Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Muhammad Farhan

Assess the effect of reservoirs in Sutlej river on high and low flow conditions in the lower parts of the basin

Master's thesis in Masters in Hydropower Development
Supervisor: Tor Haakon Bakken
July 2023

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Declaration of Authorship

I declare that I am, Muhammad Farhan, the sole author of this thesis named “Assess the effect of reservoirs in Sutlej River on high and low flow conditions in the lower parts of the basin” which has been submitted to the examination office on 2nd July, 2023. I have completely referenced any ideas and work of others whether published or unpublished. Literal or analogous citations are clearly marked as such.

Preface

It is study carried out as a Master's thesis, a 30 ECTS course with course code TBM4900 for the Master's program in Hydropower Development at Norwegian University of Sciences and Technology, Trondheim. It has been carried out in spring semester 2023. This project is the idea of Professor Tor Haakon Bakken from Civil Engineering Department at the Norwegian University of Sciences and Technology, Trondheim. The assumed readers of this study are academic researchers and students.

Trondheim, 2023-07-02

Muhammad Farhan

Acknowledgement

First of all I would like to thank God Almighty who made it possible for me to pursue and finish this study successfully.

I believe it to be my honour to be able to work with Professor Tor Haakon Bakken from Civil Engineering Department at the Norwegian University of Sciences and Technology, Trondheim as he was always helpful, available and gave proper guidance. Carrying out this study with such non existent datasets would not have been possible if not for the assistance, recommendations and guidance by him. I would also like to thank NTNU and especially Hydropower Development faculty for giving me a chance to pursue my studies at this prestigious institute and getting to experience living in Norway.

Finally, I would like to thank and appreciate my family who have always been supportive of me beyond limits, and I couldn’t be any luckier to have them as my family. My utmost appreciation to my friends from my department as well who guided and helped me whenever I was in pinch regarding my thesis.

Remark:

I would like to thank Professor Hamza Gabriel from National University of Science and Technology, Islamabad, for providing the data of Sulemanki and Islam Headworks which enabled the initiation of this study and also I would like to thank Dr. Andrea Momblanch from Cranfield University, UK for sharing their WEAP model which was helpful as it gave some idea about initiating the setup of the model.

Muhammad Farhan

Abstract

In the south Asian countries of Pakistan, India and Tibet, a considerable portion of population is directly related to agriculture. Water is the essential element for both urban and rural use. In these areas reservoirs are key-stones in the management of water resources and of major importance for the provision of a wide range of services such as irrigation, drinking water supply, flood control and hydropower production. On one hand the establishment of new reservoirs might affect the water availability positively, as they store water from the wet to the dry season and secure adequate access to water all year around. On the other hand, establishment of reservoirs might increase the total evaporation of water to the atmosphere and enable downstream users larger volumes of withdrawals and increasing the consumption. Finding the balance between the trade-offs of these two effects is a delicate management task. Acknowledging the fact that climate change, population growth, economic development, increased needs for food production (irrigation) will put additional pressure on the available water resources (Bates et al., 2008), a careful design, operation and management of the infrastructure to store and distribute water is a major challenge and responsibility of water managers.

The increasing population growth, industrial and agricultural activities have increased consumption of water resources. In future, the issues might increase with the increasing impacts of climate change. These types of modeling studies can be beneficial for developing strategies against potential problems for sustainable water resource management. In this study WEAP (Water Evaluation and Planning System) was used for modeling of Sutlej river basin. The main objectives are to collect available data, prepare the data needed for carrying out modelling study, then configure WEAP as the analytical tool and simulate effects of reservoirs on seasonal flows and propose a set of mitigation actions to enhance the water security in the lower parts of basin.

In the data scarce focused region of this study, observed and modelled data from various sources and techniques is compiled and integrated in order to create a hydrological model and estimate the flow characteristics of the Sutlej River Basin. The benchmark ratings for the model's performance indicated acceptable results. Modelled results revealed that reservoirs can have a beneficial effect during low and high flow periods on the lower part of the basin. The possible future developments could help in stabilizing the flow and meeting the water demand

through-out the year. It is the first model made on the complete length of the Sutlej basin including areas from Tibetan plateau, northern India and Pakistan.

Contents

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Abbreviations

WEAP = Water evaluation and planning systems

SEI = Stockholm Environment Institute

SWAT = Soil and Water Assessment Tool

SWIM = Soil and Water Integrated Model

HSPF = Hydrological Simulation Program Fortran

GIS = Geographical Interface System

NSE = Nash Sutcliffe efficiency

SDGs = Sustainability Development Goals

m.a.s.l = meters above sea level

P = precipitation

E = evaporation

Q = discharge/runoff

SP = snowpack

SM = soil moisture

UZ = upper ground water zone

LZ = lower ground water zone

Lakes = volume occupied by lakes

SMM = Soil Moisture Method

KGE = Kling-Gupta Efficiency

PBIAS = Percent Bias

RSR = observation standard deviation ratio

R2 = coefficient of determination

NSE = Nash-Sutcliffe Efficiency

Introduction:

Sutlej river springs in the Tibetan plateau, it is a transboundary in eastern Pakistan and northern India. On its way through India, a number of reservoirs have been built and extensive volumes are withdrawn before it enters the Pakistani borders, flows into Chenab River and then Indus River. Water is the source of life on Earth and essential for all living things. The use of water resource is crucial (Vörösmarty, Green et al. 2000). Several hydrological modelling studies are carried out to determine characteristics and water budgets of watersheds (Singh and Frevert 2003). In these studies different hydrological models are used such as WEAP (Water evaluation and Planning System) (Yates, Purkey et al. 2005), SWIM (Soil and Water Integrated Model) (Krysanova, Wechsung et al. 2000), HSPF (Hydrological Simulation Program Fortran)(Yan, Zhang et al. 2014), SWAT (Soil and Water Assessment Tool) (Neitsch, Arnold et al. 2011) etc. In these modelling studies, the real system should be simulated as close as possible by the model developed for the study. Data can be gathered from related institutes and where data is not available, open access data sets can be used (Ekeu-wei and Blackburn 2018). For the purposes of integrating data, processing data and visualization of results, the GIS (Geographical Information System), spreadsheets (Excel) and numerical calculations are used (Wurbs 1998).Many parts of Pakistan are considered water stressed. The proper utilization and integrated management of water resource is needed. Pakistan has been suffering from conditions since year 2000 especially in areas around Sutej Basin, which has caused reduction in river discharge and lesser rains occurred. The reliance on ground water has increased and extensive pumping is observed (Sufi, Hussain et al. 2011). The major inflow in the Sutlej basin is due to snowmelt and rainfall during the summer season when temperature is high. The middle and upper portion falls in greater Himalayan range. Diverse climate is observed throughout the study area. The downstream portion has tropical and warm temperature areas while the upstream undergoes cold climate. Annual precipitation ranges from ~ 299 mm to ~1273 mm during periods of 1989-2005. The majority of basin is made up of barren, shrubs, snow and glacier, water and forest (Singh, Goyal et al. 2016). The main reason for low crop production in the region is the inadequate supply of water and it can severely affect the supply and demand of agriculture (Latif and Pomee 2003). In this irrigation system the trend gets even worse due to the inequality of the allocation of water among its users at the head, middle and tail reaches (Rinaudo, Strosser et al. 1997). To solve this problem it is pertinent to develop water management alternatives for water demand and supply (Griggs and Noguer 2002).

According to a World Bank Report, Pakistan is projected to be water scarce by 2035 (Reinsch and Pearce 2005). In 1950s the water availability per capita was 5260 m^3 which has now reduced to 1100 m^3. If the population growth and annual runoff remains same, the water availability per capita would be 725 m^3 by 2025. The sustainable use of water resources is the key to safeguarding future access to water resources, automatically contributing to the sixth goal of Sustainable Development Goals (SDGs) (Connor 2015). Sustainable irrigation, energy production and other such uses of water resources contribute to second and seventh SDGs (zero hunger, affordable and clean energy) (Giupponi and Gain 2017).

Generally low flows occur at dry periods of the year. However, the changes in natural flow regime of a river can result in the general reduction in the flow regime of river (Smakhtin 2001). The river regulations increases flow rate during low flood periods and dampens floods (Stromberg, Beauchamp et al. 2007). The snow storage causes the lowest flow to occur, any low flow event during summer are the result of precipitation deficit and higher evapotranspiration (Galvez, Rojas et al. 2020).

Various studies have been carried out in developing/developed countries. Andrea and Lamprini (Momblanch, Papadimitriou et al. 2019) considering a range of climate change and socio-economic development scenarios developed a WEAP model for the western Himalayan water resource system. Their results indicated higher impact of socio-economic changes and relatively less impact of climate change. According to their study, water scarcity and excess and flood abatement are responsible for most trade-offs. Another study was carried out by Hassan and Burian (Hassan, Rais et al. 2019), WEAP system of Indus Basin was modelled to assess impacts of future demands on the Indus water resources. According to this study, the future demand in 2040 will cross the current availability of water resources resulting in severe water resource scarcity.

After analysing several applications of WEAP, it was decided that WEAP can be used for developing management plan in the low flow region of Sutlej Basin. This study focuses on integrating the data acquired through different sources, modelling the missing data of the data scarce regions, developing hydrological models and estimating water budget of Sutlej River using WEAP as the modelling tool. The study also focuses on assessing the effect of new reservoirs on the downstream under seasonal flows and assessing effect of climate change and proposing mitigation measures.

Materials and Methods:

Study Area:

The Sutlej River basin is located in eastern Pakistan, northern India and Tibetan plateau. It originates from Manasarovar and Rakshastal lakes in the Tibetan Plateau at altitude of 4572 m.a.s.l. The area of basin is around 99145 km^2. On its way from India to Pakistan, a number of run of river hydropower plants and reservoir are built. After entering Pakistan, the Sutlej river flows into the Chenab river which further flows in Indus river that ultimately falls in the Arabian sea. The altitude ranges from 74 to 6857m.a.s.l with the mean height of 2710 m.a.s.l. It consists of 4.24% glacial area. The temperature ranges during winter and summer varies greatly among the areas at downstream and upstream. During summer period the Sutlej basin experiences extensive rainfall due to monsoon from April to September. It brings humid climate and torrential rainfall. The Sutlej runoff is comprised of snow melt at top and rainfall in catchment areas. The maximum flow is during summer and monsoon is often marked by occasional floods in Sutlej. The Sutlej basin upto Islam headworks comprises of agriculture (32.7%), forest(13.9%), grassland(33.5%), wetland(0.1%), urban(0.8%), shrubland(0.4%), barren or sparse vegetation(10.6%), open water(1.3%) and snow and ice(2.3%).

