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Drought Risk Assessment in Sunkoshi River Basin: An Application of Hydrological Model

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Abstract

Drought is an event that lasts for months or years and causes economic damages, compromises ecosystem and threat food security. In order to reduce drought impacts drought risk assessment, need to be done. Commonly used methods for drought risk assessment are, observation-based method, in situ data-based method, remote sensing data-based method, model-based method. This study uses model-based method to assess the agricultural drought risk using Soil Moisture Index (SMI) in Sunkoshi, Hampuachaur. The model was optimized at 0.25° resolution by taking KGE as objective function and was analyzed at 0.015625° resolution. The model was calibrated from 1981-2000 and validated from 2001-2016. Spatial and temporal variation of drought risk was determined at the Sunkoshi, Hampuachaur basin. SMI was calculated on the basis of base period (1951-2000) for the evaluation period (2001-2016). From the area under drought August of 2006 experiences maximum area under drought i.e., 50.76 %; followed by January of 2013 (27.39%); December of 2012 (27.20%); November of 2012 (25.08%); September of 2005 (23.16%); August of 2016 (21.86%); March of 2009 (19.14%); September of 2002 (14.68%); February of 2009 (13.37%); October of 2014 (11.30%). Year 2009 and 2010 experiences maximum duration of exceptional drought i.e., for 7 months each; 2006 and 2013 for 6 months each; 2001 and 2016 for 4 months each; 2008 and 2012 for 3 months each; 2004, 2005, 2015 for 2 months each; 2002 and 2014 for 1 month each. In the evaluation period abnormally dry condition is in 2988.58 km^2 area, moderate drought is in 4327.09 km^2 area, severe drought is in 153.42 km^2 area, extreme drought is in 365.76 km^2 area, exceptional drought is in 204.16 km^2 area in Sunkoshi. Our results indicated that the mHM model can be applied in the Sunkoshi, Hampuachaur basin to evaluate the drought risk in that basin.

Keywords

Drought, Mesoscale Hydrologic Model (mHM), Koshi River Basin (KRB), Soil Moisture Index (SMI)

1. Introduction

Drought is a long-term shortage of water supply caused by atmospheric (below-average precipitation), surface water, or ground water. It can last for months or years. It has a detrimental impact on the production of groundwater, contemporary industrial goods, and electricity and is one of the most severe, unpredictable, and common natural disasters in the world.. According to the International Disaster Database (EM-DAT), the global annual loss from drought from 1960 to 2016 was approximately 221 billion dollars [1].

Climate change adds to the uncertainty of drought. According to the Intergovernmental Panel on Climate Change (IPCC), it is predicted that climate change would lead to more frequent and severe droughts, which could happen even in areas where precipitation is expected to increase. Water availability and quality will be major pressures on, and issues for, societies and the environment as a result of climate change. Climate change has emerged as a major global issue, prompting serious concern at both the national and international levels. The Earth's climate has changed significantly throughout history, and scientists have been overwhelmed by the current rapid shifts in global climate [2]. Temperature and precipitation changes have a significant impact on cryospheric processes and the hydrology of Himalayan headwater catchments [3]. Climate change is having varying degrees of impact on river basins around the world [4]. Climate change may cause frequent droughts and floods due to changes in rainfall distribution and temperature.

Droughts are classified into four types based on the scarcity of water: meteorological droughts, agricultural droughts, hydrological droughts, and socioeconomic droughts.Agrarian nations like India and Nepal, whose agriculture output employs more than 68 percent of the population, are recognized as being affected significantly by agricultural drought as a recurrent, unplanned natural calamity. The year-round unsuitability of the land for cultivation has a considerable detrimental effect on the populations of people and animals, as well as the potential for biomass and the diversity of plant species. As a result, it is critical to monitor drought characteristics in order to protect the environment and avoid unnecessary loss of life and money [1]

2. Material and Methods

2.1 Study area

The study area for this research is Sunkoshi, Hampuachaur which is shown in the Figure 1. The catchment area of the Sunkoshi, Hampuachaur basin is 18,151 km^2. The basin is roughly divided into five sections from south to north due to variations in geography and elevation: the Terai Plains (<500m), the Low River Valleys (<700m), the Siwalik Hills (700-1500 m), the Mountains (1500-2700m), the High Mountains (2700-4000 m) and the Himalayas (>4000 m). The South Asian monsoon, which is responsible for 80% of the annual rainfall, has a major impact on the Sunkoshi, Hampuwahcaur basin throughout the summer. Varying climate and geography results in the uneven distribution of precipitation. The basin experiences four seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November) and winter (December -February).

