ISSN NO. 2091-1742

SCITECH

Journal of Scientific and Technical Studies
Nepal Engineering College, Pokhara University

Research Article

DOI:10.3126/scitech.v17i1.60466

How Effective Is Inter-Basin Transfer to Manage Temporal Variation Of "Too Much" And "Too Little" Water Conditions for Irrigation in a Himalayan Basin?

Utsav Bhattarai[1,2*], Laxmi Prasad Devkota[2,3], Tek Maraseni[1]

[1] Institute for Life Sciences and the Environment, University of Southern Queensland, Toowoomba, Queensland 4350, Australia

[2] Water Modeling Solutions Pvt. Ltd., Kathmandu, Nepal

[3] Nepal Academy of Science and Technology, Kathmandu, Nepal

* Corresponding Author: Utsav.Bhattarai@usq.edu.au

Received: April 25, 2023
Accepted: June 2, 2023

Abstract

Better irrigation facilities leading to "more crop per drop" are today's needs. This study examines how the overall water balance of Sunkoshi, Marin, and Bagmati Basins will be altered by implementing the Sunkoshi-Marin Diversion Project (SMDP) to fulfill the unmet demands of the Bagmati Irrigation Project (BIP) in the Bagmati Basin via the Marin Basin in Nepal. The specific objectives are to: i) quantify "too much" and "too little" water peculiar to the study basin based on historical data; ii) evaluate water availability, irrigation water requirement, and deficits with and without SMDP; and iii) provide evidence-based recommendations on the effectiveness of the SMDP considering hydropower generation, irrigation and low- and high-flow conditions. Thirty years of historical daily flow data (two gauging stations) and precipitation data (15 stations) were obtained from the Department of Hydrology and Meteorology. Other spatial input data were acquired from relevant authorized sources. Water availability has been estimated using flow at the diversion sites while the irrigation requirements have been calculated based on secondary information. Results show that additional water is not at all required for Marin and Bagmati Basins in the monsoon season. Rather, the diverted water increases the flood hazard. Moreover, the contribution of hydropower from SMDP to the national energy demand is insignificant in the monsoon. However, the SMDP was found to play an important role in meeting the irrigation deficits during the dry season. Its contribution to hydropower production in the lean period is also commendable. However, the proposed irrigation requirement of the BIP cannot be met even after the implementation of the SMDP. More importantly, there is a high probability of the intended diversion flow not being available in the Sunkoshi River (donor) which could have severe consequences downstream. Therefore, additional options for conjunctive use need to be explored.

Keywords: Irrigation; water management; inter-basin transfer; Nepal Himalaya; Sunkoshi-Marin Diversion Project

1. Introduction

Water is different from other natural resources because of its need for sustaining life, primarily for drinking and agriculture. With increasing population and urbanization, water is sure to be highly stressed in the future (ben Fraj et al., 2019; de Andrade et al., 2011; Veena et al., 2021). Water scarcity is a critical constraint to food production and a major cause of poverty and hunger globally. Climate change is projected to add to this global problem (Essenfelder & Giupponi, 2020; Ma et al., 2021). Thus, "more crop per drop" has become today's need. The developed world is relatively better off because of available technologies and resources in coping with the possible future impacts of water scarcity (de Andrade et al., 2011; Dickson & Dzombak, 2017). However, the developing world generally lacks the technology, expertise, and financial capabilities to withstand such impacts (Devkota et al., 2020; Devkota et al., 2017; Jalilov, 2021).

Some regions of the world face high temporal variability of water. For example, the annual average precipitation of Nepal is about 1800 mm (DHM/GoN, 2017). However, nearly 80% of this occurs in the four monsoon months (June-September) whereas the remaining 20% is spread out over the other eight months. This peculiar seasonal variation is also reflected in the flow of Nepalese river basins (Devkota & Gyawali, 2015; Devkota et al., 2020; Marahatta et al., 2021). As a result, problems of floods, landslides, and other water-induced disasters are common in Nepal during the monsoon months. This indicates "too much" water. On the contrary, water available during the dry months is insufficient to meet the various competing demands (Amjath-Babu et al., 2019; Bastakoti et al., 2017). This is a condition of "too little" water. Regulation of the surplus water from the monsoon to manage the water uses in the dry period in an economic way can be effectively achieved through storage projects within a basin (Bharati et al., 2016; Chinnasamy et al., 2015; Liu et al., 2019; Marahatta et al., 2022).

On the other hand, when there is spatial variation in the water availability and usage across river basins, inter-basin transfer has proven to be an effective water management technique, especially for arid regions. For example, de Andrade et al. (2011) discuss the Sao Francisco River trans-basin diversion in Brazil. Essenfelder & Giupponi (2020) used hydrological modelling and machine learning to examine how the water balance of the Dese-Zero River Basin in Italy is altered by inter-basin water transfer. ben Fraj et al. (2019) studied the politics of inter-basin water transfers focusing on the socio-environment considering the diversions from the north (Medjerda and Ichkeul basins) to the southern region and from the center to the coast in Tunisia. Smith & Shah (2020) and Woo et al. (2021) examined the potential impacts of inter-basin water transfer on water quality in the USA and South Korea respectively. However, due to the limited availability of resources and other constraints, inter-basin transfer in Nepal is in its infancy. The Kulekhani hydropower Project (commissioned in the early 90s) diverting water from Bagmati to Narayani Basin, the Melamchi inter-basin transfer project (under construction) for augmenting drinking water supply to Kathmandu (the capital city) and Bheri-Babai diversion (under construction) for irrigation purposes are some notable examples. However, Madi-Dang diversion, Sunkoshi-Kamala diversion, Naumure-Kapilvastu diversion, and Sunkoshi-Marin diversion are some projects that have been planned for the future but are still in the study phases.

Interestingly, Veena et al. (2021) point out that the annual volume of global inter-basin water transfer of 2005 is expected to nearly double by 2025. Similarly, a study in the USA reported more than 2000 inter-basin water transfer schemes of varying magnitudes in the USA in 2017 (Dickson & Dzombak, 2017).

Although the world witnessed the development of a large number of inter-basin water transfer projects, concerns have been raised over pressing issues such as water resource imbalances, water quality, socio-environmental impacts, and large construction and maintenance costs.

Among the various planned water resources development projects in Nepal, the Sunkoshi-Marin Diversion Project (SMDP) is an inter-basin transfer project that has been prioritized by the Government of Nepal (GoN). The project is past its detailed design stage and its construction has been initialized. This project diverts water from an adjoining donor (Sunkoshi) basin for irrigating the Bagmati Irrigation Project (BIP), one of the largest irrigation schemes in Nepal with a proposed command area of 122,000 ha (DOI/GoN, 2016). The GoN has planned to divert 77 m^3/s year-round from the Sunkoshi Basin to the Bagmati Basin (where the BIP is located) via the Marin Basin (Figure 1). This study aims at analyzing the viability of the SMDP with regard to its ability to manage the "too much" and "too little" water conditions of the areas under consideration.

The specific objectives of the study are:

i) To quantify "too much" and "too little" water peculiar to the studied basins in the Nepal Himalayas considering historical data;

ii) To evaluate water availability, irrigation water requirement, and deficits for the current and future conditions with and without SMDP; and

iii) To provide evidence-based recommendations on the effectiveness of the SMDP considering irrigation, hydropower generation, and low and high flow conditions.