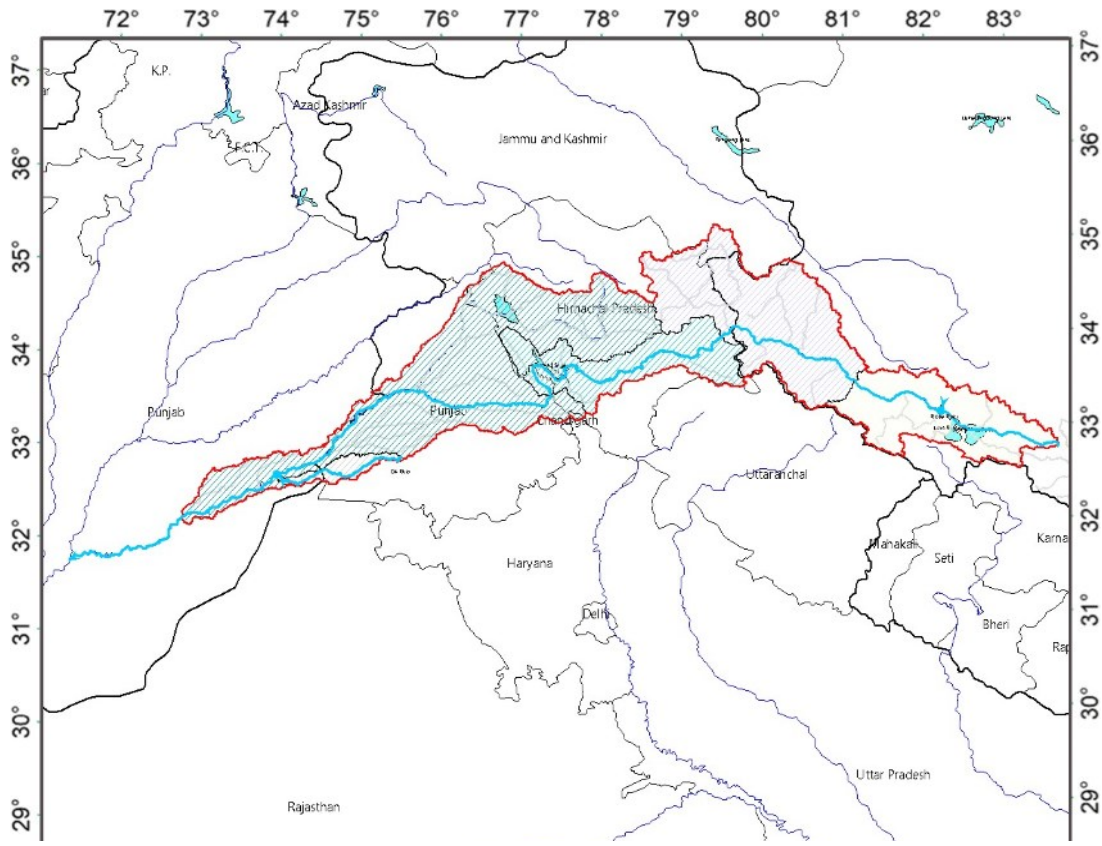

Figure 1 Location map of Sutlej river originating in Tibetan Plateau (right side of the map), crossing India (middle) then entering Pakistan and flowing into Chenab river (left).

HBV PINE

In this study as the dataset for most of the basin is non-existent, the HBV (Hydrologika Byråans Vattenbalansavdelning) model is used to simulate the head flow data at the top of Sutlej basin and obtain the required data to input for the WEAP model development. This HBV model is used to simulate runoffs and inflow. This model uses precipitation, temperature and potential evapotranspiration to calculate snow melt/accumulation, actual evapotranspiration, soil moisture storage, ground water and runoff. The software PINE-HBV that is based on this model is used in this study to determine the parameters of the basin which in turn are used to calculate the discharge at headwater area (Killigtveit 1995). The model uses daily time series of precipitation and temperature. The general equation is:

$$P - E - Q = \frac{d}{dt}; [SP + SM + UZ + LZ + lakes]$$

Where,

P = precipitation

E = evaporation

Q = discharge/runoff

SP = snowpack

SM = soil moisture

UZ = upper ground water zone

LZ = lower ground water zone

Lakes = volume occupied by lakes

The PINE-HBV V1.0 developed by Trond Rinde is used in this study. The HBV model is considered instead of other techniques as HBV model takes into account the snow routine as well and the area under study also generates runoff from snow melt.

The 4 main components of the HBV model are lower zone, upper zone, soil moisture and snow routine as shown in the figure below. The final result is the runoff from the catchment.

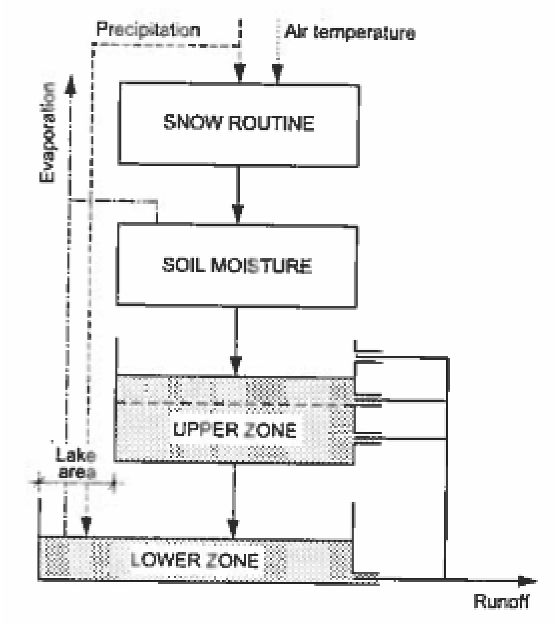

Figure 2 Structure of HBV Model

WEAP

The WEAP software is developed by Stockholm Environmental Institute (SEI). It is used to plan water resource usage with an integrated approach. It models a variety of components such as streamflow, groundwater, base flow, water demand and allocation, operation of reservoirs, power generation, water quality, financial and environmental requirements. The detailed equations used in WEAP can be found in WEAP user guide (Sieber, Swartz et al. 2005). There are five approaches used in the model. They are as Rainfall runoff, Irrigation Demands, Soil Moisture Method, the MABIA Method and Plant Growth Model.

In this study, the soil moisture method was used for most of the components as the area offers deep percolation, for irrigation catchments MABIA method was used which is a simulation of daily datasets of transpiration, evaporation and irrigation requirements and includes modules for determining evapotranspiration and soil water. The soil moisture scheme is one dimensional, based on empirical functions that describes the runoff (surface and sub-surface), evapotranspiration and deep percolation (Abera Abdi and Ayenew 2021).

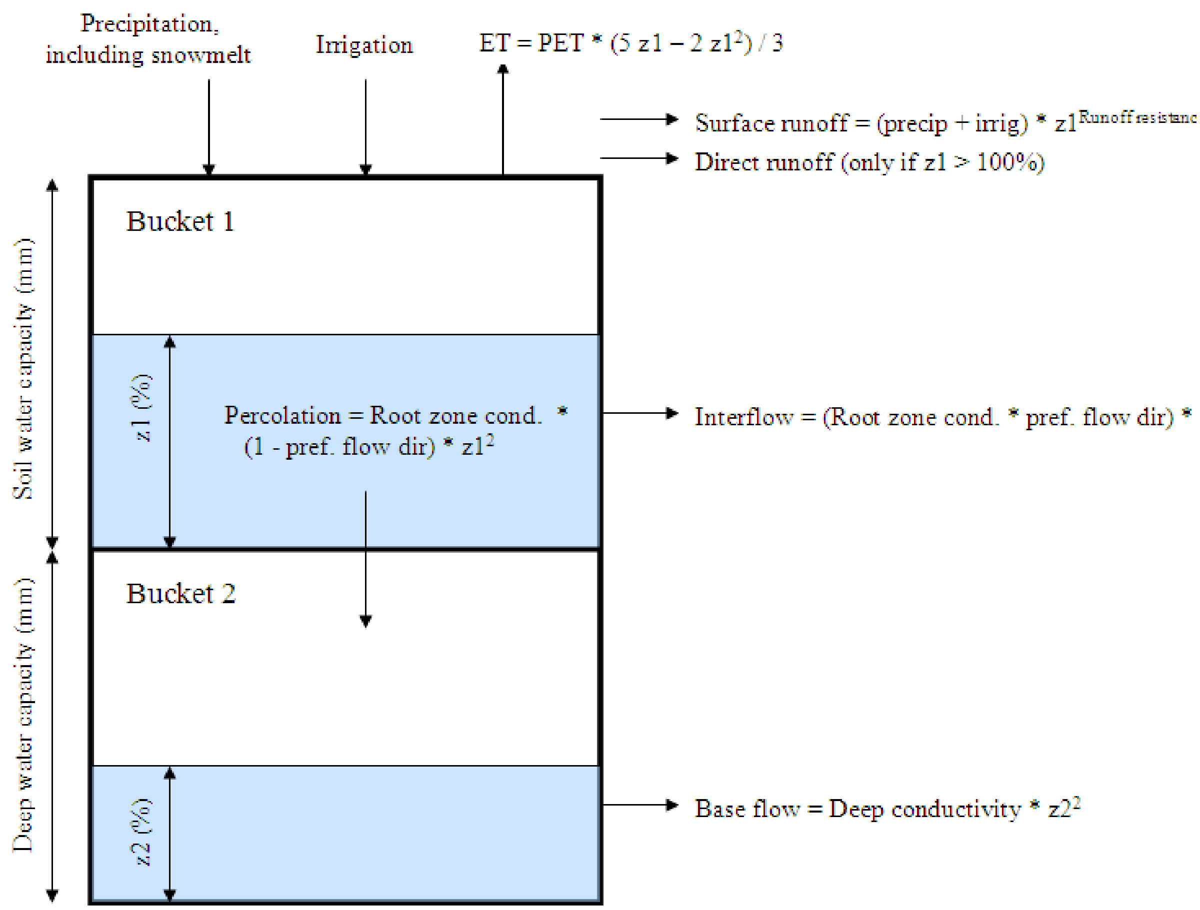

Figure 3 Conceptual diagram and equation incorporated in Soil Moisture Method in WEAP

Data Analysis and Model setup:

WEAP software offers catchment delineation mode which is helpful in determining catchments, elevation and land use. Also, GIS (Geographical Information System) software was used to determine topography and land use. Local and global data sets were used to compile and obtain the required data needed for modelling process. SRTM (Shuttle Radar Topography Mission) was used to obtain DEM (Digital Elevation Models). During modelling purposes, the inbuilt catchment delineation mode of WEAP was used as it offered better and easier detailing options.

