>
<td>Crocodile</td>
<td>Require basking substrate in close proximity to deep water</td>
</tr>
<tr>
<td>Ecological component</td>
<td>Relationship between ecology and river flow (qualitative)</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------------------------------------------------</td>
</tr>
<tr>
<td>Crocodile</td>
<td>Require habitat for camouflage – good riparian vegetation, suitable water depth and river banks suitable for burrows</td>
</tr>
<tr>
<td>Dolphin</td>
<td>50% of sightings occur at river confluences. Eddy counter currents are important for persistence</td>
</tr>
<tr>
<td>Dolphin</td>
<td>Require a high degree of lateral and longitudinal connectivity</td>
</tr>
<tr>
<td>Dolphin</td>
<td>Require high fish numbers for feeding</td>
</tr>
<tr>
<td>Macro invertebrate</td>
<td>Maintain taxon richness in areas with little or no flow alteration</td>
</tr>
</tbody>
</table>

Knowledge gaps were identified as part of the process and tabulated (Table 14).

**Table 14** A summary of the knowledge gaps identified across the chapters within this report

<table>
<thead>
<tr>
<th>Knowledge/lack of gaps – ecology and hydrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed information about rangeland ecosystems (limited information available)</td>
</tr>
<tr>
<td>Comprehensive floristic inventory at Basin scale</td>
</tr>
<tr>
<td>Comprehensive faunal inventory at Basin scale (include fish, macroinvertebrates, birds and herpitofauna)</td>
</tr>
<tr>
<td>Response to flow regime alteration of all ecological components</td>
</tr>
<tr>
<td>Detailed understanding of flow requirements of ecological components especially thresholds which once altered lead to community decline (currently limited understanding)</td>
</tr>
<tr>
<td>Identification of terrestrial, riparian and aquatic corridor linkages</td>
</tr>
<tr>
<td>Monitoring of fishes, buffalo, birds, crocodiles, dolphins, macroinvertebrates to determine important flow parameters</td>
</tr>
<tr>
<td>Parameters of the flow regime important to fishes, buffalo, birds, crocodiles, dolphin, macroinvertebrates</td>
</tr>
<tr>
<td>How to address lack of appropriate fish ladders</td>
</tr>
<tr>
<td>Mapping of upstream distribution of crocodiles and dolphins and their associated breeding success, sex ratio, and food requirements</td>
</tr>
<tr>
<td>Habitat information on water quality, depth and availability of basking and nesting for crocodiles and dolphin</td>
</tr>
<tr>
<td>A standard crocodile and dolphin survey method</td>
</tr>
<tr>
<td>Why did reintroduced gharials fail? Need to track animals to understand</td>
</tr>
<tr>
<td>Conservation plan for mugger crocodiles</td>
</tr>
<tr>
<td>How much water is needed, when and how should it be delivered?</td>
</tr>
<tr>
<td>Flow characterisation</td>
</tr>
<tr>
<td>Impacts of climate change on flow regime</td>
</tr>
<tr>
<td>Level of stream disconnection caused from hydropower infrastructure</td>
</tr>
<tr>
<td>Is the 10% rule of thumb applicable everywhere?</td>
</tr>
<tr>
<td>Quantitative data on minimum river flow requirement, especially during low flow season</td>
</tr>
<tr>
<td>Long-term monitoring plots across an altitudinal transect to monitor the impacts of climate change and human abstraction</td>
</tr>
<tr>
<td>Monitoring of climate change impacts on water resources</td>
</tr>
<tr>
<td>Studies on glacial lake outburst floods and effects downstream on ecosystems</td>
</tr>
</tbody>
</table>
The flow-ecology relationships for flora were difficult to identify, however a comprehensive understanding of the biodiversity values of both flora and fauna are presented across two chapters. Nepal and the Koshi Basin contain some of the most diverse regions throughout the world, however, there is an evident lack of floristic and faunal inventory at the Basin scale. There is also a lack of knowledge relating to connectivity between terrestrial, riparian and aquatic systems, as well as the importance of hydrological connectivity upstream and downstream, particularly in transboundary situations.