2. Materials and Methods

2.1 Study Area

The Bagmati Basin, Marin Basin, and Sunkoshi Basin are located in the central and eastern parts of Nepal in the central Himalayan region (Figure 1). The catchment areas of Bagmati Basin at Pandherodovan, Marin Basin at its confluence with the Bagmati River, and Sunkoshi Basin at Khurkot are 2700, 544, and 10209 km^2 respectively (DOI/GoN, 2016). The Bagmati Basin can be divided into three distinct regions, namely, upper (high hills including densely populated urban areas), middle (very sparsely populated forested areas in the lower hills), and lower (flat agricultural land extending up to the Indo-Gangetic plains) (ADB, 2015). The Bagmati Irrigation Project (BIP) is located on the lower part of the Bagmati Basin. It has been designed to currently irrigate 42,000 ha of cultivable land in the plain areas of Nepal with the intakes located near the Pandherodovan gauging station. The Marin River is a tributary of the Bagmati River and is situated in the lower hills of Nepal. It lies in a high precipitation zone with annual values over 2500 mm (DWIDP/GoN, 2009). The annual discharge of the Marin River just before the confluence with the Bagmati River is about 22 m^3/s (DWIDP/GoN, 2009). The SMDP is designed to divert water from the Sunkoshi River (at Khurkot) to the Marin River (at Kudule) through a 13 km-long tunnel to meet the irrigation demands of the BIP.

[Figure 1 here]

Figure 1: Location map of the Bagmati Basin, Sunkoshi Basin, and Marin Basin. BIP: Bagmati Irrigation Project; SMDP: Sunkoshi-Marin Diversion Project

2.2 Methodology

This study analyses how effective the SMDP shall be considering the water availability and demands of the study basins. The overall research methodology is presented in Figure 2. Historical daily flow data of Khurkot (in the Sunkoshi Basin) and Pandherodovan (in the Bagmati Basin) stations of 30 years (1986-2015) was collected from the Department of Hydrology and Meteorology (DHM), GoN. There is no gauging station along the Marin River. The catchment area of the Bagmati River at Phadheredovan and at the powerhouse site (Kudule) of the SMDP are respectively 2700 and 129 km^2. Flow in the Marin River at the confluence with Bagmati River was transposed using the catchment area ratio method considering Pandherodovan as the base station. Water availability was assessed at Khurkot, Marin at its confluence with Bagmati River and at Pandherodovan at fortnightly timesteps. Additionally, low flow frequency analysis was carried out by fitting Gumbel distribution to monthly flow at the Sunkoshi-Marin diversion site for each month. Monthly low flows were estimated for 5-, 10- and 20-year return periods.

[Figure 2 here]

Figure 2: Flowchart of the overall methodology. DHM: Department of Hydrology and Meteorology; IMP: Irrigation Master Plan; Pe: Effective precipitation; CWR: crop water requirement; CIR: consumptive irrigation requirement; NIR: net irrigation requirement; FIR: field irrigation requirement; na: application efficiency; GIR: gross irrigation requirement; nc: conveyance efficiency; SMDP: Sunkoshi-Marin Diversion Project

Water uses, namely, irrigation and hydropower, for the considered basins, were evaluated for the current as well as future scenarios. Long-term observed daily precipitation data from 13 stations for the lower Bagmati Basin and five stations of the Marin Basin was used to calculate effective precipitation. Crop water requirements for the Marin, as well as the Bagmati basins, were estimated considering the cropping pattern and intensity based on the recommendations of the Irrigation Master Plan by GoN (DoWRI/GoN, 2019). Percolation loss was taken as 10% of the consumptive irrigation requirement, conveyance efficiency as 70% and application efficiency 70% for the dry season and 85% for the monsoon season (Punmia et al., 2009), and the gross irrigation water requirement (GIR) was calculated. The design discharge, effective head, and overall efficiency for the hydropower project were taken from DOI/GoN (2016). Environmental flow for downstream release has been considered as 10% of the minimum of the monthly flows (MoEWRI/GoN, 2001). The ratio of the irrigable to agricultural land for the Marin basin was assumed 0.4 which has been prescribed by the DOI/GoN (2007) for the hills of Nepal. The current scenario refers to the case of the existing irrigated areas of the BIP while the future scenario deals with the planned expansion of its irrigated command area with and without SMDP. Recommendations were made regarding the applicability of the SMDP based on the results of the analysis.

3. Results and Discussion

3.1. Low-flow Analysis of Sunkoshi River

Average long-term monthly flows, estimated low-flows of 5-, 10- and 20-year return periods, and SMDP diversion at Khurkot are shown in Figure 3. It can be seen that there is a probability of failing to meet the proposed diversion flow even once in five years for February, March, and April. Further, there is a high probability of failing to meet this requirement for all the months of the dry period (December-May) once in 20 years. This is exactly what Marak et al. (2020) and Rollason et al. (2021) have warned pointing out that although inter-basin water transfer has been seen to be temporarily effective, its sustainability is not assured because of the dynamic hydrology. Additionally, Du et al. (2020) and Liu et al. (2019) question the downstream impacts on the river flow and its environment which will be largely altered by the water diversion. This will have a long-term impact on the overall hydrology as well as the biotic and abiotic components of the environment. Thus, it is evident that when environmental flow releases and existing downstream water uses are additionally considered, the year-round diversion of 77 m^3/s from the Sunkoshi River at Khurkot is to be revisited.

[Figure 3 here]

Figure 3: Monthly low-flow analysis of Khurkot (SMDP diversion site) in the Sunkoshi River. Q_5, Q_10, and Q_20 refer to the flows of 5-, 10- and 20- years return periods respectively; Q_SMDP is the proposed year-round diversion flow (77 m^3/s); Q_LTMA is the long-term average monthly flows; high flows have been truncated to zoom in on low-flows.

3.2 Power Generation

Although the major reason for implementing the SMDP is augmenting irrigation, the GoN has also envisioned generating 40 MW of hydropower by constructing a run-of-the-river (ROR) project from a net head of 61 m and design discharge equivalent to the diversion discharge of 77 m^3/s including flushing discharge (DOI/GoN, 2016). Our analysis found that generation of 40MW of power is possible from May to October, that is during the monsoon assuming that the design discharge and other physical conditions remain the same. However, the targeted power generation cannot be met by the hydropower project in almost 40% of the time in March and about one-third of the time during February and April. In some months, the possible power generation is as low as 18 MW (Figure 4). It is interesting to note that power generation is maximum in the case of January and November almost throughout the analyzed period with only a very few incidents generating less than 35 MW. This uncertainty due to the variable hydrology is to be duly considered while fixing the power generation capacity of this project. Furthermore, Nepal is a ROR hydropower-dominated country with a current total installed capacity of about 1396 MW out of which ROR installed capacity is 1304 MW (~93%) (NEA/GoN, 2021). Generating hydropower from the diverted water contributes to meeting the national energy demand during the dry period of the year to some extent. However, it has very little significance from the power generation point of view during the monsoon and post-monsoon seasons in which almost all the ROR projects throughout the country are operating at their full capacities (Devkota et al., 2022; Marahatta et al., 2022). Furthermore, the operation of the hydropower project during the monsoon amplifies the flood risk in the downstream areas with the additional discharge and increases the likelihood of damage to the turbine blades. Developing countries have not been able to construct such inter-basin transfers in large numbers mainly because of financial and technical resource limitations (Annys et al., 2019; Jalilov, 2021). Therefore, investing a huge capital in the hydropower project (about USD 4500/kW) (Best, 2017) to be operated for dry season benefit only also needs to be a serious point of consideration before finalization of the project in the best interest of the nation.