Due to the high elevation in the north and low in the south the river flows from north to south. The Sunkoshi and Hampuachaur basin's vegetation has a clear vertical zonation due to a large elevation gradient and climate change. The vegetation in the basin includes the majority of all vegetation types on earth, including forest, grassland, and shrubland. The population in the plains and middle mountains is high whereas the population is scattered in the higher mountains, where agriculture and livestock are the main livelihood options for the communities. Water is also seen as a limited resource in the basin as a result of its declining availability due to its importance for agriculture, electricity generation, and many other uses in addition to drinking.. Based on the landform characteristics, the basin can be divided into the downstream, midstream and upstream reaches. The basin is one of the tributaries for the Koshi River Basin.

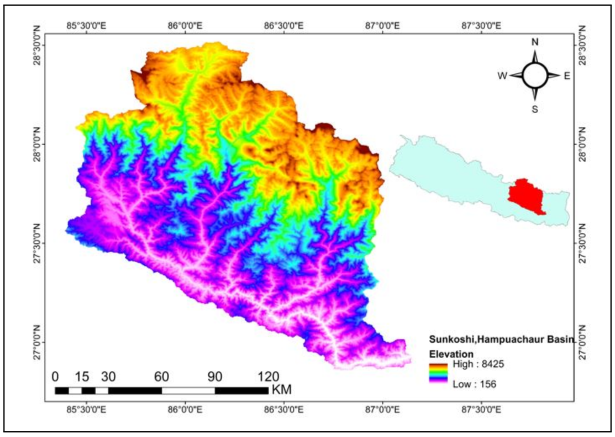

Figure 1: Location and details of the Sunkoshi river basin

2.2 Methodological framework

For this research work, mesoscale hydrologic model (mHM) was used as a tool for the assessment of agricultural drought risk in the Sunkoshi, Hampuachaur basin. mHM model was successfully applied in almost all the basins of Germany and in South Asia [5] [6] [7] [8] [9]. The overall framework comprises of two steps. In the first step different data required for mHM is prepared. In the second step the mHM is implemented to reconstruct monthly soil moisture using historical meteorological forcings, morphological variables, and land cover data and the SMI is estimated with a non-parametric kernel-based cumulative distribution function [8] based on the mHM's historic soil moisture reconstruction. The generated SMI maps are separated into five classes based on SMI values namely abnormally dry, moderate drought, severe drought, extreme drought and exceptional drought. The methodological framework for this study is shown in Figure 2. The data required for mHM model are collected like morphological data like Digital Elevation Model (DEM), Land Cover (LC), Information of gauge stations (idgauges), Slope, Aspect, Different soil class horizon, Soil class identification; meteorological data like Precipitation, Maximum Temperature (tmax), minimum temperature (tmin), average temperature (tavg); Leaf Area Index (LAI) data; Observed discharge data of hydrological station developed by Department of Hydrology and Meteorology (DHM). The model is calibrated and validated against the observed discharge data. Soil moisture is extracted as model output and used to calculate the Soil Moisture Index (SMI). Thus, the calculated SMI is used to assess the agricultural drought risk in the Sunkoshi, Hampuachaur basin on the basis of different SMI class obtained namely as abnormally dry, moderate drought, severe drought, extreme drought and exceptional drought.