Wetlands and aquatic ecosystems are well recognised for their significant role in supporting high biodiversity and providing food, water and livelihoods security. The National water plan of Nepal, released in 2005, encourages integrated water resource management to promote sustainable water use. It emphasises meeting the needs of the current generation, without compromising the needs of future generations, while at the same time maintaining the freshwater ecosystems of Nepal. However, significant research investment is required to better understand the water requirements of ecological components; and to understand the flow characteristics and connectivity of rivers, streams and wetlands under conditions of natural flow variability (where possible) to protect aquatic ecosystems into the future. Providing such critical ecological baseline data for selected species then provides a way to monitor water resources, especially under predicted increasing abstraction, particularly from hydropower development, to ensure detrimental ecosystem decline is not occurring. Baseline data also means the current environmental flow ‘rule of thumb’ (10% of the rivers mean monthly flow should be maintained within the river throughout the year in the dewatered sections) for dammed or diverted river systems in Nepal can be tested and amended for each potentially impacted river system. There is currently little understanding as to whether the environmental flow ‘rule of thumb’ is sufficient to protect all aquatic ecosystems across Nepal, yet it is the main determinant of environmental flow allocations.

5.3 Conclusion

The bringing together of the current state of knowledge for the Koshi Basin in the one report has been welcomed by the local experts. We are hopeful that Doody et al. 2016 will be widely distributed within the Nepal academic and government communities. It is a contribution to building the strong evidence base that is required to guide the future management of Nepal’s water and natural resources which will be under pressure from development projects and climate change.
6 Policy actor perspectives on water governance in the Koshi Basin

Tira Foran and Shawahiq Siddiqui

This research project engages with the topic of how expert knowledge can influence water governance, with a focus on the Koshi transboundary Basin, and expert knowledge in the form of river basin modelling. We asked: Can river basin modelling lead to greater mutual understanding of development benefits and trade-offs within the Ganges basin? If so, how? This project was a preliminary exploration of the above central research question, pursued through 42 semi-structured interviews with a variety of state and non-state actors working in the domain of water governance in India, Nepal, and Bangladesh. This chapter presents initial findings based on content analysis of 25 interviews.

The institutional context for this research includes a number of dynamics at domestic and transboundary levels. The Koshi Basin has no existing official framework or organisation for cooperation around integrated river basin planning. Existing international agreements are relatively narrowly focussed. For example, treaties focus on the governance of particular water infrastructure schemes (such as the Koshi Barrage) and are bilateral as opposed to multilateral. International river agreements also do not cover contemporary issues.

For example, the governments of India, China, and Nepal have endorsed large hydropower schemes for domestic consumption, schemes which can be controversial for social, environmental, and economic reasons (Dixit and Gyawali 2010, Alley 2012, Alley 2014, Choudhury 2014). In Nepal, as a result of generous benefit sharing provisions which some developers have offered, large run-of-river hydropower schemes are not necessarily opposed by local people (Lord 2016). However both state and civil society organisations in Nepal have expressed caution about the costs of large storage dams, and different positions are held about the appropriate contribution of hydropower to national development (Gyawali 2009, Dixit and Gyawali 2010).

One obstacle to hydropower development has been the absence (until October 2014) of a power trade agreement between India and Nepal, which has restricted export-oriented schemes. An eventual boom in hydropower development could result in unbalanced development unless governance processes better represent the interests of people whose livelihoods depend on sustained access to water and sustained ecosystem services (Alley 2014, King and Smith 2016).