[Figure 4 here]

Figure 4: Variation in power generation from the proposed Sunkoshi-Marin Diversion Project

3.3 Impact of Floods on Marin Basin

The historical one-day maximum flood peak at Padherodovan is 7,550 m^3/s. Transposing this to the proposed hydropower project site (Kudule) in the Marin River using the catchment area method, it comes out to be 360 m^3/s. It is witnessed that the frequently occurring floods are creating problems of inundation to adjacent agricultural land. It is to be noted here that Marin Basin lies in a rain-pocket area, and it is located in the Siwalik range. As a result, erosion and sediment issues are already prominent in this basin, particularly during the monsoon. GoN has been desperately carrying out a lot of river training works to mitigate the associated flood impacts. With an addition of another 77 m^3/s (which is more than 20% of the maximum value) from Sunkoshi in the monsoon, the flooding situation will be aggravated. Moreover, riverbed scouring and riverbank erosion will also increase as an impact of the added runoff in the river. Hence, these issues need careful attention. Thus, diversion of water from the Sunkoshi River during the monsoon season is detrimental to the Marin Basin from floods, erosion and sedimentation points of view.

3.4 Water Balance

Water Availability

The long-term annual average flow of the Marin River at Kudule and Bagmati River at the BIP intake site are respectively 6 and 127 m^3/s. Similar to the condition of most Nepalese rivers, in the Marin and Bagmati too, about 80 percent of the flow occurs during the four months of monsoon (June – September) and only about 20 percent is available for the remaining eight months (Figure 5). The critical dry period, that is from December to May, has about 8% of the flow with the minimum flow occurring in March.

[Figure 5 here]

Figure 5: Long-term flow variation of Marin and Bagmati Rivers. Q_monthly: average monthly flow; Q-avg: average annual flow

Irrigation Water Requirement and Deficit

a) Marin Basin

The Gross Irrigation Requirement (GIR) for 2146 ha of irrigable land of the Marin basin and the estimated flow available in the Marin River at fortnightly intervals is shown in Figure 6. Water deficit period has been marked as the time in which the GIR exceeds the availability of river flow. It can be seen from the plot that the deficit period lasts from the second half of October to the first half of May.

[Figure 6 here]

Figure 6: Average fortnightly flow availability required for year-round irrigation and deficit in Marin Basin. Q_avail: available long-term average flows; Q_DemandAvg: average gross irrigation requirement; Q_Deficit: irrigation water deficit; high flows have been truncated to zoom in on low-flows.

Analysis of the 30 years' data shows that deficits in irrigation water vary among the months of a year and also inter-annually. The variation is maximum in the second half of October. However, maximum deficit of 3.67 m^3/s is seen in the first half of April. The monsoon months do not witness any such deficit except a very small amount in the second half of June.

[Figure 7 here]

Figure 7: Average fortnightly irrigation water deficit and its variability in the Marin Basin

b) Bagmati Basin

The current irrigable area of the BIP is 47,700 ha while the proposed area to be irrigated after Sunkoshi-Marin Diversion is 122,000 (DOI/GoN, 2016). GIR was computed for these two phases ("Without SMDP" and "With SMDP") based on crop water requirement for BIP command area from (DoWRI/GoN, 2019). Long-term average of the water available for irrigation, GIR and water deficit is shown in Figure 8.

[Figure 8 here]

Figure 8: Average fortnightly flow availability required for year-round irrigation and deficit in Bagmati Basin a) "Without SMDP" scenario and b) "With SMDP" scenario. Q-avail: average available flow; Q_DemandAvg: average irrigation demand; Q_Deficit: average unmet demand. High flows have been truncated to zoom in on low-flows.

Figure 8a shows that irrigation water deficit of the "Without SMDP" scenario which begins from the second half of October until May, with the highest deficit of up to 81 m^3/s, occurring in March's second half. However, it begins from the first half of October up to May first half in case of "With SMDP" scenario (Figure 6b). The maximum deficit in this scenario also occurs in the second half of March (149 m^3/s), similar to the "without SMDP" case.

The variation in water deficits for "Without SMDP" and "with SMDP" are shown in Figures 9a and 9b respectively. The water deficit for "Without SMDP" ranges (difference between maximum to minimum in a given period) from zero during the monsoon period to 80 m^3/s in the second half of October. The maximum deficit is more than 90 m^3/s (second half of April 1992). In case of "With SMDP", the maximum range is 186 m^3/s occurring in the first half of October and the maximum deficit of 206 m^3/s also in the first half of October (in 2000).

[Figure 9 here]

Figure 9: Average fortnightly irrigation water deficit and its variability in the Bagmati Irrigation Project command area. Q_SMDP: proposed year-round diversion from the Sunkoshi-Marin Diversion Project

Further from Figure 9a, we can see that five fortnights (February II, March II, April I and II, and October II) out of the 24 have a maximum deficit greater than 77 m^3/s. Almost 10% of the 720 fortnightly periods of the 30-year analysis duration (30*24=720) have water deficit more than the amount of flow diverted to the Marin Basin from Sunkoshi River. The diverted water cannot meet the water deficit for 10% of the time, even in the "Without SMDP" scenario. The condition is more severe for the "With SMDP" scenario. The deficit exceeds 77 m^3/s for more than one-third (35%) of the considered time horizon. This can be observed from the second half of January to the first half of May and the first and second halves of October (10 out of 24 fortnights). These values indicate that it is not sufficient for the BIP to solely rely on the SMDP to fulfill its current and future unmet demands. Additional options for conjunctive use such as with groundwater in the Terai areas of Nepal need to be explored. Conjunctive use of water in addition to inter-basin transfers has been seen to be successful in other parts of the world, for example in China (Ma et al., 2021). Furthermore, as rightly pointed out by Akron et al. (2017), there is doubt over such transfer projects being economically feasible in the long run. Moreover, the active involvement of multiple stakeholders to minimize the associated socioeconomic impacts due to such large-scale diversion projects is of utmost importance (Veena et al., 2021). Therefore, there are still mixed reactions in favor of and against the implementation of the SMDP at the community, national and implementation levels.

4. Conclusion and Recommendations

This study analyzed how the overall water balance of the Sunkoshi Basin, Marin Basin and the Bagmati Basin will be altered because of the Sunkoshi-Marin Diversion Project (SMDP) which is on the priority list of the Government of Nepal. Seasonal assessment of water availability in these river basins were carried out using historical flow data. Irrigation water requirement was calculated using historical precipitation data and other spatial secondary information. The impacts of the inter-basin water transfer on irrigation deficit and hydropower were evaluated at fortnightly timestep.