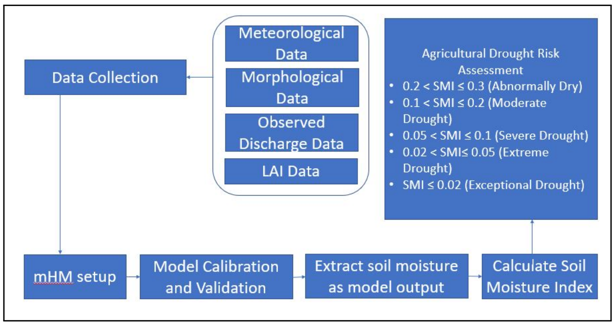

Figure 2: Methodological Framework for this study

3. Results and Discussions

3.1 Performance of mHM model

The model parameters were optimized at 0.25° resolution for 2000 iteration steps by using Kling Gupta Efficiency (KGE) as objective function. For the application purpose the model was calibrated and validated at 0.015625° resolution. The calibration period was taken from 1981-2000 and the validation period was taken from 2001-2016. The goodness of fit values obtained for Calibration period are Pbias=3, NSE=0.81, R^2=0.82, KGE=0.9 and for validation period are Pbias=1.6, NSE=0.9, R^2=0.91, KGE=0.93. The hydrographs of calibration and validation period are shown in the Figure 3 and Figure 4 .

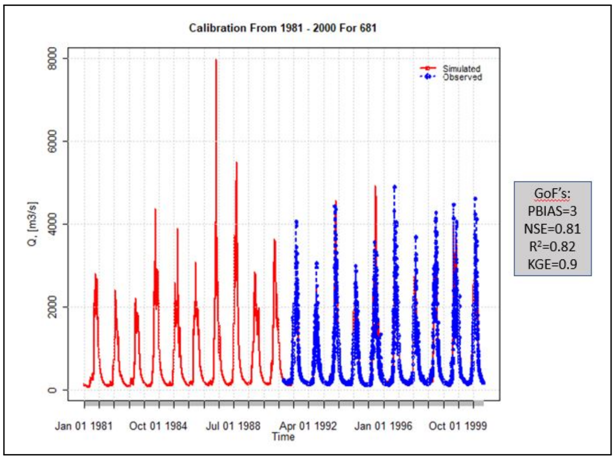

Figure 3: Calibration From 1981-2000 For Sunkoshi, Hampuwachaur

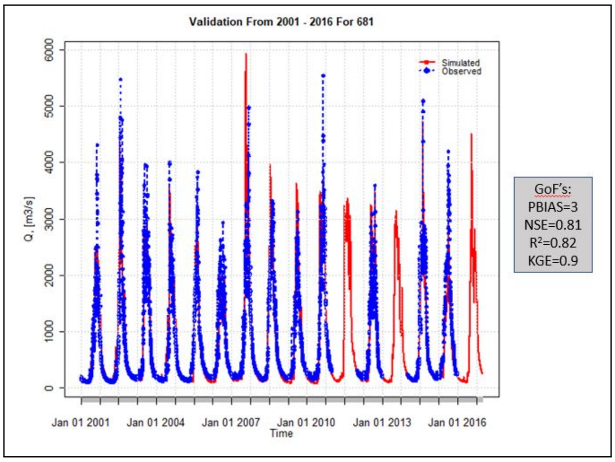

Figure 4: Validation From 2001-2016 For Sunkoshi, Hampuwachaur

3.2 Drought Risk

For the assessment of agricultural drought risk the drought period is divided into base period or reference period and analysis period or evaluation period. The base period is taken from 1950-2000 and the evaluation period is taken from 2001-2016. On the basis of reference period the drought is characterized for evaluation period.

3.2.1 Area under drought

The monthly area under drought of Sunkoshi, Hampuachaur basin is determined for the evaluation period from 2001-2016. August month of 2006 experiences maximum area under exceptional drought with 50.76 % area, followed by January of 2013 with 27.39 %, December of 2012 with 27.20 %, November of 2012 with 25.08 %, September of 2005 with 23.16

%, August of 2016 with 21.86 %, March of 2009 with 19.14 %, September of 2002 with 14.68 %, February of 2009 with 13.37 %, October of 2014 with 11.30 %. The area under drought of other months of evaluation period experiencing exceptional drought are shown in the Figure 5.