Aware of such risks as well as opportunities, development donors have supported technical efforts, as well as civil society-led efforts, around transboundary cooperation and dialogue. With respect to technical efforts, in recent years, several organizations (including World Bank, IWMI, CDKN, CSIRO, and ICIMOD) have invested resources into building catchment water balance or river basin models in the Ganges and/or its tributary river basins. Such interest is based on the expectation that better knowledge of hydrological flows and balances will increase understanding of potential development benefits and trade-offs within a basin (e.g. using tools such as hydro-economic modelling). In some OECD countries, such knowledge assists decision-makers to negotiate outcomes in contested spaces (e.g. water sharing between Australian states). Donors...
and investors expect that better knowledge and mutual understanding will, in-part, support domestic and international development agendas, which in turn will help achieve the Sustainable Development Goals.

However, complicating this process, prior histories of interaction, involving complex forms of competition and cooperation, within and between nation states, exist around water in the Koshi, and more broadly, in the Ganga-Brahmaputra-Meghna Basin. Particular projects such as the Koshi Barrage, Gandak Barrage (1964), or proposed projects such as the Koshi High Dam (Chatara Gorge) or the proposed Pancheswar Dam on the Mahakali river symbolize, to some observers, unresolved issues between or within countries (Dhungel and Pun 2009; World Bank 2014).  

Such issues suggest that initiatives involving the use of expert knowledge as platforms transboundary dialogue and cooperation will inevitably take place in a context of considerable social complexity. The Ganges Strategic Basin Assessment (GSBA) is a case in point. Led by World Bank, this three-year study involved literature review and a new basin-scale hydrological and economic initiative, conducted by a number of regional research institutes and consultants. The Assessment’s objective was to gain:

>a better understanding of the dynamics of the river basin from a system-wide perspective, by creating a knowledge base and suite of modeling tools that can be used to examine the potential impacts of development in the basin and support an information-based dialogue within and between riparian countries. This new information is envisaged to encourage, rather than conclude, debate on critical transboundary management issues in the Ganges. (World Bank 2014: )

The GSBA undertook to answer a set of ten strategic questions, including the potential for upstream water supply infrastructure to control flooding, and augment low-season flows downstream (Sadoff et al. 2013; World Bank 2014). The study offered many insights on the strategic questions, in line with its objective of catalysing technical debate. For example, asking whether building major water storage infrastructure upstream will suffice to control flooding downstream in Bihar, the authors answer in the negative, arguing that most of the flooded area in Bihar is outside of the Koshi Basin, most of the rivers are embanked, and that most floods are caused by rainfall and embankment breaches. They argue that although upstream water storage could double dry season flows, similar benefits could be obtained by better groundwater management, and in any case, the value of such flows is unclear (Sadoff et al. 2013).

The GSBA however met with a cool reaction from water professionals and other policy actors in Nepal, as well as among some key Indian policy actors (Pun 2013; Interview 2, state planner, 1/4/14; Interview 7, state planner, 22/5/14). Reasons provided for the unfavourable reactions to the study ranged from its exclusion of detailed hydrological data from India (which the study was not permitted to access), to a belief that the authors had underestimated the value of upstream

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1 For example, critics argue that location of the Koshi Barrage adjacent to the Nepal-India border is sub-optimal, resulting in India receiving a majority of the benefits, notably for irrigation (969,110 ha in India vs. 34,690 ha Nepal) and flood control. Supporters have argued that Nepal received an appropriate share of benefits, without having to invest any financial resources in the scheme (Dhungel and Pun 2009)).

2 Notably, the Institute of Water Management (Bangladesh), IIT (Delhi), and Integrated Natural Resources Management, Ltd (Delhi).
storage dams for downstream flood control and agricultural benefits (Interview 10, inter-governmental expert, 12/6/14).

The mixed stakeholder reaction to the GSBA underscores the importance of creating a conducive governance context around expert knowledge generation in the Ganga Basin. Accordingly, this project attempted to understand that context by inviting experienced policy actors to share their perceptions and insights related to the interface between expert knowledge and governance.

6.1 Methodology for conceptualizing water governance

In order to understand the potential of modelling in the context of south Asian and transboundary water governance, it is helpful to begin with a conceptual framework that situates expert knowledge within governance processes. By governance, we mean the characteristic structures and dynamic processes by which society makes decisions about what its objectives are, and its strategies and means to achieve those objectives. Those structures and processes are multi-level and include feedback loops (Figure 32).

