INTEGRATED WATER RESOURCES MANAGEMENT THROUGH EFFICIENT RESERVOIR OPERATION IN SWAT RIVER BASIN, PAKISTAN

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ABSTRACT

Pakistan receives approximately 80% of water through glacier/snowmelt of Himalayan and Hindukush ranges. Country faces alternate high floods in summer due to monsoon precipitations combined with accelerated glacier/snowmelt while agriculture droughts in winters due to insufficient water storage. Rainfall and snowmelt runoff modelling was performed in Swat River Basin considering degree day method for efficient reservoir operation to mitigate floods/droughts, water scarcity and energy crisis in the country. The proposed strategy considered environmental flows, existing irrigation requirements, proposed irrigation and municipal water supply requirements and hydropower generation in the order of priority of releases from reservoir besides conserving the flood water to carry over it for drought periods. Implementation of Integrated Water Resource Management policies like water conservation, crop substitution, rainwater harvesting, high efficiency irrigation systems, recycling of effluents and desalination of sea water remain the final solution to overcome the challenges of water scarcity, floods and drought mitigation.

Keywords: Snowmelt, DDF, Reservoir Operation, IWRM

INTRODUCTION

"Pakistan suffers from Floods in summer and Droughts in winter"

Pakistan possesses water resources of all kind including the groundwater, precipitations and glaciers. Country receives water mostly in summer from May to September. The main source of inflow in whole Indus Basin is glacier/snowmelt which is approximately 80% of the total inflow received during the whole year (Young and Hewitt, 1990). Pakistani rivers receive an average water inflow of 170.195 Billion Cubic Meter (BCM) annually. About 82% i.e. 139.560 BCM of the total inflow occurs in 3 months of summer and remaining 18% i.e. 30.635 BCM is received in rest of the year. This unequal distribution of inflows causes the surface water to drain into sea during summer without any utilization due to insufficient storage while shortages are faced in winter. (Sufi *et. al*., 2011). An average of 38 BCM water drains into the sea. More concentrated flows in summer and very little in winters has compelled the communities on pumping groundwater excessively which is resulting in depletion of groundwater resources as well. The study area namely Swat River Basin is located along the North West border of Pakistan with Afghanistan in Khyber Pakhtunkhwa Province, and lies between Latitude 34° 20'to 35° 56'N and Longitude 71° 20'to 72° 50' E as shown in Figure 1. The analysis of Moderate Resolution Imaging Spectroradiometer (MODIS) data of the basin analyzed in Geographic Information System (GIS) software reveals that Swat River is a snow dominant basin where the snow cover is available throughout the year as shown in Figure 2. Maximum and minimum snow cover are 62% and 11% in the months of February and September respectively. The study area has two major irrigation canals. Irrigation water supplies in these canals remain under stress during the whole year where the cumulative shortages for two canal commands in Swat Basin are 164% and 298%. Similarly, Pakistan is on the verge of water scarce country as the water availability is expected to reduce to 900 m^3/capita/year in the year 2020. If these issues are not addressed in time, the situation will become worse than ever before. Therefore, constriction of storage reservoirs is most feasible solution to address these issues altogether.

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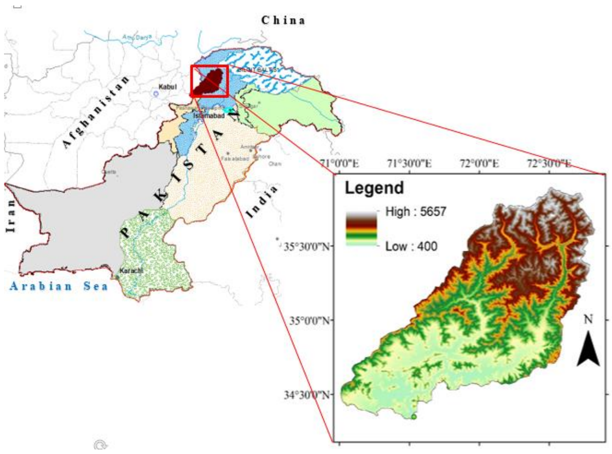
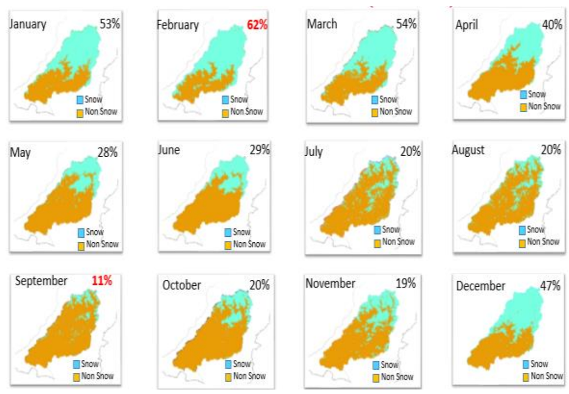