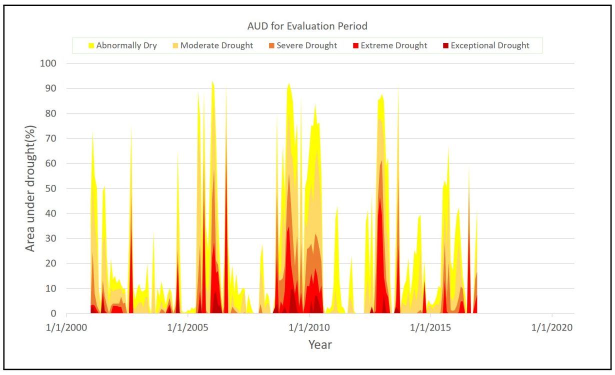

Figure 5: Time series plot for area under drought of Sunkoshi River Basin in Evaluation Period

3.2.2 Drought duration

Year 2009 and 2010 experiences maximum duration of exceptional drought i.e., for 7 months each; 2006 and 2013 for 6 months each; 2001 and 2016 for 4 months each; 2008 and 2012 for 3 months each; 2004, 2005, 2015 for 2 months each; 2002 and 2014 for 1 month each. The months of evaluation period experiencing exceptional drought are shown in the table Table 1.

Table 1: Drought affected year and respective months

Drought Year	Drought month in respective year
2001	Jan, Feb, Mar, Jul
2002	Sep
2004	Apr, Aug
2005	Jul, Sep
2006	Jan, Feb, Mar, Apr, May, Aug
2008	Aug, Sep, Dec
2009	Jan, Feb, Mar, Apr, May, Jun, Jul
2010	Jan, Feb, Mar, Apr, May, Jun, Jul
2012	Aug, Nov, Dec
2013	Jan, Feb, Mar, Apr, Aug, Sep
2014	Oct
2015	Aug, Sep
2016	Apr, May, Aug, Nov

3.2.3 Drought magnitude

On the basis of SMI values obtained drought condition in the Sunkoshi, Hampuwachaur basin is categorized as abnormally dry, moderate drought, severe drought, extreme drought and exceptional drought. Where the abnormally dry condition is a situation where the value of SMI lies between 0.2 to 0.3, moderate drought condition is a situation where the value of SMI lies between 0.1 to 0.2, severe drought condition is a situation where the value of SMI lies between 0.05 to 0.1, extreme drought condition is a situation where the value of SMI lies between 0.02 to 0.05 and exceptional drought condition is a situation where the value of SMI is less than 0.02. Out of the total area of Sunkoshi, Hampuwachaur basin 2988.58 km^2 area experiences abnormally dry condition. Similarly, 4327.09 km^2 area experiences moderate drought condition, 153.42 km^2 area experiences severe drought condition, 365.76 km^2 area experiences extreme drought condition, 204.16 km^2 area experiences exceptional drought condition. The spatial variation of various drought class is shown in Figure 6.

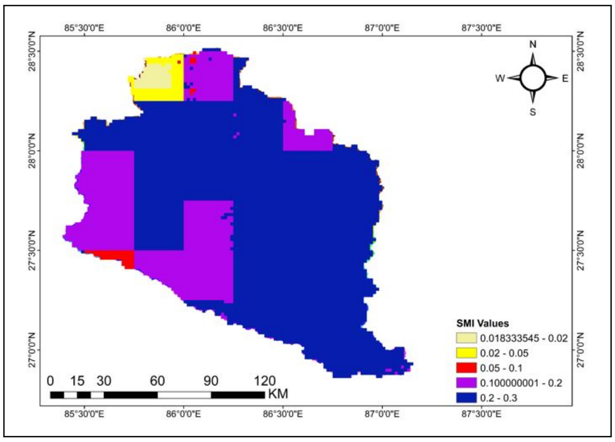

Figure 6: Drought risk characterization in the Sunkoshi River Basin

3.2.4 Drought risk on the basis of frequency

For the evaluation period we have monthly values from 2001-2016 the average value of SMI in the evaluation period cannot provide the clear picture of drought condition in the Sunkoshi, Hampuwachaur basin so for the clear picture of drought condition we apply the frequency analysis approach. Suppose we have 192 SMI maps then in a particular pixel how many times a particular class of drought has occurred on the basis of frequency. The SMI maps on the basis of frequency are shown in the Figure 7, Figure 8 Figure 9, Figure 10, Figure 11.