Figure 32 Dore et al. (2012) presents a framework for analysing transboundary water governance complexes. It involves six key areas for consideration: the broad Context that decision-making takes place, the Arenas that contest ideas, the Drivers which direct the discussion, the Tools for guiding discussion, the Decisions that result and the Impacts that result from the process.

An initial governance context includes structures by which stakeholders are represented (more or less equitably), how decision making power is distributed formally and informally, and mechanisms by which power-holders may or may not be held responsible for their decisions. Within the governance context there exist action arenas, which are venues shaped by existing rules, power resources, and patterns of conflict or cooperation (Ratner et al. 2013).

Decisions or management actions are visualized as taking place in action arenas in which different actors interact (in conflict or cooperation), making use of different resources (including expert knowledge) and appealing to various rules which may favour their individual or group objectives. Actors are assumed to be goal-seeking, but act within bounded rationality (Weible et al. 2012). Decisions taken (or avoided) in such arenas lead to outcomes, and actors’ evaluations of them. Feedbacks occurs from outcomes to the governance context and to action arenas.
Scholars of environmental governance have offered a number of propositions for how expert knowledge (e.g. Strategic Environment Assessment, hydro-economic modelling) interacts with an array of other forces to shape water-related decision making. Dore et al. (2012) visualize expert or technical knowledge as one of several ‘tools’ – i.e. socio-technical practices – which could influence action ‘arenas.’ Decision arenas are however influenced by larger contexts as well as specific mediating processes (shown as ‘drivers’ in Figure 32).

Although expert knowledge (i.e. scientific knowledge) could be regarded as a technical tool, we consider it more accurate to regard expert knowledge as one of several kinds of representational input into political arenas. Thus modelling cannot help but co-exist with other forms of knowledge, (such as the experiential knowledge of actors).  

Literature associated with the Advocacy Coalition Framework (ACF) proposes that ‘information’ and expert knowledge can influence policy processes in the following ways (Weible 2008):

- instrumentally, when knowledge is used directly by receptive policy actors to inform governance decisions (with a minimum of reframing)
- politically, when expert knowledge is actively manipulated as a power resource, to strengthen the prior political positions of actors, in a moderately or highly contested policy arena
- learning, as when knowledge allows policy actors learn, over an extended period of time, through dialogue with each other, resulting in changes to actors’ causal beliefs or goals.

The socio-political properties of the arena influence how knowledge is used. The ACF views policy decisions as flowing from the competition of rival coalitions, which compete for access to power. A coalition is a multi-actor network which shares core values and is coordinated by entrepreneurial principal members. The ACF distinguishes between “unitary”, “collaborative”, and “adversarial” policy domains, with the number of actors and the degree of political contestation increasing from unitary to adversarial. The domestic and transboundary water politics of the Ganga and Koshi Basins appear to best fit the model of an “adversarial” policy domain (e.g. Dhungel and Pun 2009). The ACF proposes that learning occurs best in collaborative policy domains. In such domains, rival political coalitions exist which nonetheless have some degree of cross-coalition interaction or brokerage, for example via alternative dispute resolution or deliberative venues (Weible 2008).

6.2 Research methods for interviewing policy actors

Research methods included a review of several relevant literatures. In addition to the water governance and policy process literature introduced above, we surveyed literature on transboundary water politics (e.g. Jägerskog and Zeitoun 2009, Earle et al. 2010) and on water relations in South Asia, particularly between India and Nepal (Dhungel and Pun 2009), including primary documents.