It was seen that additional water is not at all required for Marin and Bagmati Basins in the monsoon season because "too much" is already available during this time. Rather, the diverted water is likely to increase the flood hazard of the Marin River. Moreover, this diversion has an insignificant contribution to the national energy demand during the monsoon through hydropower generation which is a by-product of this project. On the other hand, the SMDP has been found to be of great value in meeting the irrigation deficits in the command areas of both the Marin and Bagmati basins during the dry season because of "too little" water during this time. Its contribution to hydropower production in the lean period is also commendable. However, the proposed irrigation requirement of the BIP cannot be met even after implementation of the SMDP. And more importantly, there is a high probability of not even having the intended diversion flow available in the Sunkoshi River which could have severe consequences downstream. Therefore, firstly, the magnitude of the diversion flow needs to be re-assessed. Secondly, additional options of conjunctive use such as with groundwater in the Terai areas of Nepal need to be explored by GoN in order to fulfill the unmet irrigation demand of the BIP during the dry period. Furthermore, diverting water in the dry season only and shutting down or partially operating the project in the monsoon season could be a management option for dry season unmet demand minimization, increasing the project life of the SMDP and flood risk reduction in the study basins.

Thus, designing the SMDP project relying only on the historical observed data is seen to be very risky. Development and application of a robust decision support system with a strong model-base to optimize the available water amongst the competing uses by minimizing the unmet demand is highly recommended in this context. Contrary to the project-by-project approach, an integrated basin management approach is more effective in terms of evaluating the upstream-downstream impacts of this inter-basin diversion project. Finally, incorporating the impacts of climate change on the hydrology as well as crop modelling of the study basins could be potential areas of future research.

References

ADB. (2015). Nepal: Innovations for More Food with Less Water (RDTA 7967 – REG). Asian Development Bank.

Akron, A., Ghermandi, A., Dayan, T., & Hershkovitz, Y. (2017). Interbasin water transfer for the rehabilitation of a transboundary Mediterranean stream: An economic analysis. Journal of Environmental Management, 202, 276–286. https://doi.org/10.1016/j.jenvman.2017.07.043

Amjath-Babu, T. S., Sharma, B., Brouwer, R., Rasul, G., Wahid, S. M., Neupane, N., Bhattarai, U., & Sieber, S. (2019). Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. Applied Energy, 239, 494–503. https://doi.org/10.1016/j.apenergy.2019.01.147

Annys, S., Adgo, E., Ghebreyohannes, T., van Passel, S., Dessein, J., & Nyssen, J. (2019). Impacts of the hydropower-controlled Tana-Beles interbasin water transfer on downstream rural livelihoods (northwest Ethiopia). Journal of Hydrology, 569, 436–448. https://doi.org/10.1016/j.jhydrol.2018.12.012

Bastakoti, R. C., Bharati, L., Bhattarai, U., & Wahid, S. M. (2017). Agriculture under changing climate conditions and adaptation options in the Koshi Basin. Climate and Development, 9(7), 634–648. https://doi.org/10.1080/17565529.2016.1223594

ben Fraj, W., Elloumi, M., & Molle, F. (2019). The politics of interbasin transfers: socio-environmental impacts and actor strategies in Tunisia. Natural Resources Forum, 43(1), 17–30. https://doi.org/10.1111/1477-8947.12165

Best, R. (2017). Switching towards coal or renewable energy? The effects of financial capital on energy transitions. Energy Economics, 63, 75–83. https://doi.org/10.1016/j.eneco.2017.01.019

Bharati, L., Gurung, P., Maharjan, L., & Bhattarai, U. (2016). Past and future variability in the hydrological regime of the Koshi Basin, Nepal. Hydrological Sciences Journal, 61(1), 79–93. https://doi.org/10.1080/02626667.2014.952639

Chinnasamy, P., Bharati, L., Bhattarai, U., Khadka, A., Dahal, V., & Wahid, S. (2015). Impact of planned water resource development on current and future water demand in the Koshi River basin, Nepal. Water International, 40(7), 1004–1020. https://doi.org/10.1080/02508060.2015.1099192

de Andrade, J. G. P., Barbosa, P. S. F., Souza, L. C. A., & Makino, D. L. (2011). Interbasin Water Transfers: The Brazilian Experience and International Case Comparisons. Water Resources Management, 25(8), 1915–1934. https://doi.org/10.1007/s11269-011-9781-6

Devkota, L. P., Bhattarai, U., Khatri, P., Marahatta, S., & Shrestha, D. (2022). Resilience of hydropower plants to flow variation through the concept of flow elasticity of power: Theoretical development. Renewable Energy, 184, 920–932. https://doi.org/10.1016/j.renene.2021.11.051

Devkota, L. P., & Gyawali, D. R. (2015). Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. Journal of Hydrology: Regional Studies, 4, 502–515. https://doi.org/10.1016/j.ejrh.2015.06.023

Devkota, R., Bhattarai, U., Devkota, L., & Maraseni, T. N. (2020). Assessing the past and adapting to future floods: a hydro-social analysis. Climatic Change, 163(2), 1065–1082. https://doi.org/10.1007/s10584-020-02909-w

Devkota, R. P., Pandey, V. P., Bhattarai, U., Shrestha, H., Adhikari, S., & Dulal, K. N. (2017). Climate change and adaptation strategies in Budhi Gandaki River Basin, Nepal: a perception-based analysis. Climatic Change, 140(2), 195–208. https://doi.org/10.1007/s10584-016-1836-5

DHM/GoN. (2017). Observed Climate Trend Analysis in the Districts and Physiographic Regions of Nepal. Department of Hydrology and Meteorology. Government of Nepal. www.dhm.gov.np

Dickson, K. E., & Dzombak, D. A. (2017). Inventory of Interbasin Transfers in the United States. Journal of the American Water Resources Association, 53(5), 1121–1132. https://doi.org/10.1111/1752-1688.12561

DOI/GoN. (2007). Development of Database for Irrigation Development in Nepal. Department of Irrigation. Government of Nepal.

DOI/GoN. (2016). Draft Report for Detailed Feasibility of Sunkoshi Marin Diversion Project. Department of Irrigation. Government of Nepal.

DoWRI/GoN. (2019). Irrigation Master Plan 2019. Department of Water Resources and Irrigation. Government of Nepal.

Du, X., Chen, J., Gu, S., & Chen, G. (2020). An Analysis of Influences of Interbasin Water Transfer on Water Resources Carrying Capacity over Dianchi-Pudu River Basin. IOP Conference Series: Earth and Environmental Science, 525(1). https://doi.org/10.1088/1755-1315/525/1/012040

DWIDP/GoN. (2009). Detailed Studies for the Preparation of River Training Master Plan of the Marine River. Department of Water Induced Disaster Preparedness. Government of Nepal

Essenfelder, A. H., & Giupponi, C. (2020). A coupled hydrologic-machine learning modelling framework to support hydrologic modelling in river basins under Interbasin Water Transfer regimes. Environmental Modelling and Software, 131. https://doi.org/10.1016/j.envsoft.2020.104779

Jalilov, S.-M. (2021). Emergence of Water-Energy-Food Nexus Resulting from Interbasin Water Transfer: Economic Analysis for a Transboundary River Basin in South Asia. https://doi.org/10.1061/(ASCE)

Liu, K., Wang, Z., Cheng, L., Zhang, L., Du, H., & Tan, L. (2019). Optimal operation of interbasin water transfer multireservoir systems: an empirical analysis from China. Environmental Earth Sciences, 78(7). https://doi.org/10.1007/s12665-019-8242-z