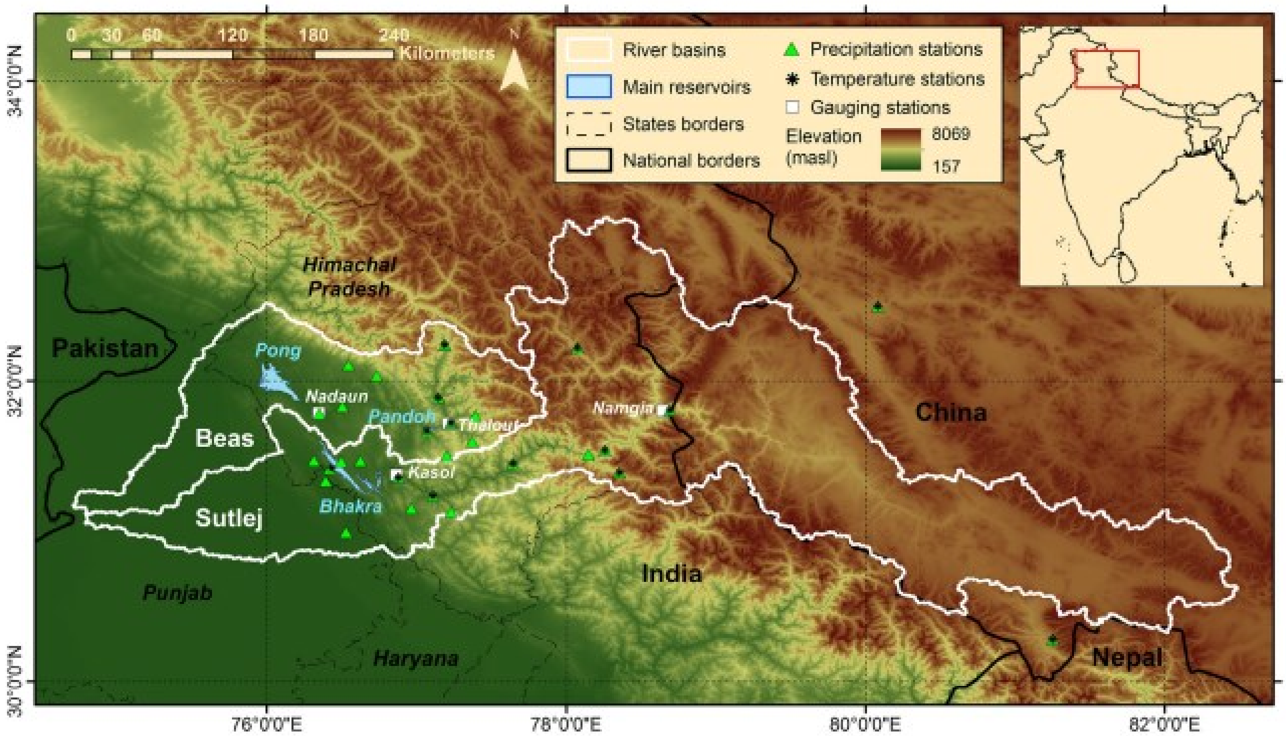

Figure 4 Sutlej and Beas river basins with climate and flow monitoring networks (Momblanch, Papadimitriou et al. 2019)

WEAP offers detailed catchment delineation data. Following details about areas in the Sutlej basin were obtained using it.

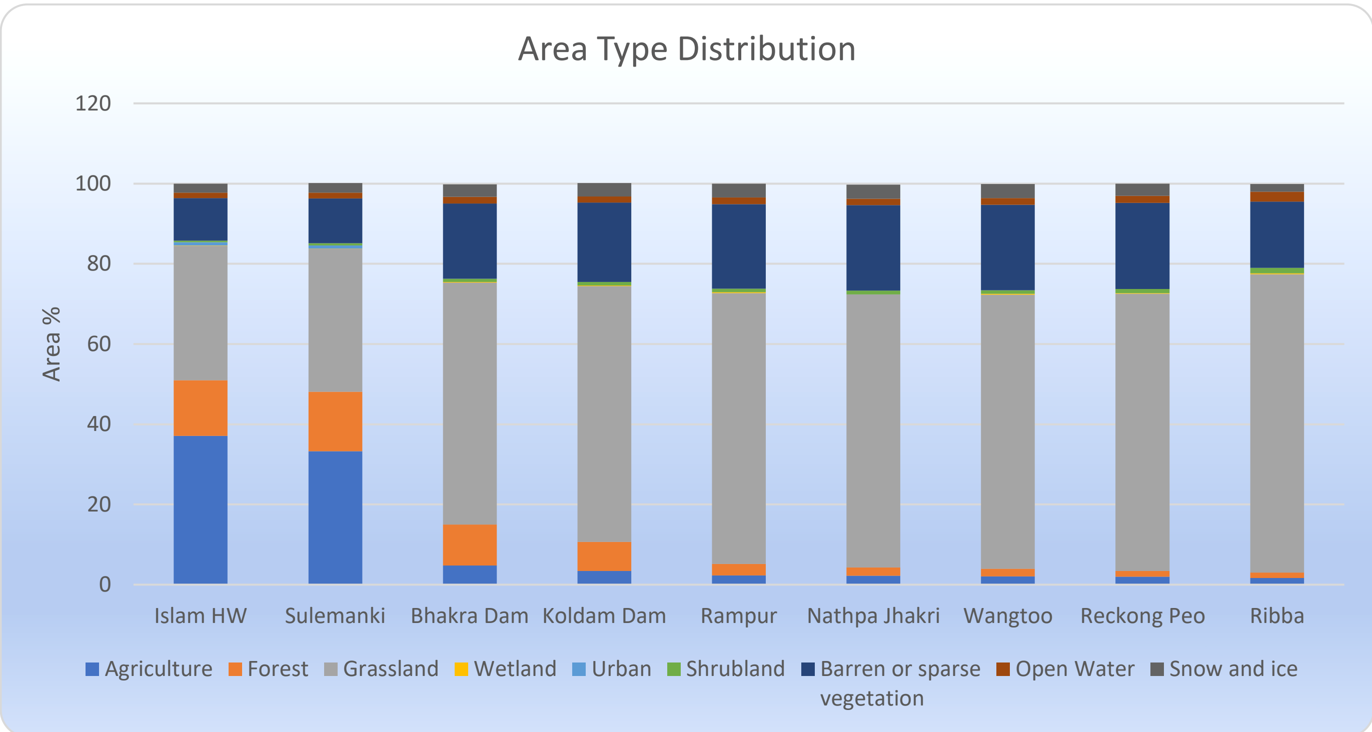

Figure 5 Catchment Delineation Data obtained through WEAP at different points in the Sutlej basin

Pine-HBV was used to simulate unknown discharge at the headwater area using the known discharge at tailwater (Sulemanki headworks and Islam headworks). Temperature and precipitation data was obtained from online global databases. The parameters for tailwater region were obtained using all the known datasets and then those parameters were used for simulating discharge at top. Some of the parameters regarding snow/glacial area, total area, elevation profile were obtained using WEAP's catchment delineation mode. Thornthwaite method and CLIMAWAT software were used for obtaining evapotranspiration values. Then the simulated data for headwater regions was obtained using the parameters obtained from using known data of tailwater areas, the catchment details obtained from WEAP and evapotranspiration values calculated.

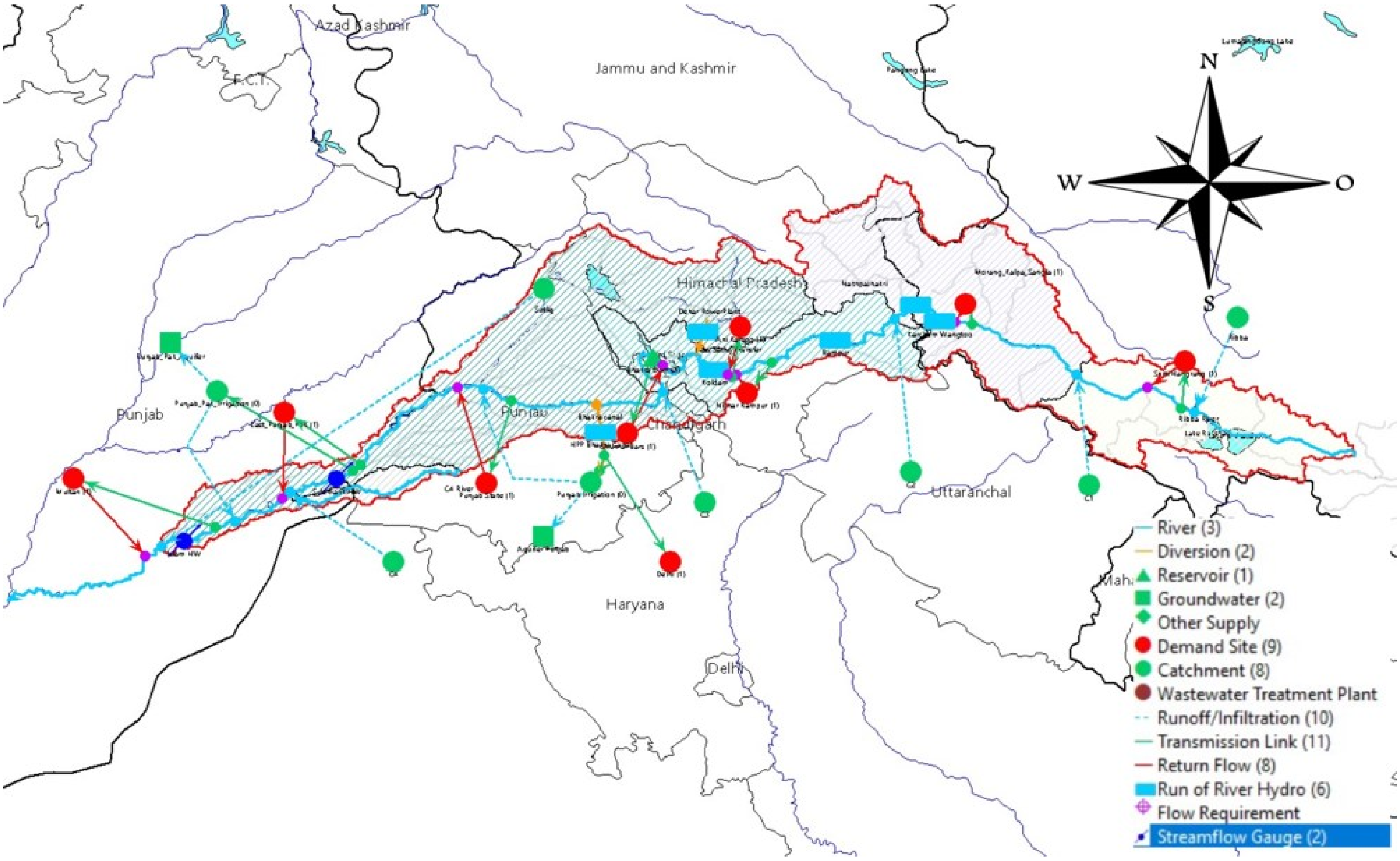

Figure 6 Formulation of the study area model for analysis in WEAP

Only monthly precipitation dataset was available, so it was converted into the daily data for use in Pine-HBV by equally distributing among the number of days. After compiling all the data and integrating it, the model was run on WEAP. The data ranged from 1986 to 2015. First half of the period was used for calibration up to 2000 and later for validation. Monthly discharge data was used for calibrating the model in WEAP. The coefficients such as R^2 (coefficient of determination), NSE (Nash-Sutcliffe Efficiency) (Nash and Sutcliffe 1970), KGE (Kling-Gupta Efficiency) (Gupta, Kling et al. 2009), PBIAS (Percent Bias) (Moriasi, Gitau et al. 2015) and RSR (observation standard deviation ratio) (Moriasi, Arnold et al. 2007) are used to verify the integrity of the model and to evaluate the model performance. Here, R^2, KGE and RSR values were used as benchmark.