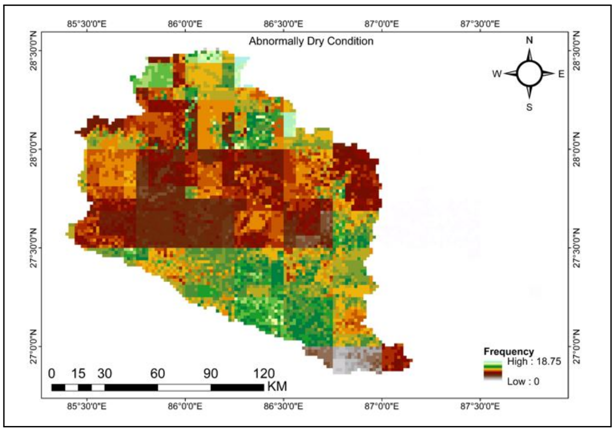

Figure 7: Abnormally Dry Condition in the Sunkoshi, Hampuwachaur on the basis of frequency

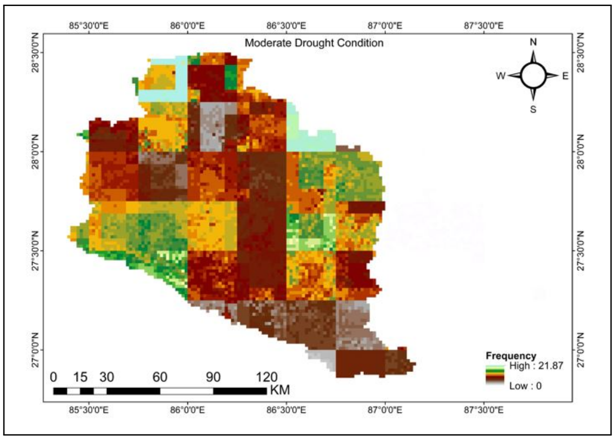

Figure 8: Moderate Drought Condition in the Sunkoshi, Hampuwachaur on the basis of frequency

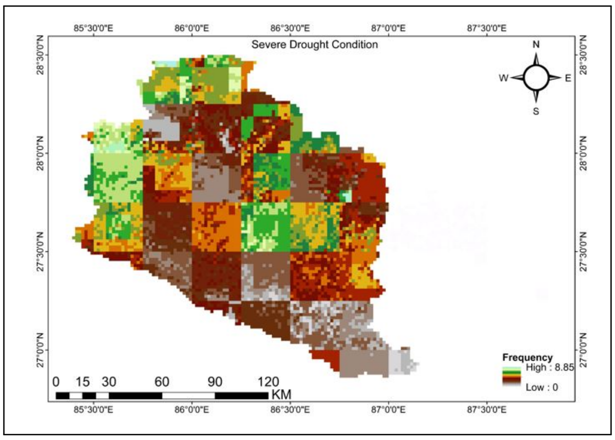

Figure 9: Severe Drought Condition in the Sunkoshi, Hampuwachaur on the basis of frequency

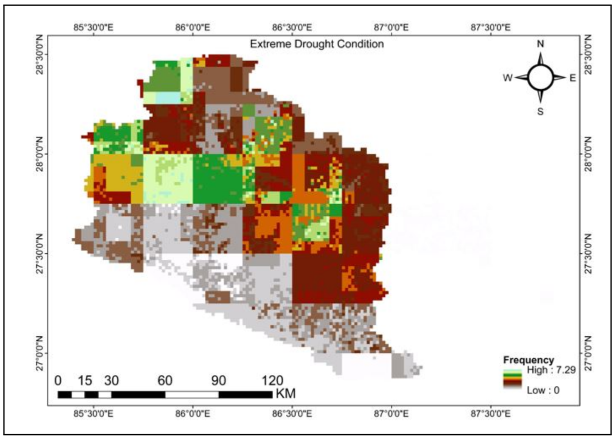

Figure 10: Extreme Drought Condition in the Sunkoshi, Hampuwachaur on the basis of frequency