A semi-structured confidential interview technique, with an interview guide consisting of seven topics, was designed and approved by the CSIRO Human Research Ethics Committee

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3 All forms of knowledge, including expert knowledge, are inescapably influenced by - and influence – particular social values. How dominant actors initially conceive an issue influences the receptivity of those actors to particular forms of knowledge. For example, if actors conceive of river basin development primarily in terms of hydropower and irrigation infrastructure development, they may be receptive mainly to quantitative scenarios. If their focus is on rural livelihoods and rural development they may be most receptive to socially-detailed analysis.
We conducted a total of 42 interviews with participants based in Nepal, India, and Bangladesh. A first set of interviews was conducted in Nepal in April 2014, followed by a second set conducted in India and Bangladesh (June-November 2014). A final set was conducted in Nepal in October 2014 (coinciding with a newly elected Indian government). With few exceptions, interviews were conducted face-to-face.

Respondents were selected through invitations based on known authority or expertise in either water modelling or water governance (broadly defined). Respondents consisted of senior staff persons affiliated with state and inter-governmental organisations (29%); independent organisations (both not-for-profit and for-profit) (36%); and academic or research organisations (36%). Interview transcripts or summaries were analysed for content manually, using QSR Nvivo software.

6.3 Initial findings from assessment of interviews

Interview findings are based on a content analysis of 25 interviews (9 from Nepal, 16 from India and Bangladesh).

6.3.1 Development challenges

Given the importance of context to our research topic, we were interested in how respondents framed development challenges and opportunities of the Koshi Basin. Respondents identified 35 issues as challenges. Figure 33 shows the top twenty (out of 35) challenges by number of respondents referring to the issue, as well as number of references (i.e. comments directed at a given topic) within a given interview.

![Figure 33 Ranking of top 20 issues by number of references and respondents](image.png)
The set of issues shown in Figure 33 received 83% of all references to challenges. Just under two thirds of references were to a set of 13 issues, which fall into two clusters: a smaller cluster around the biophysical challenges of the Koshi and Ganga basins, including the complexity and dynamic nature of the Koshi system, and a larger cluster around the social complexity of water governance. With respect to the latter cluster of issues, the institutional (treaty based) framework of water governance received pointed criticism:

None of the India-Nepal river treaties have worked. . . this whole business of treaties is catching the whole thing from the wrong end. Because a treaty becomes a government-to-government agreement without taking anybody else into consultation or consideration and which effectively becomes a hydrologist to hydrologist or hydrocrat to hydrocrat agreement, who think that everybody else is a fool, treaties are reduced to narrowed-down exercises of bureaucratic vision or at best a hydrologist’s vision of river control. Treaties should be the culmination of an agreement not the starting point. . . a CBO to CBO [community-based organisation] network, engagement and exchange is a must to enhance governance in the Kosi Basin. [Interview 5, journalist, 10/6/14]

The following quote reflects on how the presence of multiple interests, values, and discourses impacts on modelling:

Some voices don’t like [the Ganges Strategic Basin Assessment] because it implies there’s not an opportunity for a big storage capacity in Nepal for flood mitigation [however] most of people with technical mind know that [upstream storage capacity] won’t have much impact on the nature of flows in Bangladesh or Bihar. It doesn’t mean it won’t have any impact on Bihar or it won’t have any impact on flooding in Nepal, it will and the report shows that, but one of the things the author [of the Assessment] did I guess is discount the value of [flood regulation]. They didn’t put an economic value on it and they didn’t seek the value of the social benefits that might occur. . . . [By contrast] the Nepalese seem to have put too high a value on the price of the electricity above market rates to make it look like worth more than what it is.

[Interview 10, inter-governmental expert, 12/6/14]

While the above respondent believed in the potential of modelling to serve as a platform for negotiations around benefit sharing, comments made by other respondents attest to challenges related to the production of useful knowledge. One respondent argued strongly for stakeholder identification, inclusion of multiple interests, and knowledge integration:

We need an enumeration of the diversity of stakeholders from the macro to the micro level. Tabulation of what water means across the spectrum, you talk to fishermen they’ll tell you we need river to have eggs and pulses, you talk to someone who wants hydro-electricity, he says freeze it in a reservoir and give us electricity, there are competing users, and that has to be mapped properly, we have not done the mapping properly, in fact in this mapping we need to bring in . . . a fish ecologist, biologist, river ecologist and so forth. . . .