Here, coefficient of determination uses the ratio of the total squares of regression to the total squares of the values around the average to define the goodness of fit. Value of 1 means perfect fit and values greater than 0.5 are generally considered acceptable (Yaykiran, Cuceloglu et al. 2019).

$$R^2 = \frac{\sum[(Q_{stm} - Q^{-}{}_{stm})(Q_{obs} - Q^{-}{}_{obs})]^2}{\sum(Q_{stm} - Q^{-}{}_{stm})^2 \sum(Q_{obs} - Q^{-}{}_{obs})^2}$$

Here Q_{stm} is flow rate model result, Q^{-} is the average flow rate and Q_{obs} is observe flow rate.

Nash-Sutcliffe Efficiency uses the relative magnitude of residual variance to observed variance to define the goodness of fit. Its value ranges from 1 to negative infinity. Generally, values between 0 and 1 are acceptable.

$$NSE = 1 - \frac{\sum(Q_{obs} - Q_{stm})]^2}{\sum(Q_{obs} - Q^{-}{}_{obs})^2}$$

Kling Gupta Efficiency deals with temporal dynamic while maintaining the distribution of flows. Its values ranges from 1 to negative infinity. The values between 0 and 1 are considered acceptable.

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}$$

Here, r is the mean, α is standard deviation and β is the corelation between data and observation.

Percent Bias is the average trend of simulated values as compared to the observed values. The values greater than 0 indicates overestimation and less than 0 indicates underestimation.

$$PBIAS = \left[\frac{\sum(Q_{stm} - Q_{obs)})}{Q_{obs}}\right] * 100$$

The observation standard deviation ratio is the ratio of the root mean square error and standard deviation of the observed data. Its value ranges from 0 to higher positive numbers, higher numbers indicate poor performance.

$$RSR = \frac{\sqrt{\sum(Q_{obs} - Q_{stm})]^2}}{\sqrt{\sum(Q_{obs} - Q^{-}{}_{obs})^2}}$$

Results and Discussion

As most of the discharge data at upstream was simulate therefore the WEAP's calibration period was taken as almost half the total duration 1986-2000 and model was simulated from 2000 onwards. The R^2 value for calibration was 0.5 and for modelling with considering the Bhakra Dam in the system was 0.72 and without considering the Bhakra reservoir was 0.59. The values of R^2 are not so high as the data was non-existent and for some regions non available for being classified by the authorities but it is acceptable as the all the values are above 0.5. As the impact of data limitation is higher for such a large-scale basin, achieving higher model performances could be difficult. The effect of water transfer to and from other basins, changes in reservoir operations, climatic anomalies could also have caused lower performance of the model. The KGE value with reservoir was 0.16 with reservoir and 0.15 with reservoir. The RSR value with and without reservoir were both 1.1.

When comparing the simulated and observed runoff at the bottom gauge of Sulemanki headworks while considering the Bhakra Dam in the system, we get the following results as shown in figure below.

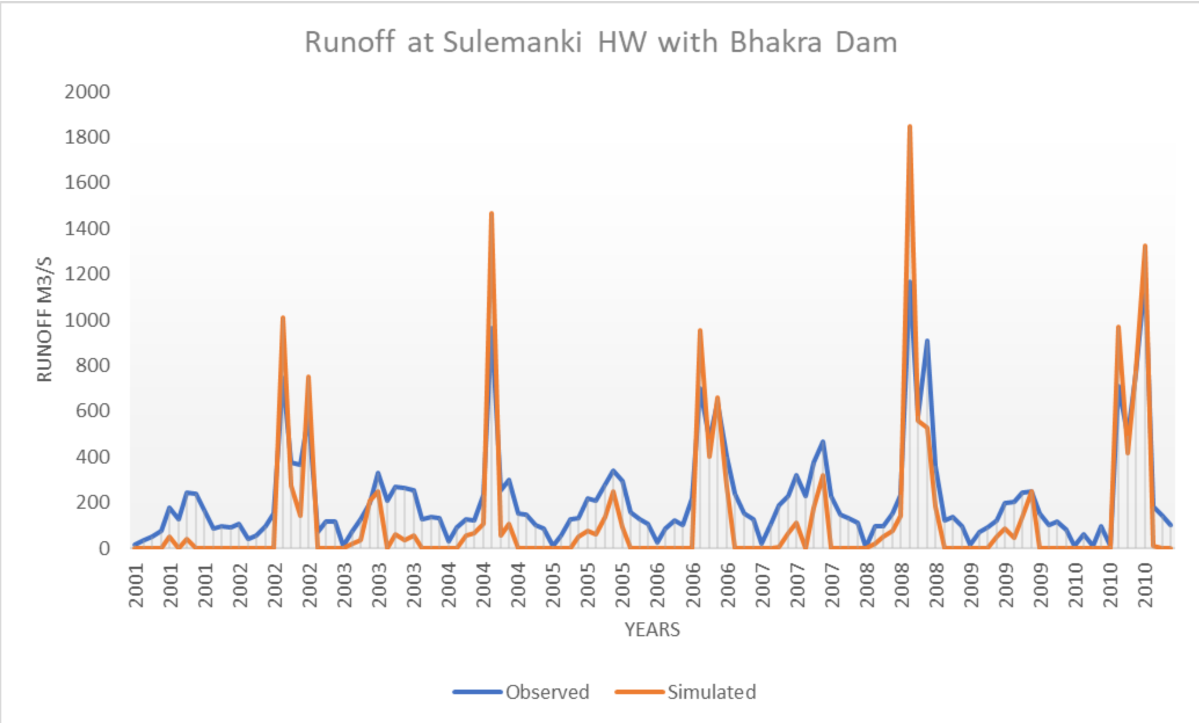

Figure 7 Runoff comparison at Sulemanki HW, simulated and gauged considering Bhakra reservoir in the system

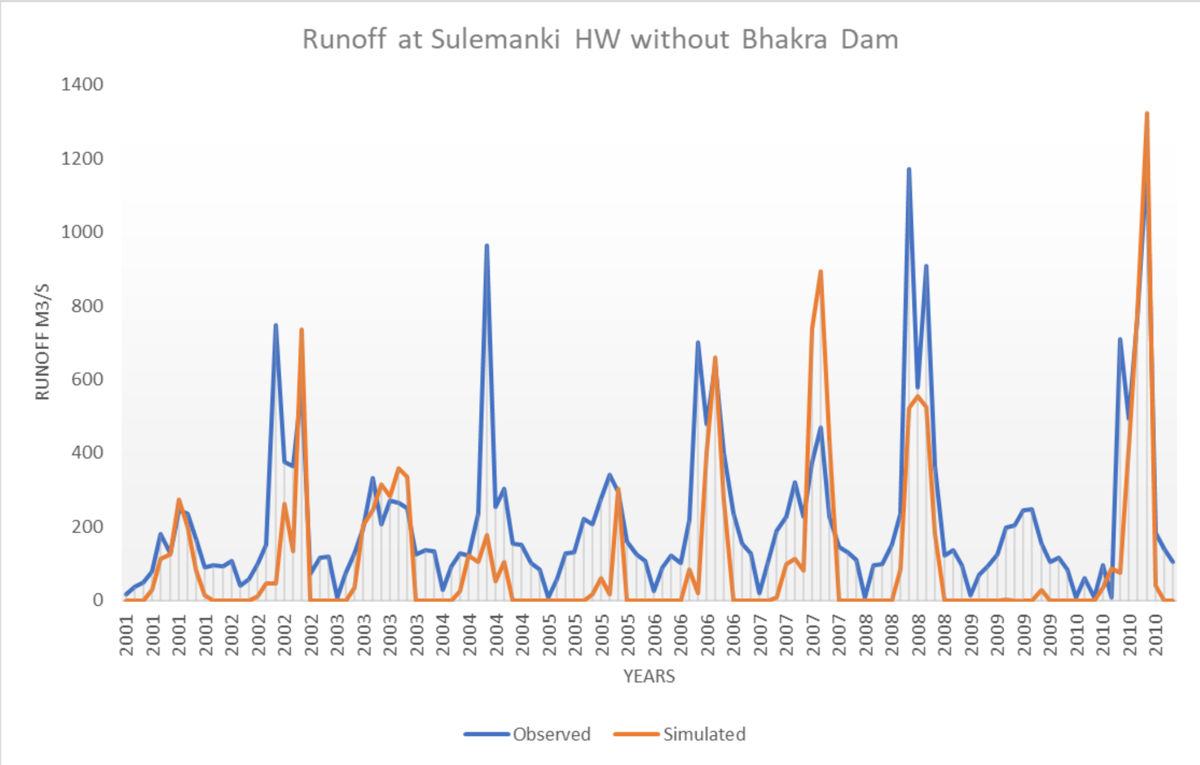

Figure 8 Runoff comparison at Sulemanki HW, simulated and gauged without considering Bhakra reservoir in the system

The difference in the simulated discharges in both conditions shows that in absence of a reservoir, higher flow instances occur in most of the summers which indicates inefficient water resource usage. Whereas in presence of reservoir, peaks are relatively low for most summers and indicates the possibility of water usage for other purposes and diversions. The discrepancies could be the result of lack of routing components, missing reservoir operations data and most of data being classified due to it being in hotspot of regional conflicts. The performance of simulation of baseflow is also affected by the uncertainty in water consumption rate data and unavailability of ground water data.

The principle of the law of conservation of mass forms the basis of the water budget equation used in WEAP. It considers all the flow entering and leaving the system and water stored in a certain period of time. The average annual water demand was simulated on WEAP for the years 2001-2010 as shown in figure below. It represents high water demand during low flow periods and low during high flow periods excluding the time for crop irrigation.