Source: HydroSHEDS data, USGS



Source: MODIS data, NASA

Figure 1: Location map of Swat River Basin

Figure 2. Snow extent in Swat River Basin

THEORY AND METHODOLOGY

The methodology adopted for conducting the current research is shown in Figure 3. Rainfall Runoff Inundation-Snow (RRI-Snow) model (Sayama, 2015) was used to estimate the rainfall and snowmelt runoff in the study area for efficient reservoir operation to mitigate the floods and droughts. RRI Snow uses temperature index method comprising air temperature, temperature lapse rate, MODIS 8 days' snow cover data and degree day factor. Degree Day Factor & Lapse Rate change throughout the year (Afzal, 2014). So as a first step, the snow module was modified to incorporate the variable degree day factor and temperature lapse rate which was considered constant in the existing snow module. RRI model was modified to take into account the variable river/channel diversions keeping in view the daily diversions in irrigation network of Pakistan. To achieve the final goal, existing basic level dam module was modified for reservoir operation to account for dead storage, live storage, gross storage, hydropower generation, floods attenuation and drought mitigation strategy. Now the module can also handle hydropower generation in accordance with the standards set by Government of Pakistan, i.e. four hours peak generation from 6:00 PM to 10:00 PM and 20 hours off-peak hours power generation from 10:00 PM to 6:00 PM of next day. The modified module comprises the reservoir releases based on the priority of environmental flows, existing irrigation requirements, proposed irrigation and municipal water requirements and finally the hydropower generation. The model computes the water requirements for specific number of conservation days (in this case 30 days) and compares it with the available volume of water in the reservoir. If the live storage in the reservoir is sufficiently more than the 30 days' requirements, water is released according to the demands along with releases from power house according to the schedule of peak and off-peak hour plant discharge @ 544 and 163.2 m^3/s respectively. In case the live storage is less than the 30 days' requirements then the reservoir operation truncates the releases in the order of peak plant discharge, off-peak plant discharge, upstream water demands and lastly the existing downstream demands.

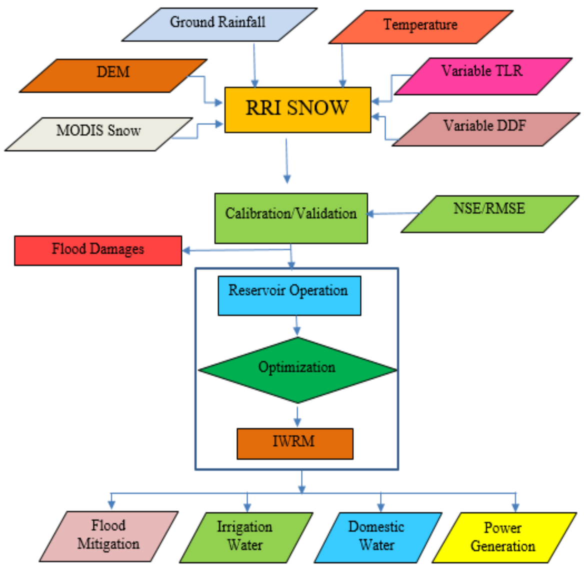


Figure 3. Research Methodology

DATA

For current research, the discharge measurement data was collected from Surface Water Hydrology Project (SWHP, WAPDA), temperature and rainfall data from Pakistan Meteorological Department and canal diversion data from Khyber Pakhtunkhwa Irrigation Department for the year 2000 to 2006. Similarly, the topographic data in the form of Digital Elevation Model (DEM) data with 30 second resolution and MODIS 8 days' snow cover 500 m resolution data was downloaded from HydroSHEDS and NASA websites respectively, and processed in GIS for preparing input files of RRI-Snow.

RESULTS AND DISCUSSIONS

The RRI-Snow model was calibrated and validated for two different stations, i.e. Chakdara station at which major part of snowmelt runoff is contributed and proposed Mohmand dam site which is the target station of this study. The model was calibrated at Nash Sutcliffe Efficiency (NSE) value of 85% and 74% for Chakdara station and proposed Mohmand dam site for the year 2005 as shown Figure 4 and 5 respectively while NSE value for validation was found to be 80%.