Ma, Y., Chang, J., Guo, A., Chen, L., & Wang, X. (2021). Conjunctive Operation of Interbasin Transferred Water and Local Water in a Multisource Diversion-Supply-Allocation System. Journal of Water Resources Planning and Management, 147(10), 05021018. https://doi.org/10.1061/(ASCE)wr.1943-5452.0001426

Marahatta, S., Aryal, D., Devkota, L. P., Bhattarai, U., & Shrestha, D. (2021). Application of swat in hydrological simulation of complex mountainous river basin (Part ii: Climate change impact assessment). Water (Switzerland), 13(11). https://doi.org/10.3390/w13111548

Marahatta, S., Bhattarai, U., Devkota, L. P., & Aryal, D. (2022). Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. International Journal of Energy and Water Resources. https://doi.org/10.1007/s42108-021-00174-w

Marak, J. D. K., Sarma, A. K., & Bhattacharjya, R. K. (2020). Assessing the Impacts of Interbasin Water Transfer Reservoir on Streamflow. Journal of Hydrologic Engineering, 25(10), 05020034. https://doi.org/10.1061/(ASCE)he.1943-5584.0001984

MoEWRI/GoN. (2001). Hydropower Development Policy. Ministry of Energy, Water Resources and Irrigation, Government of Nepal

NEA/GoN. (2021). A Year in Review Fiscal Year 2020/21. Nepal Electricity Authority, Government of Nepal.

Punmia, B. C., Lal, P. B. B., Jain, A. K., & Jain, A. K. (2009). Irrigation and Water Power Engineering (Sixteenth). Laxmi Publications (P) Ltd.

Rollason, E., Sinha, P., & Bracken, L. J. (2021). Interbasin water transfer in a changing world: A new conceptual model. Progress in Physical Geography. https://doi.org/10.1177/03091333211065004

Smith, E. A., & Shah, S. (2020). Hydrodynamic Modeling Results Showing the Effects of the Luce Bayou Interbasin Transfer on Salinity in Lake Houston, TX. https://doi.org/10.21423/twj.v11i1.7094

Veena, S., Singh, R., Gold, D., Reed, P., & Bhave, A. (2021). Improving Information-Based Coordinated Operations in Interbasin Water Transfer Megaprojects: Case Study in Southern India. Journal of Water Resources Planning and Management, 147(11), 04021075. https://doi.org/10.1061/(ASCE)wr.1943-5452.0001456

Woo, S. Y., Kim, S. J., Lee, J. W., Kim, S. H., & Kim, Y. W. (2021). Evaluating the impact of interbasin water transfer on water quality in the recipient river basin with SWAT. Science of the Total Environment, 776. https://doi.org/10.1016/j.scitotenv.2021.145984

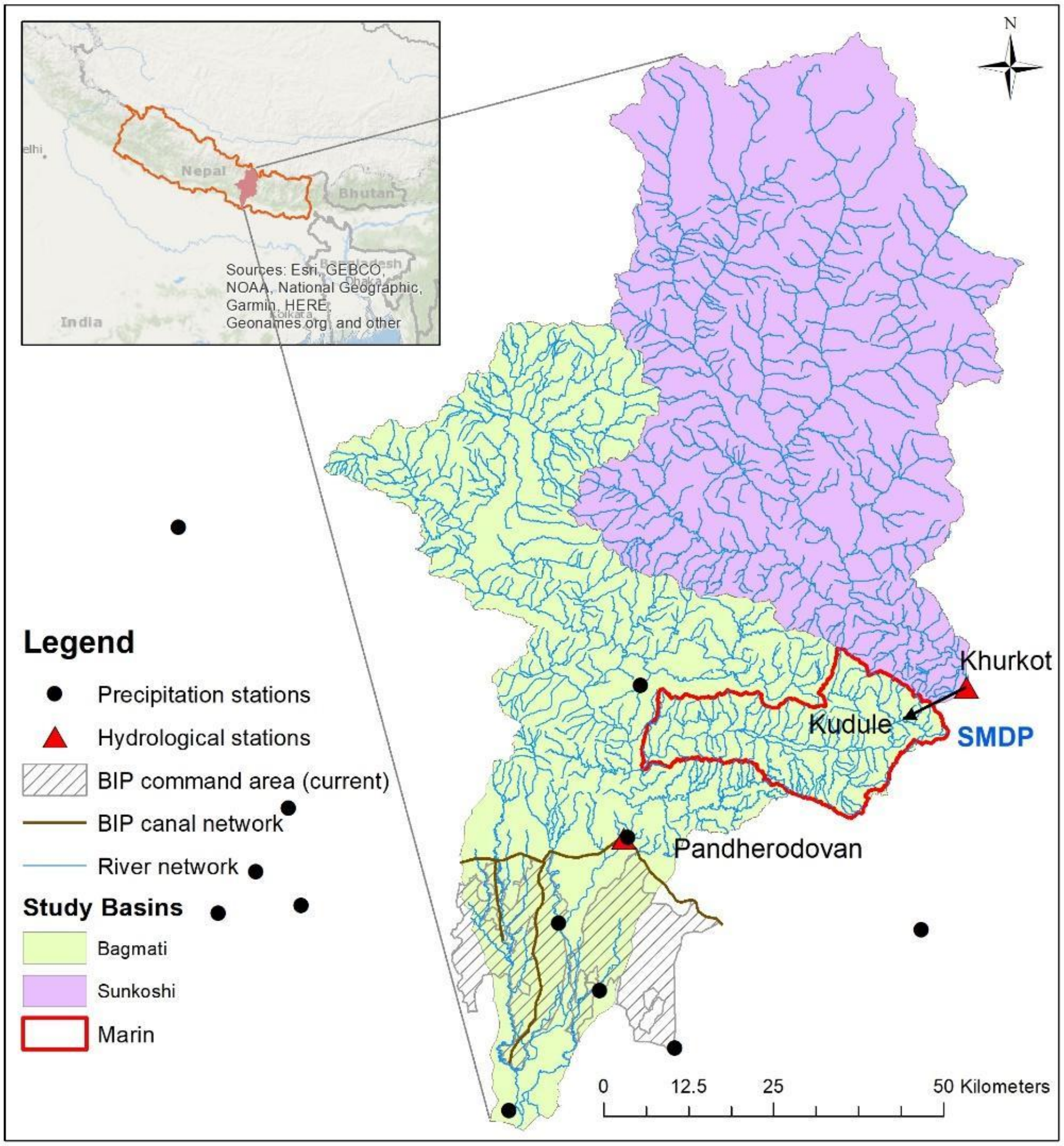


Figure 1: Location map of the Bagmati Basin, Sunkoshi Basin, and Marin Basin. BIP: Bagmati Irrigation Project; SMDP: Sunkoshi-Marin Diversion Project