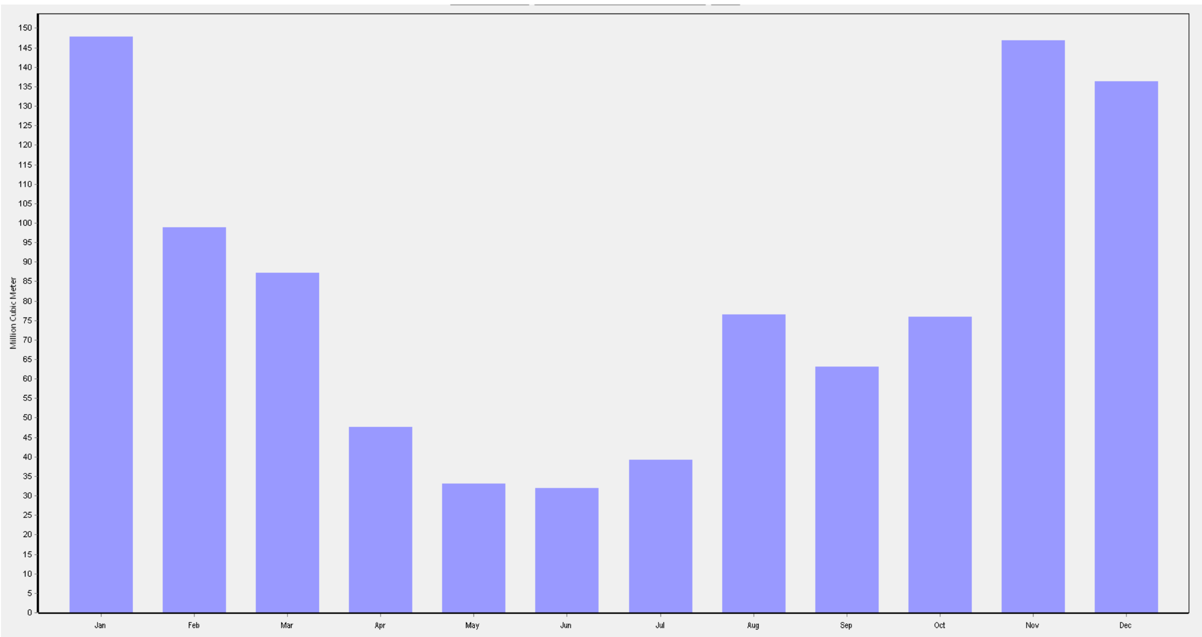

Figure 9 Water demand

It shows that the water demand is high during the winter due to the irrigation cycle which is also during the dry and low flow season whereas the demand is low during summer which is high flow season. Hence, building reservoirs with long term storage could be beneficial in meeting the water demand during low flow periods and preventing droughts.

Conclusion:

This model has been successfully calibrated and modelled for the Sutlej River basin where most of the area in downstream is agricultural land and upstream is grassland. The results considering the Bhakra reservoir and considering without it in the system are compared to evaluate the effect of reservoir development in the river during the high and low flows. From the hydrological results obtained from the model it is evident that the reservoirs can be helpful in meeting the high water demand during the low flow periods of winter and storing the water during the high flow periods due to high rainfall brought by monsoon and glacier melt during summer. This study is among the first ones done on the complete length of Sutlej basin including the areas in Tibetan plateau, north India and Pakistan. Considering the objective of the study, the model performance indices were still within acceptable ranges considering the unavailability, non-existence of much of the data needed for the modelling purposes and much of the data being used was simulated using other methods and software. It indicates that simulating unknown data through Pine-HBV for use in WEAP is a possible approach. The increase in mean temperature is increasing the glacier melt but decrease in total glacial presence decreasing the runoff. Considering the area under effect is large, reservoirs can be beneficial against both issues. This model setup maybe used as a baseline for future studies on the Sutlej River basin. The development of all the countries containing the areas of Sutlej River basin strongly depends upon their ability to efficiently manage and operate the water resources according to the demand. A proper cross-country water policy (other than Indus Water Treaty). which should involve sharing of data as well as most of the data in upper portion is classified, needs to be developed considering the effects of climate change and areas under study being the one of the most effected by climate change.

Future works might investigate detailed study of the effects of climate change on complete basin and its economic impact as well. For low flow periods, detailed reservoir operation might be incorporated into model as well.

Availability of data and material

All data used for this study are included within the manuscript.

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Appendix

Discharge at Sulemanki Modeled and Observed

Year	Timestep	Observed m3/s	w/o Bhakra Dam	with Bhakra Dam
			Modeled m3/s	Modeled m3/s
2001	1	17.21480826	0.093865355	0
2001	2	36.75446103	0.087631173	0.096611111
2001	3	50.36698302	0.095640046	0.102824846
2001	4	77.25779205	27.79784452	0.098407022
2001	5	180.4276701	112.1467573	51.65684568
2001	6	127.650939	124.2326528	0.095368441
2001	7	245.5600162	272.9354769	42.2933179
2001	8	236.9196678	202.2262022	2.810292052
2001	9	166.3562867	79.89001775	0.107269676
2001	10	88.65605556	15.03034799	0
2001	11	94.8501983	0.084253858	0
2001	12	93.6762662	0.077314815	0
2002	1	108.2407654	0	0
2002	2	39.03485185	0.107348765	0
2002	3	57.81498765	0.104769676	0
2002	4	98.73585802	12.63131096	0.093582176
2002	5	151.650716	46.78852778	0.092687886
2002	6	745.9205432	46.30351235	1009.681481
2002	7	376.2093086	261.8411358	277.3400988
2002	8	364.760963	133.3175679	141.5970123
2002	9	578.8927901	736.9328395	752.8350123
2002	10	72.09959259	0.020983719	0.112582562
2002	11	116.4946049	0	0
2002	12	119.6522099	0	0
2003	1	8.430468364	0.104060957	0.007064082
2003	2	76.61423457	0.017798302	21.24974228
2003	3	127.0466049	34.34519444	37.06594136

2003	4	196.6556543	202.9484815	207.6252346
2003	5	331.1969136	244.7618025	249.7881235
2003	6	206.657284	316.3253086	0.101833719
2003	7	272.0385926	282.5233827	60.81262346
2003	8	264.6954568	358.8943457	38.34967901
2003	9	252.0816049	335.3720247	57.81387037
2003	10	126.6102593	0.119221836	0
2003	11	135.8224938	0	0
2003	12	132.9595062	0.009399344	0
2004	1	30.06233642	0.005003125	0
2004	2	92.49499383	0.088177083	0.088177083
2004	3	127.9190988	26.28519753	54.49975309
2004	4	122.9002716	121.8720494	68.21358025
2004	5	235.4877531	103.6282099	109.5970123
2004	6	964.070321	176.9569753	1465.204444
2004	7	253.2216049	53.39239506	54.78978395
2004	8	302.4860494	103.5050123	104.9298025
2004	9	153.0186173	0.101400463	0.11577392
2004	10	150.0851358	0.005195177	0.009137809
2004	11	102.1211852	0.091217978	0.091217978
2004	12	85.5942716	0	0.106297068
2005	1	9.173760802	0	0.11160571
2005	2	58.10133951	0	0.011670833
2005	3	129.3690741	0.110517747	0.103353009
2005	4	131.4714198	0.111943287	49.65380342
2005	5	220.1577037	0.111321759	74.548761
2005	6	207.0094198	18.33889969	63.21597
2005	7	278.0548395	60.8987716	139.1739126
2005	8	340.7755309	15.99722531	247.0447673
2005	9	296.0057778	303.2475309	91.01866049
2005	10	160.6165802	0.004620563	0.102118056
2005	11	126.6210617	0.092595293	0

2005	12	106.5306173	0.002114047	0
2006	1	24.70610648	0.109836034	0
2006	2	89.05140741	0.003601559	0
2006	3	121.7882469	0.107520062	0.100410494
2006	4	100.7701111	0.10738233	0.100533565
2006	5	217.3522469	82.95108025	0.111703318
2006	6	701.205284	21.32525463	956.345679
2006	7	478.5317037	401.7040741	402.5590123
2006	8	638.4696296	660.7005432	661.5571852
2006	9	400.0162963	271.0526667	271.8265926
2006	10	237.453358	0.119177855	0.120753858
2006	11	155.2532469	0	0.015615895
2006	12	127.5375802	0	0.119432485
2007	1	20.33307407	0.09801196	0.11733642
2007	2	106.0081852	0.018061458	0.013531636
2007	3	189.2604198	7.31446142	8.009841049
2007	4	227.1462716	98.05374074	64.54994444
2007	5	320.9193086	112.2114691	112.9168642
2007	6	228.6501481	80.85211111	0.097103395
2007	7	376.1451111	737.1917037	180.9260864
2007	8	468.7318025	894.6405926	321.1581975
2007	9	227.350321	433.875358	0.100826003
2007	10	145.4512963	0.113604938	0
2007	11	130.4776667	0.011878781	0.094850309
2007	12	111.4228272	0.09801196	0
2008	1	8.229584105	0.106761188	0
2008	2	96.00630247	0.018254051	22.01965586
2008	3	98.48547531	0.112847222	51.98360494
2008	4	150.9693333	0.027449074	75.43875926
2008	5	236.5212593	84.82014815	143.7088025
2008	6	1169.673284	523.8979259	1847.744395
2008	7	577.8406914	555.946963	556.5240988

2008	8	909.2887901	526.4062222	526.9760494
2008	9	363.5286173	181.4998519	182.0581111
2008	10	123.638642	0.01102064	0.009475231
2008	11	136.4284691	0.104088735	0.095715664
2008	12	96.39951235	0	0.00239858
2009	1	15.3082037	0	0
2009	2	70.58603086	0.112287423	0.097336806
2009	3	91.85558025	0.121336034	0.004039468
2009	4	123.8717654	0.107511574	49.65380342
2009	5	199.0816667	2.793109954	86.85912631
2009	6	204.4966049	0.107154321	47.41573
2009	7	246.3240988	0.122626157	139.1739126
2009	8	247.041284	0.122328704	247.0447673
2009	9	155.0985556	29.41618519	0.097105324
2009	10	103.7721728	0.110606867	0.103436343
2009	11	115.2502222	0	0
2009	12	84.35275926	0	0
2010	1	8.882223765	0.130658951	0
2010	2	60.16480247	0.115347608	0
2010	3	8.882152778	0.119304012	0
2010	4	95.00017284	34.58359259	0.098232639
2010	5	8.882189043	85.77530247	0.109121528
2010	6	710.2989136	74.24349383	968.1352099
2010	7	492.0921975	415.4254321	415.7785185
2010	8	767.9093333	778.2178765	778.5655309
2010	9	1190.726716	1323.980444	1324.322765
2010	10	184.9377778	41.00148457	10.88198534
2010	11	140.4933827	0.018457523	0.016208873
2010	12	103.482358	0.011226157	0.126209105