These are rivers, which are running through complex sociologies, complex histories and we have no historian, we have no sociologist in the Central Water Commission; we think we need to talk to them. No. They should come talk to us.

[Interview 11, researcher, 2/7/14]

By contrast, other respondents attempted to simplify the challenge of problem representation by arguing that a particular knowledge domain was fundamental:
In water resources management, the social aspects and the kind of managerial aspects have started gaining prominence but the fact is that it is a resource, which is primarily governed by the laws of physics . . . hydrology, hydrodynamics, and climate sciences . . . are the governing factors. Now if you only look at [the social] side and forget about this then there’s always a lack of solution, because you have not really understood the variability and the problems of the ground.

[Interview 1, state planner, 16/6/14]

However, as we explore below, other respondents expressed a sense of caution about the limitations of models as tools to inform decision making.

### 6.3.2 Development opportunities

Figure 34 shows 21 issues identified by respondents as opportunities. Assessed by numbers of comments in respondent interviews, references to opportunities were fewer than to challenges (36 v. 107 respectively).

![Figure 34 Ranking of opportunities by number of references and respondents](image)

Most respondents did not identify transboundary collaboration *per se* as a near-term opportunity (Figure 34). However, a subset of respondents expressed a clear desire for the governance context to be reformed, so as to allow for strategic planning and dialogue:
I am optimistic that there will be a Ganga planning process in India and maybe some more detailed sub-basin plans in India for the Ganga . . . for the Koshi I think it will be a river-basin planning process largely driven by . . . the [Nepal] Government but possibly there will be some conversation also with Bihar Government around flooding and sediment issues. There’s a lot of hydro development happening in the Koshi Basin and not a lot of basin scale strategic assessments about major benefits and to whom they’re occurring and what could be done to mitigate the impacts of the benefits that’s been shared. So there hasn’t been a basin planning process and I think that can happen, it needs to happen and it needs a good strong analytical base.

[Interview 10, inter-governmental expert, 12/6/14]

The absence of transparency amongst partnering countries of India, Nepal and Bangladesh leads to loss of confidence in the outcomes. . . . Nepal is open to discuss concerns [with the Ganges Strategic Basin Assessment] if India and Nepal are agreeable to have a dialogue on all the residuary issues. . . . My organisation wants to interact with [international actors] to develop a harmonised strategy for the Koshi Basin.

[Interview 1, state planner, 1/4/14]

Respondents who explicitly supported such dialogue and planning however differed regarding the need for inclusive participation. Whereas the quotes above focus on state-led planning and dialogue, other respondents emphasized the need for processes which were inclusive of – and accountable to – villagers and other less powerful actors.

There should be architecture to enable dialogue between stakeholders to communicate their knowledges and their interest. See the point is, this is not a level playing field when it comes to interest: power is pulling the river to itself against the laws of gravity, you have to understand that. [Interview 11, researcher, 2/7/14]

As I said CBO [community-based organisation] to CBO exchange should be enhanced! Unless there’s a push from the bottom it [trans-boundary water cooperation] cannot happen. . . . a high magnitude push from the bottom. . . Nepal-India is actually the easiest border, therefore CBO to CBO exchange is possible. . . . today the situation is so bad that Bihar politicians have gone and told the villagers that you people find a solution we will implement it. We’ve gone in a lot of villages and we are getting feedback [on Kosi basin management] from the villages. . . . Local NGO’s in that border area are very de-spirited, demoralized because they’ve been struggling for the past 60 years for changes and reforms, in 2008 there was this massive flood and yet nothing happened. So they’re demoralized and they have good reasons to be. They’ll have to obviously interact with the government but I think to start with they need to have a joint common narrative.