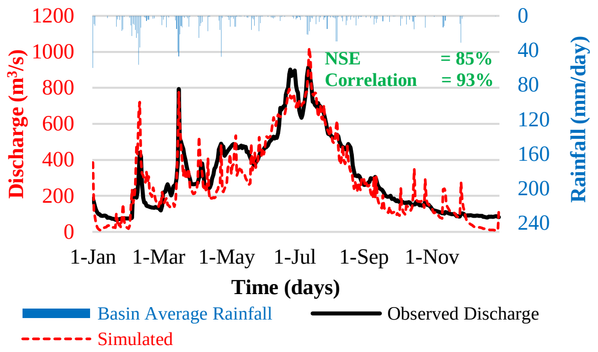


Figure 4. Calibration at Chakdara station

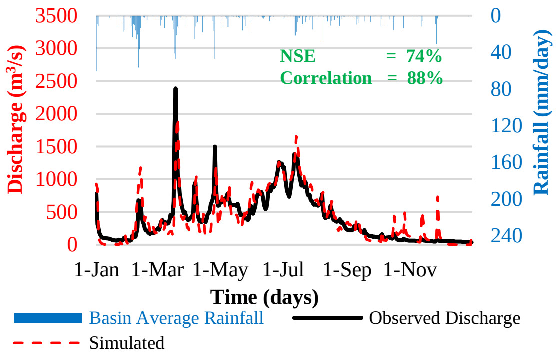


Figure 5. Calibration at proposed Mohmand site

A module has been developed for operation of proposed dam. As the main focus of current study is to reduce the flood disaster. JICA estimated a 100 years' return period flood as 5,013 m^3/s and 200 years return period flood as 5,720 m^3/s in its Feasibility Study conducted in the year 2000. Due to limitations of data availability, the existing one day rainfall for the year 2005 was increased tentatively to a level that could generate the floods approximately same as concluded by JICA. A flood of 100 years return period was considered for analysis and optimization of flood mitigation. Figure 6 shows the flood mitigation and attenuation of 100 years return period flood. As evident from Figure 6, the flood peak of 5,115 m^3/s has reduced to 2,807 m^3/s which is 45% attenuation. The continuous flood situation of 62 hours persists where the inflow discharge is more than 3,000 m^3/s. The model has been optimized on the principle of constant rate-constant outflow discharging rate. The principle has been adopted for various threshold values of flood. When the reservoir is at flood storage level, 30% of 100 years return period (target flood) is discharged to keep the reservoir within normal conservation level for avoiding any anticipated flood. When inflows into the reservoir are in the range between 25 to 35% of the target flood, the releases from reservoir are increased to 60% of the target flood while between 35 to 85% of the target the flood, the releases are further increased to 62.5%. In this way, an extra sufficient flood storage is achieved by lowering down the reservoir storage for absorbing anticipated high flood. Finally, when the inflow increases beyond 85% of the inflow of target flood, a continuous discharge of 55% of the target flood is released from the reservoir. In this way,

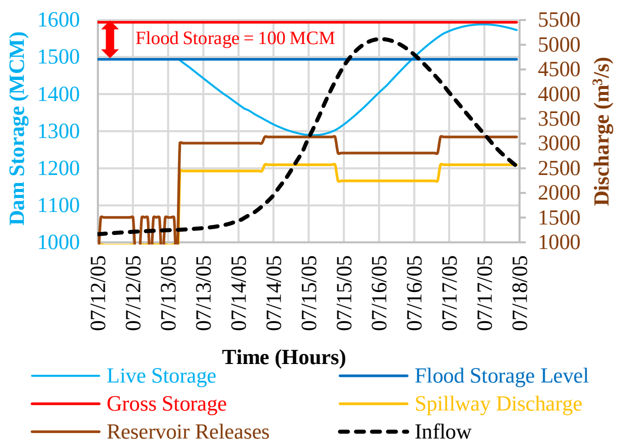


Figure 6. Flood mitigation and attenuation

within the available flood storage of 100 MCM, a flood slightly higher than 100 year return period of 5,115 m^3/s has been mitigated. With this operation, the downstream community is saved from being hit by a large scale flood of 100 years return period and only the peak of 3,133 m^3/s is encountered. Same model was tested for 200 years return period, and an attenuation of 45% was achieved to reduce the flood peak from 5,823 to 3,203 m^3/s compared with 42% achieved by JICA. Similarly the model has been optimized to mitigate agricultural droughts. The strategy adopted for agricultural drought mitigation is to assure the water supply to the users with Zero shortage throughout the simulated conservation days. Analysis were carried out by optimizing the reservoir operation with the view of how much storage should remain in the reservoir in order not to fall below the demand of 30 conservation days. The total downstream and proposed upstream demand for the month of January are 16.38 and 13.46 m^3/s making an amount of 77.34 MCM to be met at the initialization of model. If an initial reservoir storage of 100 MCM is reserved, the reservoir operation is able enough to manage the reservoir releases based on the priorities of demand defined in the dam module.
Figure 7 shows the existing downstream (Environmental flow, Lower Swat Canal and Doaba Canal) and proposed upstream (left bank canal, right bank canal, and municipal water supply) water demands. Figure 8 shows the results of optimized dam operation wherein all existing the downstream and proposed upstream water demands are met perfectly as demand and supply curves overlap and still sufficient storage is available in the reservoir to cater for any agriculture drought. Besides, water demand fulfillment, not only the floods and droughts have been mitigated but considerable amount of cheap hydropower is also generated.