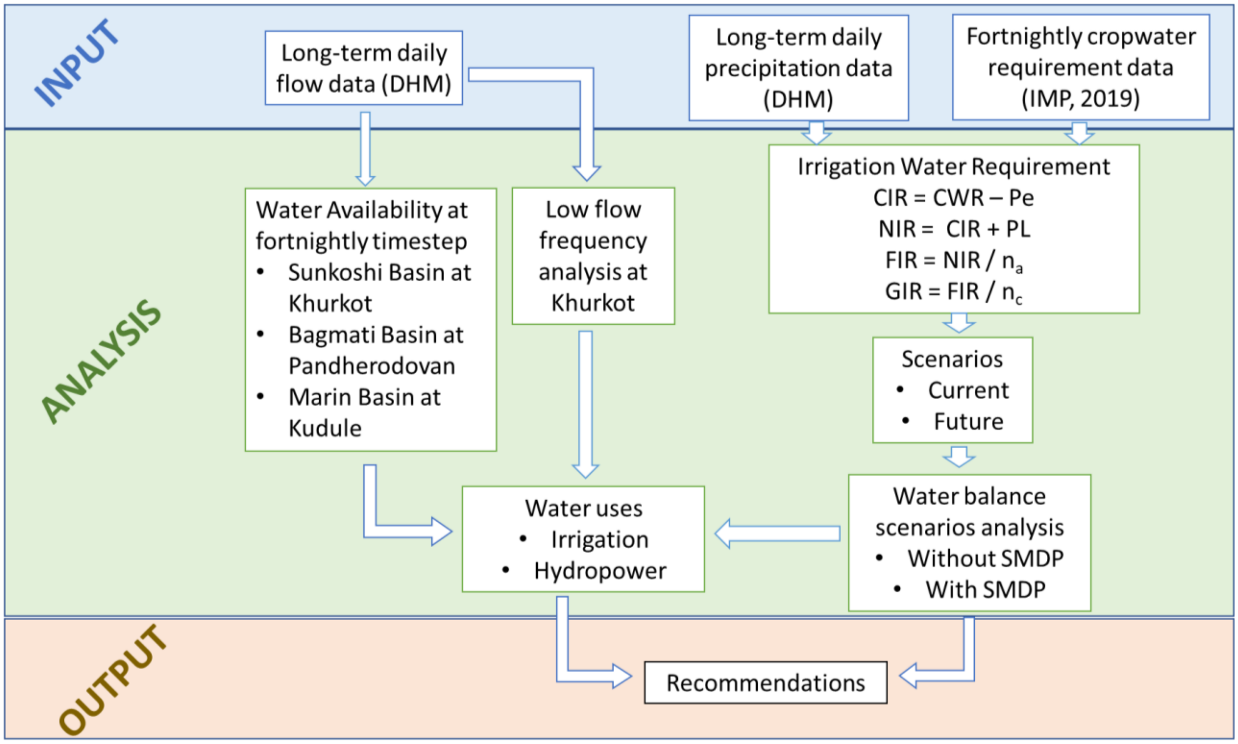


Figure 2: Flowchart of the overall methodology. DHM: Department of Hydrology and Meteorology; IMP: Irrigation Master Plan; Pe: Effective precipitation; CWR: crop water requirement; CIR: consumptive irrigation requirement; NIR: net irrigation requirement; FIR: field irrigation requirement; na: application efficiency; GIR: gross irrigation requirement; nc: conveyance efficiency; SMDP: Sunkoshi-Marin Diversion Project

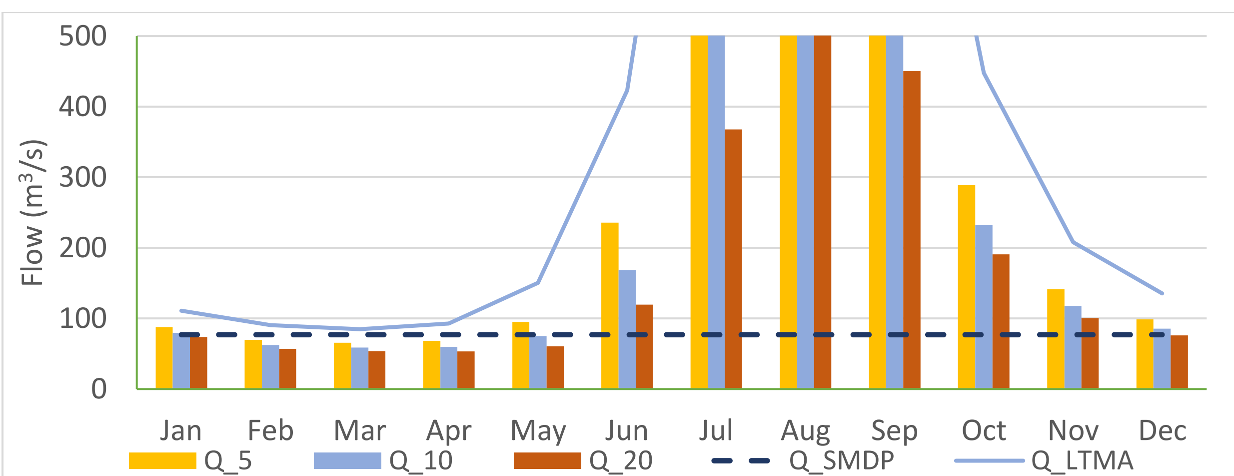


Figure 3: Monthly low flow analysis of Khurkot (SMDP diversion site) in the Sunkoshi River. Q_5, Q_10 and Q_20 refer to the flows of 5-, 10- and 20- years return periods respectively; Q_SMDP is the

proposed year-round diversion flow (77 m3/s); SMDP: Sunkoshi-Marin Diversion Project; Q_LTMA is the long-term average monthly flows; high flows have been truncated to zoom in on low-flows.

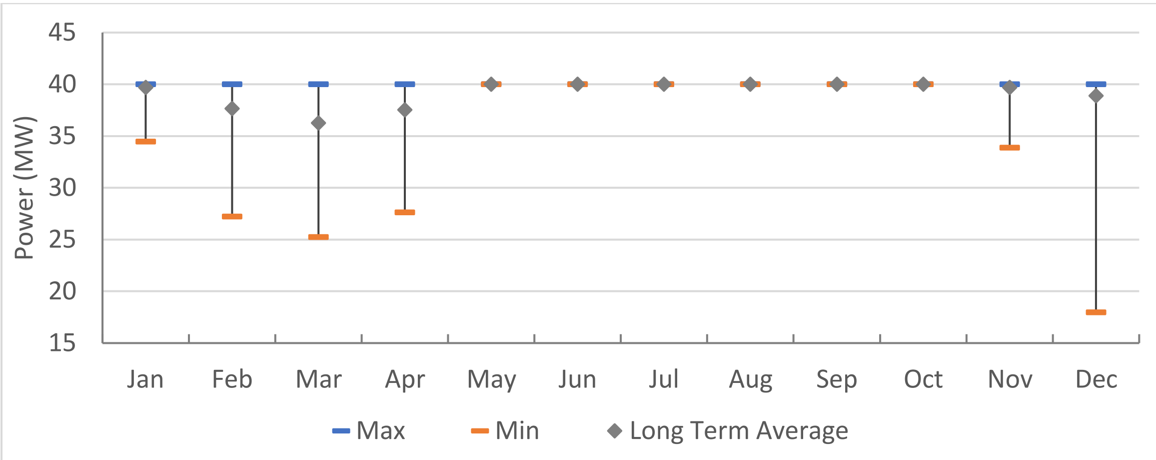


Figure 4: Variation in power generation from the proposed Sunkoshi-Marin Diversion Project