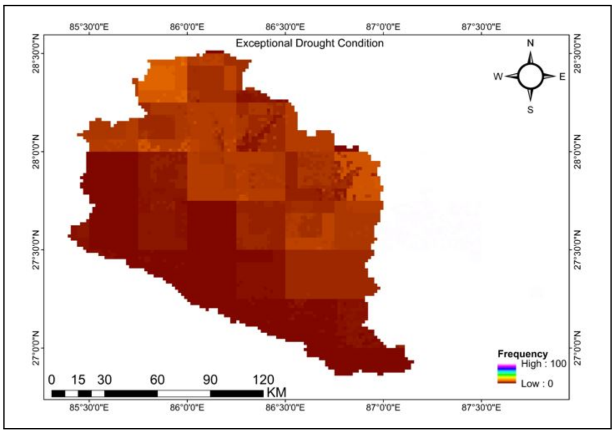

Figure 11: Exceptional Drought Condition in the Sunkoshi, Hampuwachaur on the basis of frequency

3.2.5 Drought risk at the palika level

Model based drought risk assessment can also be applied to determine the drought risk in one of the high drought risks palika. The area under high stress of drought can be identified and can be useful on the palika level for the policy makers and concerned authorities in order to take important steps to minimize the impacts caused by the drought on the palika level. It will help to introduce several programs in the palika level by the identification of the area under high stress of drought in order to minimize the impacts caused by it. Since the exceptional drought was seen on the Chinese portion so on the palika level the drought risk is characterized on the basis of moderate drought i.e., SMI value between 0.1 to 0.2. The selected palika for drought risk characterization is Khumbupasanglahmu rural municipality which is situated in the Solukhumbu district. The rural municipality has an area of 1539 km^2. The area under drought of the rural municipality is 204 km^2. The drought risk in the rural municipality is shown in the Figure 12.

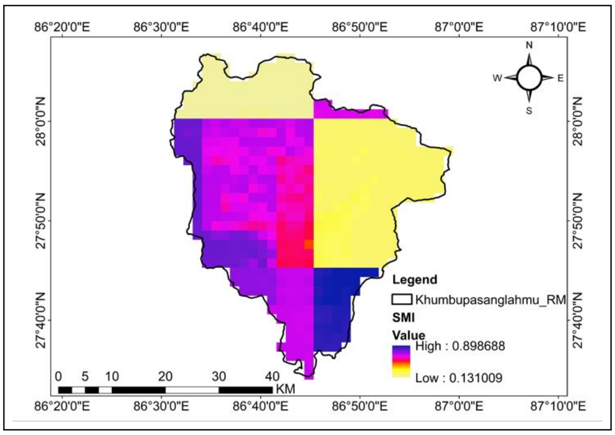

Figure 12: Drought risk assessment at the palika level

4. Conclusions

This study evaluated the applicability of model-based approach to evaluate the drought risk based on soil moisture index (SMI). The key conclusions from this study are as follows:

- The mHM model was successfully calibrated and validated in the Sunkoshi River Basin for hydrological applications. The model parameters were optimized at 0.25° resolution (at coarse resolution) and the model was calibrated and validated at 0.015625° resolution (at fine resolution) for the application purpose.
- Soil moisture data obtained from calibrated and validated mHM model was used to calculate the Soil Moisture Index (SMI) and the drought was characterized on the basis of obtained soil moisture index (SMI) for the Sunkoshi River Basin. Detailed drought maps for the basin at 0.015625° X 0.015625° (1.7 km X 1.7 km) resolution using proposed drought classification were prepared. Area, intensity and frequency of drought across the Sunkoshi Basin were obtained and mapped. Drought intensity varied from abnormally dry condition to exceptional drought condition. August of 2006 experiences maximum area under exceptional drought, followed by January of 2013, December of 2012, November of 2012, September of 2005, August of 2016, March of 2009, September of 2002, February of2009, October of 2014.
- The model-based approach was applied to determine the drought risk in one of the most drought affected municipality within the watershed

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