Monthly streamflow Sulemanki HW

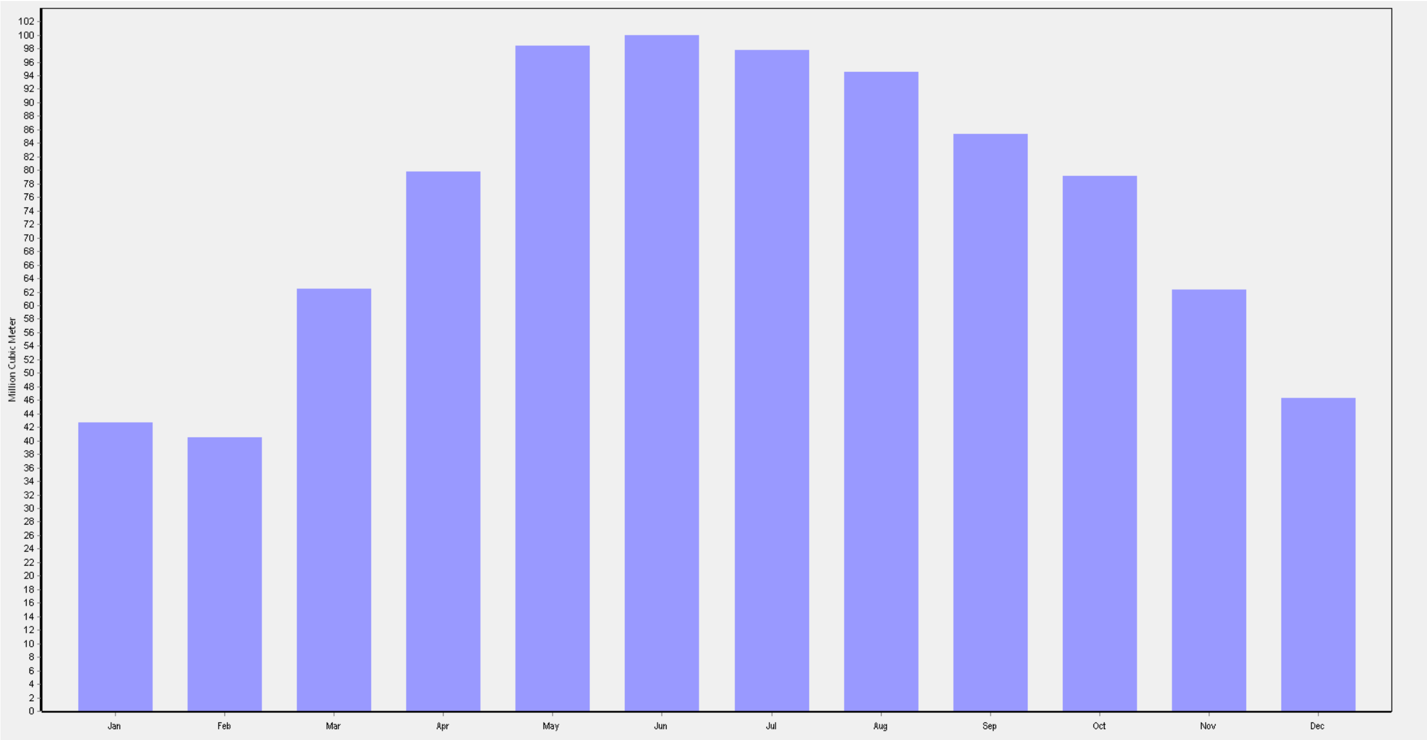

Figure 10 Streamflow at Sulemanki HW, monthly

Calibration

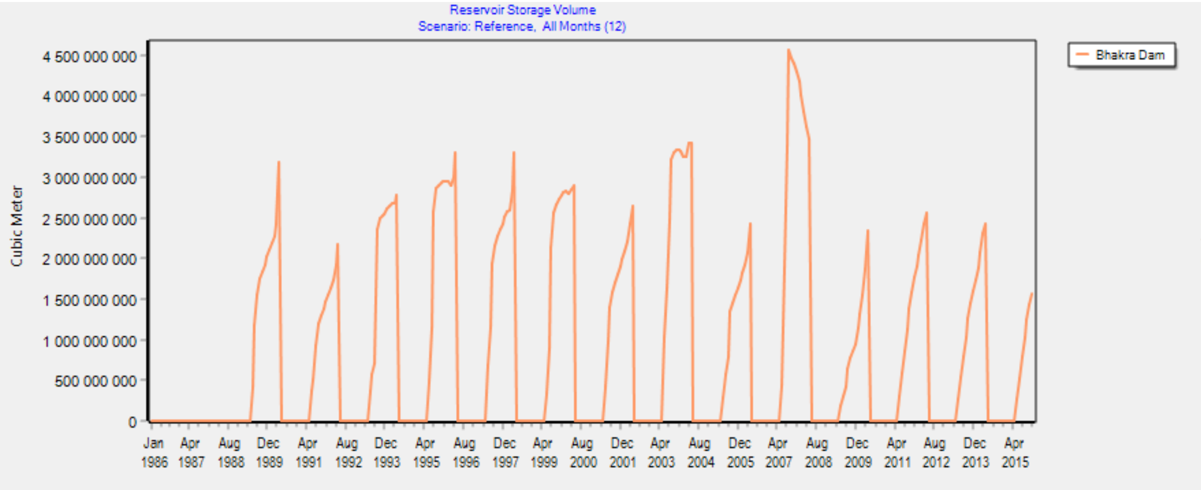

Figure 11 Reservoir Storage Volume

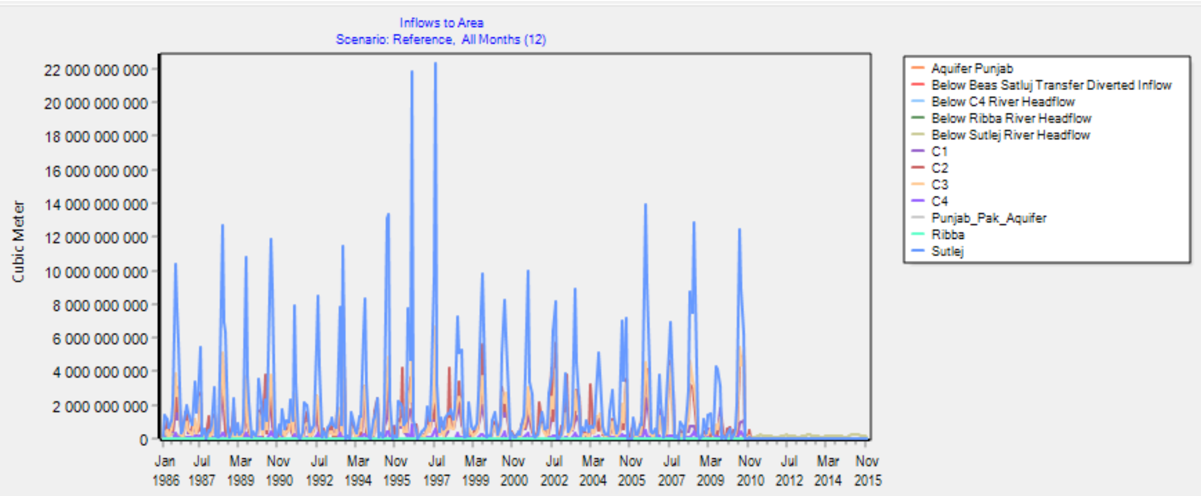

Figure 12 Inflow wrt Areas

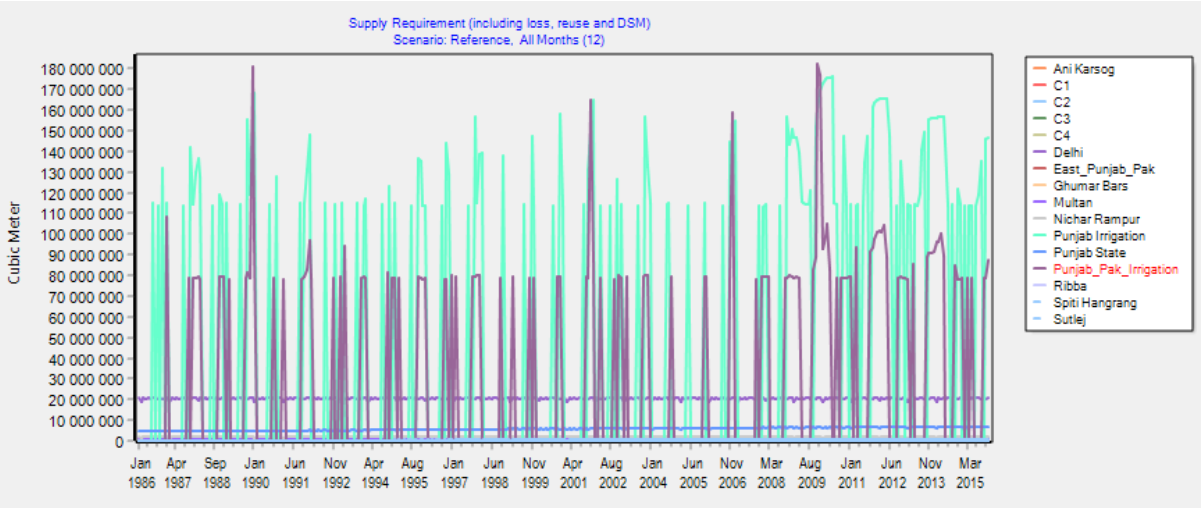

Figure 13 Supply requirements

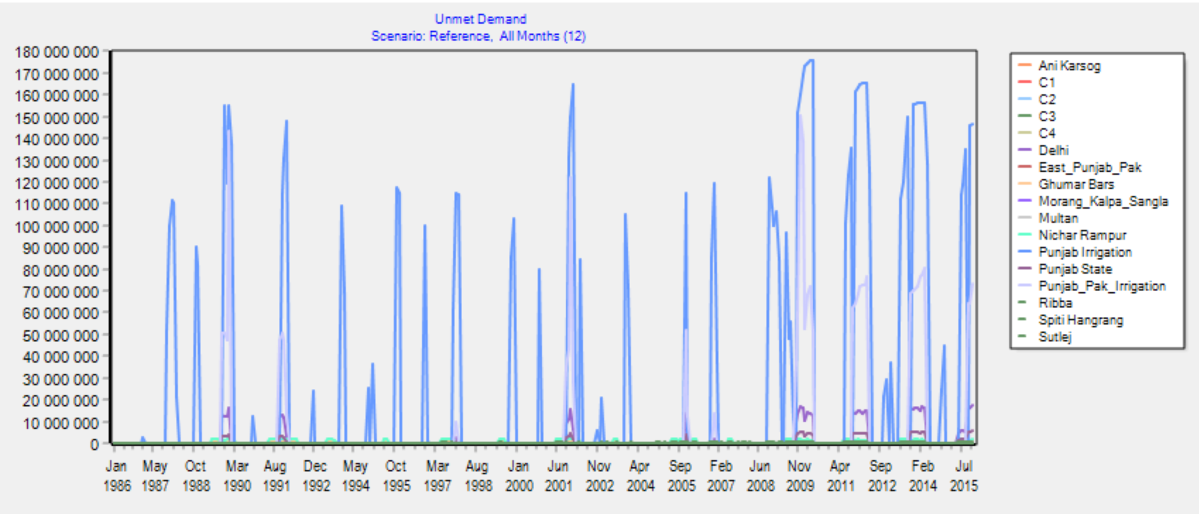