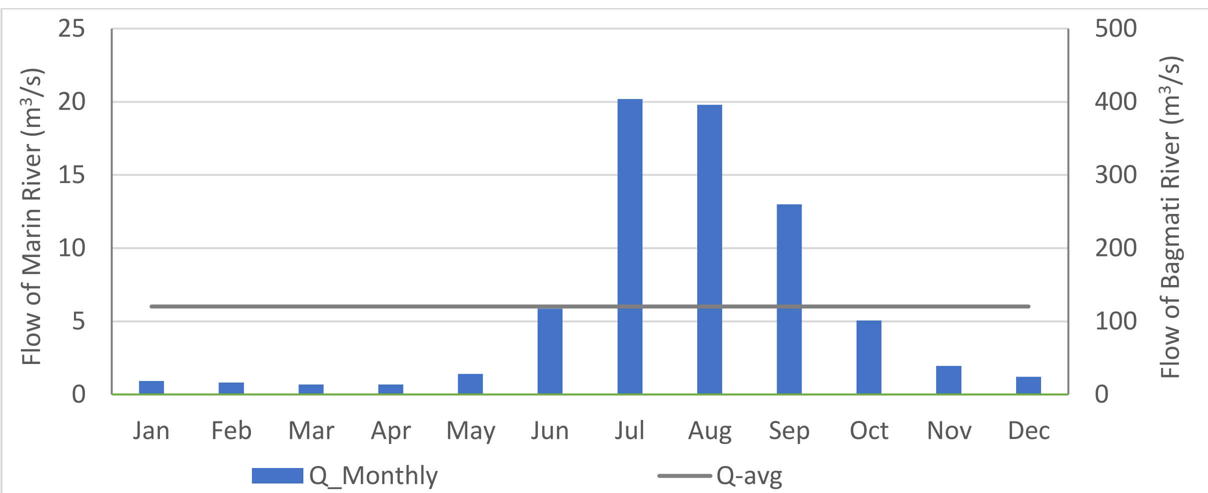


Figure 5: Long-term flow variation of Marin and Bagmati Rivers. Q_monthly: average monthly flow; Q-avg: average annual flow

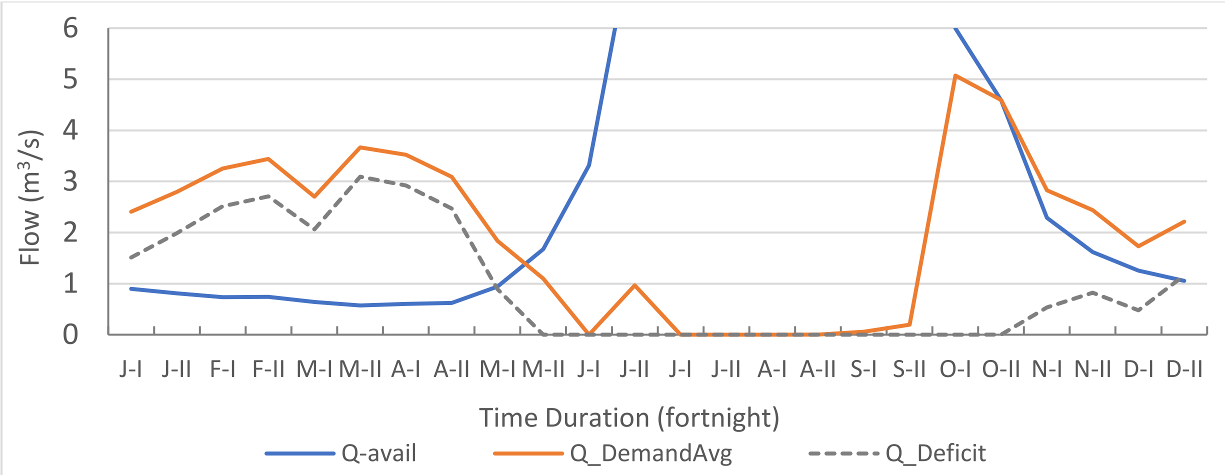


Figure 6: Average fortnightly flow availability required for year-round irrigation and deficit in Marin Basin. Q_avail: available long-term average flows; Q_DemandAvg: average gross irrigation requirement; Q_Deficit: irrigation water deficit; high flows have been truncated to zoom in on low-flows.

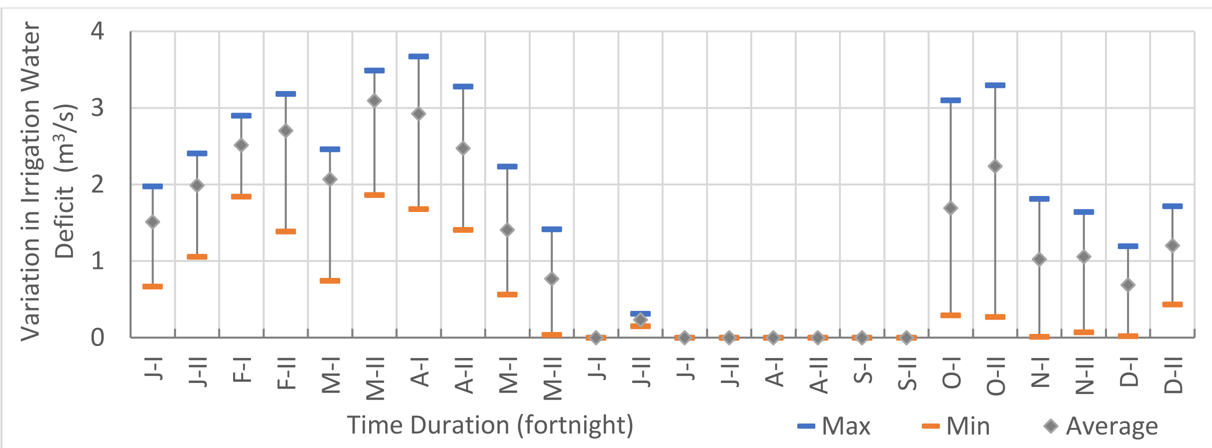
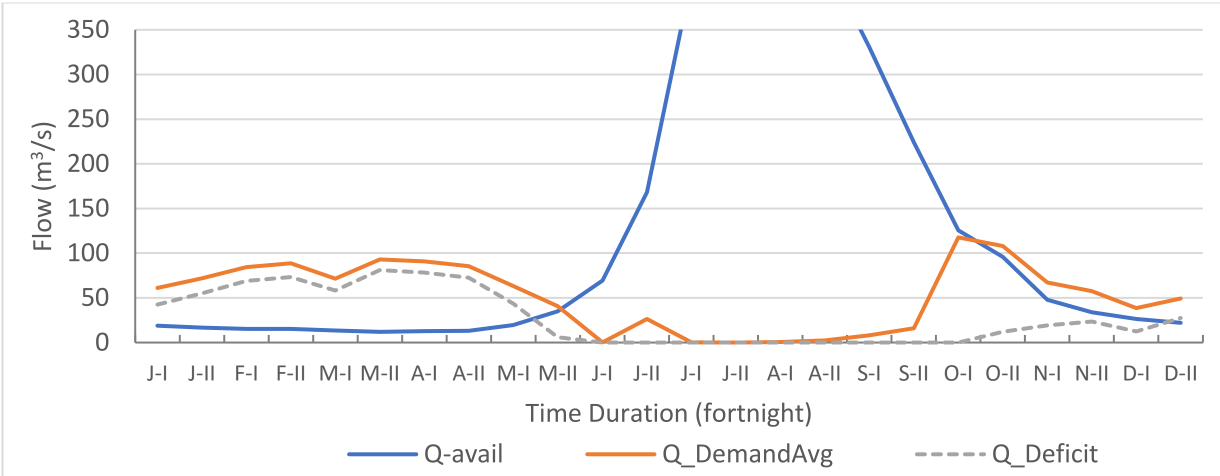
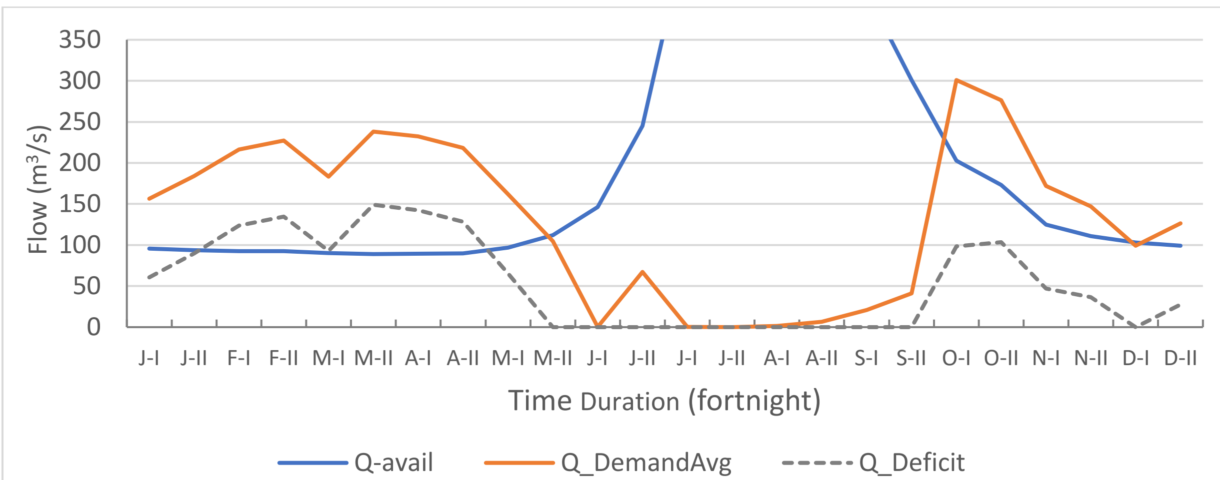