[Interview 5, journalist, 10/6/14]

6.3.3 Role of modelling

We detected three perspectives on the role of river modelling in Koshi Basin governance. First, a minority of respondents regarded modelling as a source of credible and vital knowledge. This group of respondents regarded the hydrological knowledge produced by models to be instrumental to basin governance, for example to control problems of flooding in the lower basin:

Koshi has an inbuilt problem of sedimentation, so the modelling of Koshi right from its confluence to its entire upper reach is necessary. . . . there is no model for Koshi and there is no model for Ganga as well. Ganga is not creating any problem, but Koshi is
problematic. Therefore we need a modelling exercise for Koshi, which should tell us what will be the water level in different scenarios, possible submerges due to this water level and how it can be contained using channelization. And not just hydrodynamics, sediment modelling is also an important part of this. Whatever sediments are coming from Nepal is it being disposed of in Ganga? . . . Dredging of the river is completely ruled out. What we can do is that we can train the river to do that bit itself. What we can do is channelize the river so that the flow velocity increases and the river then itself tries and erodes the sediment deposited on its bed.

[Interview 15, researcher, 26/8/14]

A second group of respondents were proponents of modelling not so much for its ability to serve as an authoritative source of knowledge – and hence instrument to inform governance decisions – but for its ability to provide a platform for incremental learning, dialogue, and negotiation. As two proponents put it:

A part of modelling is to provide information where information may not exist due to gaps. We may have flow record data for 20 years but with modelling we can turn them into 50 years time series because we have got rainfall data for 50 years and that just provides you a strong database. It doesn’t have to be about testing options for future, it can just be to increase the information of the system. A part of value of modelling in my mind is to provide a means for people to get an agreed and shared view of how the system works through filling gaps in data through extrapolations or interpolations, but also then testing their assumptions. . . . there is a need to advocate for the value of robust system modelling to help people get . . . a shared understanding of how system works and as a way to facilitate them working together on what are the interventions and courses of actions, to get to a mutually agreed future basically. . . . it needs to be done in a way that [builds] the capacity within the government and stakeholder groups locally to do the modelling themselves rather than outsourcing to some third-party. And done in a way that they are transparent enough and open enough so that they can see the assumptions, test the assumptions, interact with models in some way. Modelling should be there to support an adaptive management process that is always a learning process.

[Interview 10, inter-governmental expert, 12/6/14, emphasis added].

The key question . . . is whether these kind of exercises are helpful . . . if you have a kind of a consensus-based modelling then it'll give you a solution that everybody agrees and the probability of finding solution to address the basin wide problems can be enhanced. . . . Suppose we don't agree on any other aspect, let there be a consensus on the use of a common method, a common computational algorithm a common database, and then we can have piecemeal solutions, everybody may look at his own thing and arrive at a solution and then if these kind of piecemeal solutions are then negotiated and brought to the table, negotiations could become much easier.

[Interview 1, state planner, 16/6/14]

A third group of respondents expressed reservations about the scope of modelling:

Policymakers should only use models along with local knowledge. Since models only give you indications, models do not give the [magnitude] of the situation based on which decisions are to be made at local level. Therefore, the [results] given by the models should be studied carefully before implementing them for policy making. [Interview 7, state planner, 22/5/14]
Water governance deals with what is essentially a ‘wicked’ problem . . . for which there is no optimum solution. A wicked problem cannot be solved with linear scientific and engineering solutions (such as models). Models can play a role in solving parts of the problem (such as what will happen to water flow if a dam is built here or there) but complex issues of who should get water when and how and for what are political questions that must be decided through open and interactive processes. [Interview 2, researcher, 9/6/14]

This third position emphasizes the need for modelling as a socio-technical process to harmonize with other forms of knowledge and prevailing modes of decision making. Whereas the second position appeared to hold a straightforward belief in the ability of modelling to facilitate “an agreed and share view” of the system, respondents in the third group were explicit about the constraints of the prevailing governance context and its challenges. They displayed scepticism about the potential for modelling to serve as a platform to enhance the transparency and authoritativeness of decision making. At times these respondents expressed their scepticism in strong terms:

Is modelling a real requirement of a policy maker? Assuming that X becomes the Water Minister again, would he be solving water problems based on modelling? [Interview 9, researcher, 3/4/2014]

6.4 Discussion and conclusions

The Koshi Basin encapsulates problems of cooperative and equitable water resources development. Respondents considered hydropower development as an opportunity, while on the other hand discussing the disparity of interests, values, and discourses as a challenge. This tension between the techno-economic potential of hydropower, and multiple socio-political challenges, is also reflected in the literature (Dhungel and Pun 2009, Alley 2014). Nepal-India water relations in particular embody this tension between a technical potential and a far more complex reality. One of the defining aspects of that relation thus far is that it has involved unresolved grievances, particularly around the Koshi Barrage, both in terms of social impacts, as well as ongoing operational management:

There are compensation issues relating to land on Nepal side arising from implementation of treaty conditions between India and Nepal on Koshi. The poor and inadequate land management system has led to poor farmers not being compensated for the land that is under Koshi Dam. The implementation of Koshi project is never looked at from Nepal’s side.

[Interview 2, state planner, 1/4/14]

The Koshi Project doesn’t benefit Nepal except for the inundation in the wet season. Due to that we have lot of inundation. The project is controlled by India. Nepal has to beg India to open the gates at the Kosi Barrage and on consistent request one or two gates are opened by then damage has already happened. The project is bad.

[Interview 5, 4/4/2014]

Respondents referred to the India-Nepal water relation in a manner consistent with bargaining, that is, negotiation based on pre-defined interests, as opposed to a more open conversation to explore deliberation:
[The] southern face of Himalayas do not have the storage, essentially of the kind of storage that one finds in northern Siberia or Russia or in the Canadian context. . . . My argument . . . which is also Nepal’s Government argument. . . . is it’s just not possible to have full control over the Ganges . . . thus whatever storage capacity [could be built] thus becomes more valuable for anyone. . . . Given that India is land rich and water scarce and given that there are prolonged dry seasons in India, any water that comes [from upstream] is of immense value.

[Interview 9, researcher, 3/4/2014]

The benefits [of cooperation] are actually known, two critical aspects are missing: one the realization on the part of Government of India about the real value of water. And then the sort of extremist kind of position of Government of Nepal on trying to keep on asking for all kinds of real and perceived benefits and payments. Like of course everything has an economic value, for power it could be very easily sorted out, but then [Nepal will] go on to say that because this power gets generated in a regulated way then you’ll get the regulated supplies, so you’ll save a lot of in your flood damages, so out of those flood damages we should also get something. Then whatever agricultural productivity you’ll increase so out of that we also need to have something. So now there has to be some kind of meeting ground. You know the maximalist approach on either side is not really working out.

[Interview 1, state planner, 16/6/14]

The interviews conducted, along with the literature reviewed, lead us to several initial conclusions. First, the governance context in the Koshi Basin offers no existing institutional arena for modelling to serve as a neutral platform to explore transboundary cooperation. The lack of a straightforward entry point to an existing venue limits the potential of expert knowledge to facilitate learning around the possibilities for flood risk mitigation, agricultural productivity, and other basin development issues.

Second, a subset of respondents explicitly valued more dialogue and cooperative planning, and explicitly called for institutionalized transboundary cooperation, whether state-state or community-to-community (Section 1.3.2). Third, respondents held divergent perspectives regarding the role of modelling, with these perspectives appearing to correspond to the three roles of expert knowledge recognized in the academic literature (i.e. instrumental, learning, political).

In conclusion, more investment is needed in opening up a variety of spaces for dialogue. In the authors’ opinion, the challenge of divergent beliefs and multiple values means that such spaces are urgently required. The delivery of models or modelling knowledge is not a prerequisite for dialogue. The practice of dialogue and the production of useful expert knowledge need to proceed together.
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