Figure 14 Unmet Demand

Demand Site Inflows and Outflows

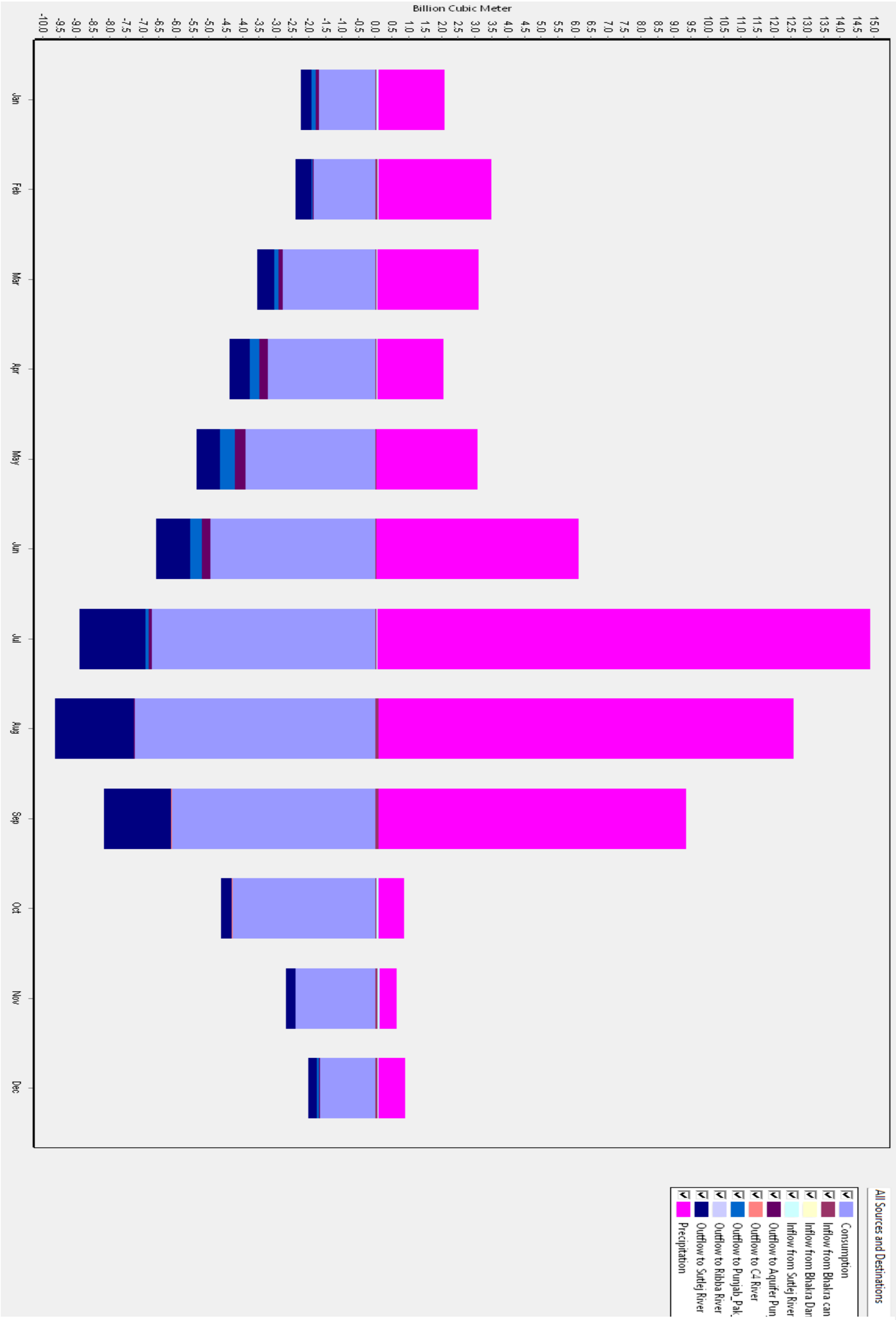

Figure 15 Inflows/Outflows

Inflows to areas

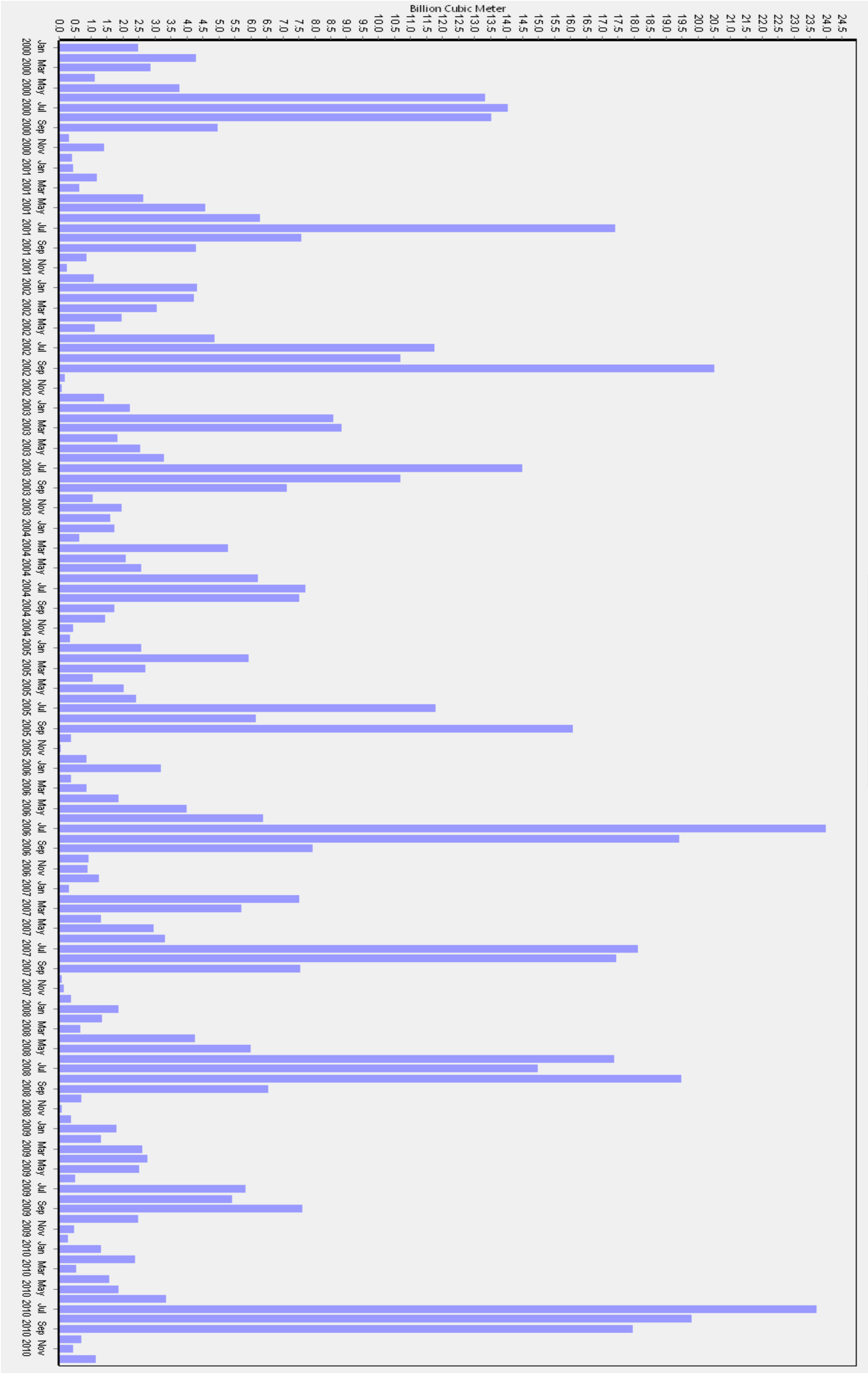

Figure 16 Inflows to areas

Streamflow

Figure 17 Streamflow

Streamflow to Sulemanki gauge comparison

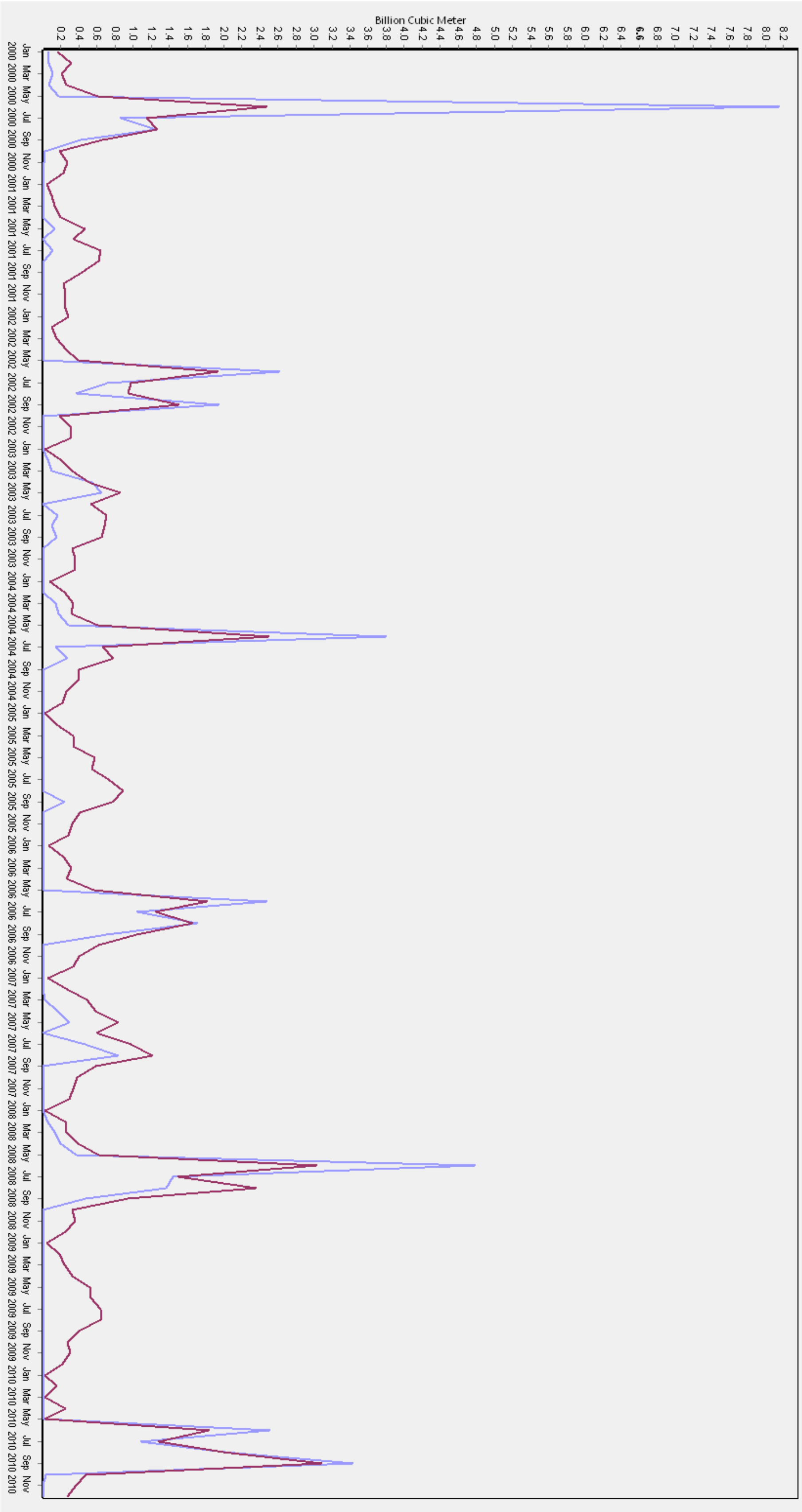

Figure 18 Streamflow comparison