Figure 7: Average fortnightly irrigation water deficit and its variability in the Marin Basin

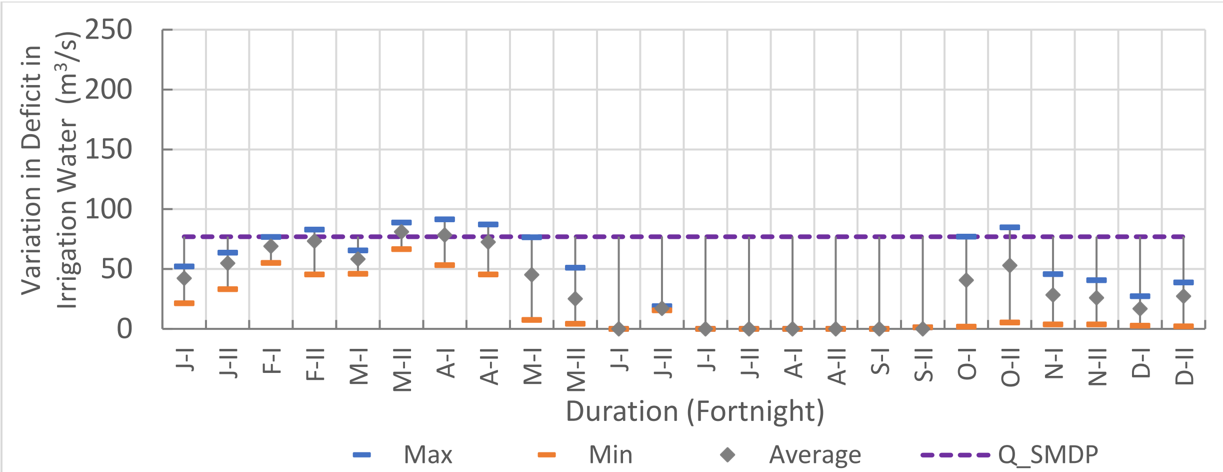


a) “Without SMDP” scenario (current irrigable area of BIP: 47,700 ha)

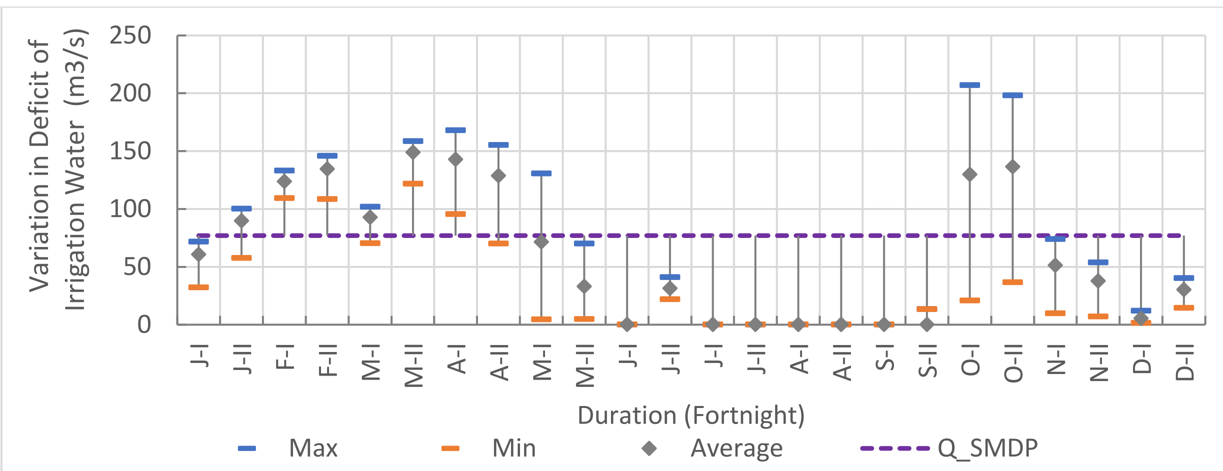


b) “With SMDP” scenario (propose irrigated area of BIP after SMDP: 122,000 ha)

Figure 8: Average fortnightly flow availability required for year-round irrigation and deficit in Bagmati Basin a) “Without SMDP” scenario and b) “With SMDP” scenario. BIP: Bagmati Irrigation Project; SMDP: Sunkoshi-Marin Diversion Project; Q-avail: average available flow; Q_DemandAvg: average irrigation demand; Q_Deficit: average unmet demand. High flows have been truncated to zoom in on low flows.



a) “Without SMDP” scenario



b) “With SMDP” scenario

Figure 9: Average fortnightly irrigation water deficit and its variability in the Bagmati Irrigation Project command area. Q_SMDP: proposed year-round diversion from the Sunkoshi-Marin Diversion Project