Sutlej Catchment Precipitation

Figure 19 Precipitation in Sutlej Catchment

ET Actual

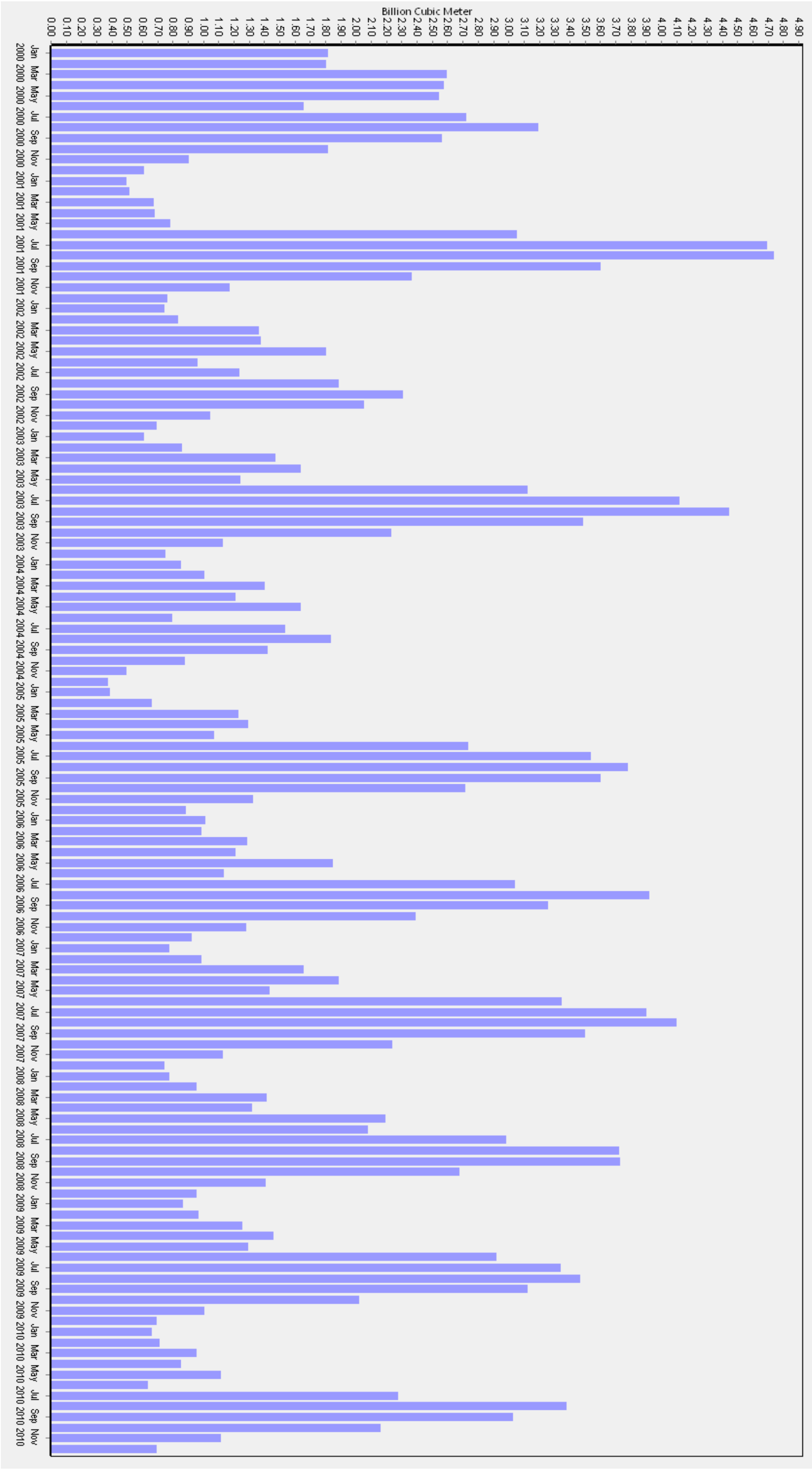

Figure 20 Evapotranspiration

Surface Runoff

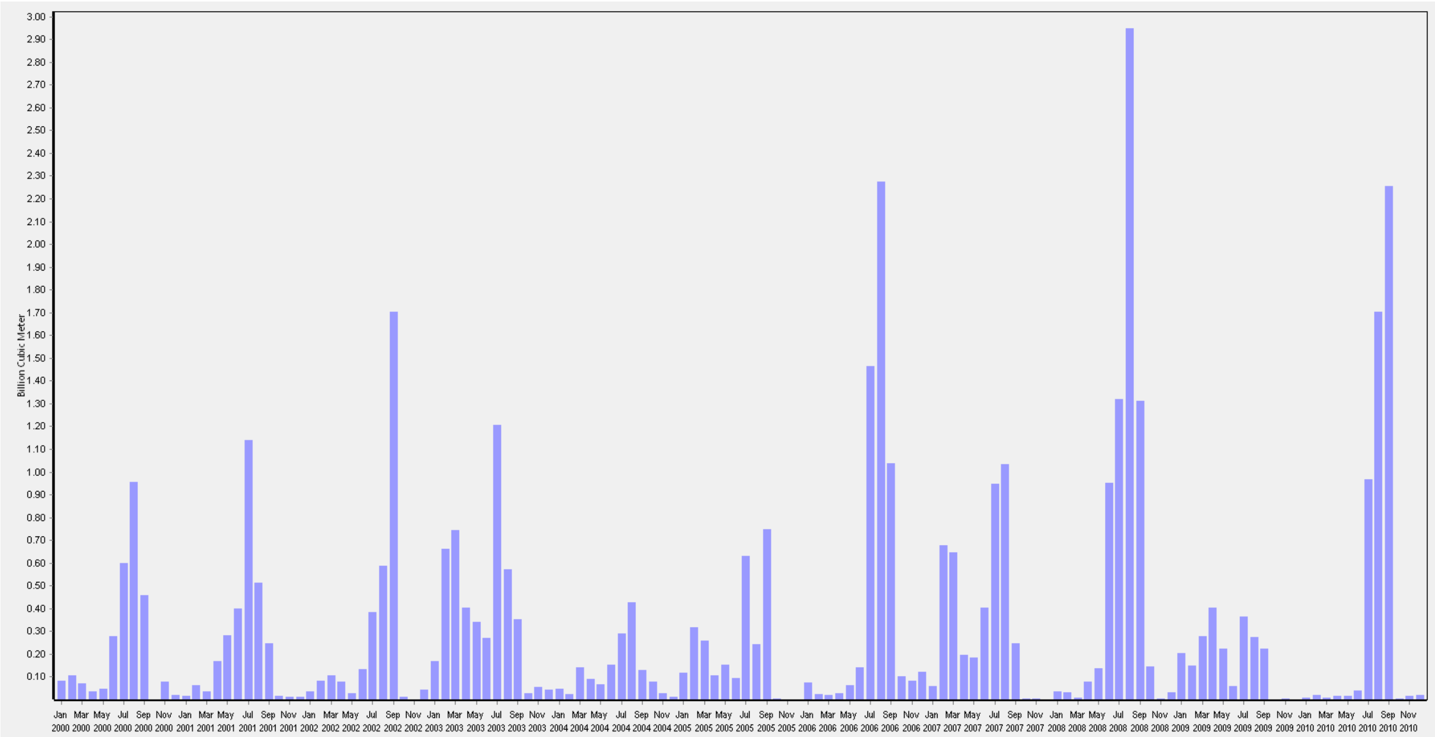

Figure 21 Surface runoff

GIS watershed

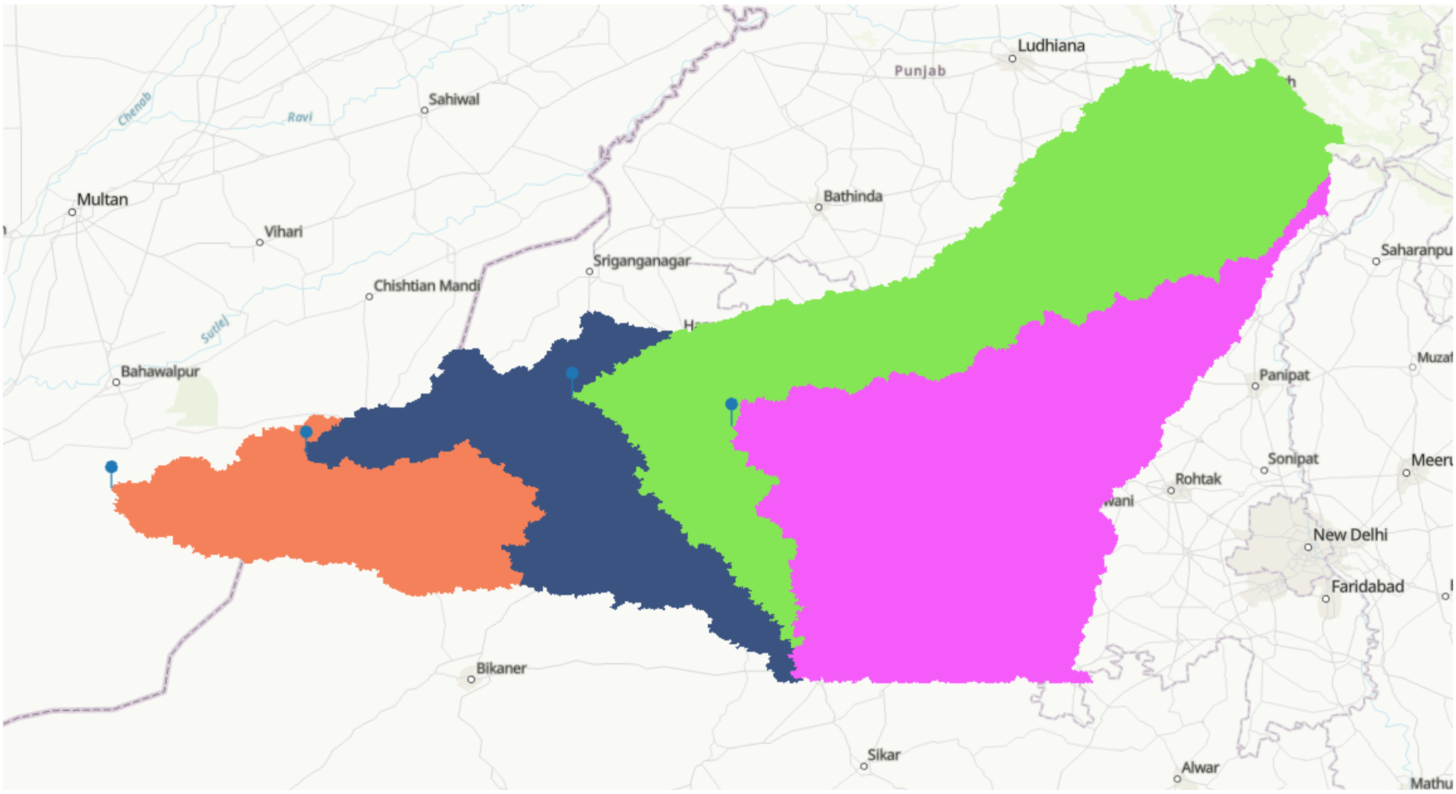

Figure 22 GIS Watershed

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