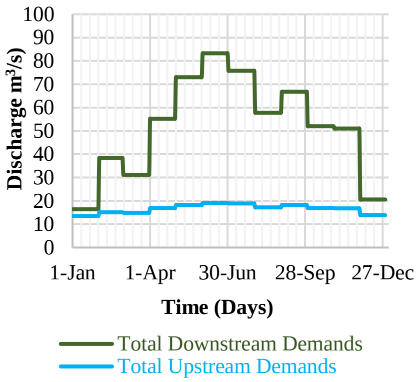


Figure 5. Water Demands

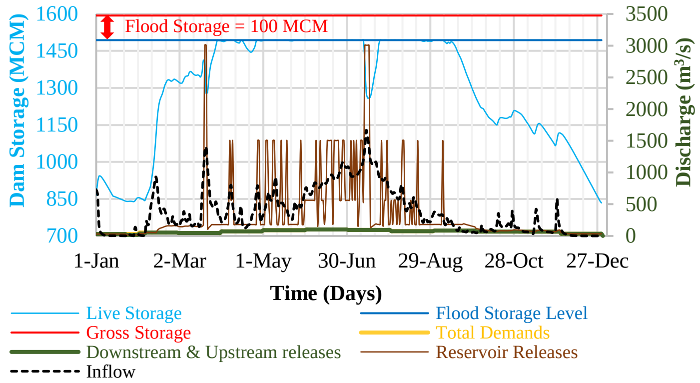


Figure 6. Water demand fulfilment by dam operation

The power plant operation is shown in Figure 7. The module suspends or partially suspends the peak and off-peak hour power plant operation during low flow season or low storage in the reservoir as can be seen during January to February and September to December. It fulfills the 30 days' demand of irrigation and domestic water supply on top priority. After meeting the priority demands, the remaining water is allocated for power generation. The module adjusts the power generation based on the available quantity of water within live storage of reservoir, i.e. it will generate the power keeping in the view the given schedule of demand of peak and off-peak hours. It is evident that the power plant is operating for four hours at 544 m^3/s while 20 hours at 163.2 m^3/s in a day. Keeping in view the plant operation, it can be concluded that if an inflow of 226.66 m^3/s continues to flow in the reservoir, the ideal plant operation of peak and off-peak hour can work throughout the day. Figure 8 explains another scenario that when the reservoir reaches to flood storage level of 1,494 MCM, peak power plant operation continues throughout the day irrespective of peak and off-peak demand. It ensures conserving the flood control capacity by keeping the reservoir at its flood storage level so that a margin of 100 MCM always remains there even when a flood situation occurs at 1,494 MCM level. The total energy generated during the whole year is approximately 3,097 GWh which is shown in Figure 9.
The spillway operation of proposed dam is shown in Figure 10. Keeping in view the importance of water resources especially in context of water scarcity, the module has been designed to avoid the operation of spillway to the maximum possible extent. However, as the basic purpose is to mitigate floods/droughts and that's the main focus of this research. Based on these limitations, the spillway

operation has been designed to initiate when the reservoir is at flood storage level of 1,494 MCM or the inflow discharge into the reservoir is 25% of the target flood of 100 or 200 years return period.

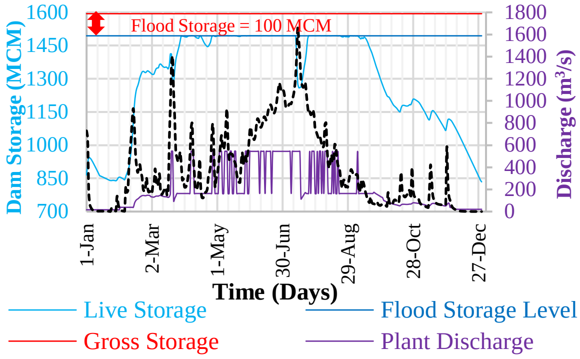


Figure 7. Power Plant Operation

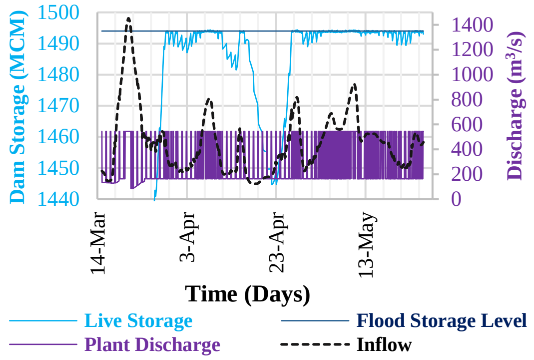


Figure 8. Peak & off-peak power generation

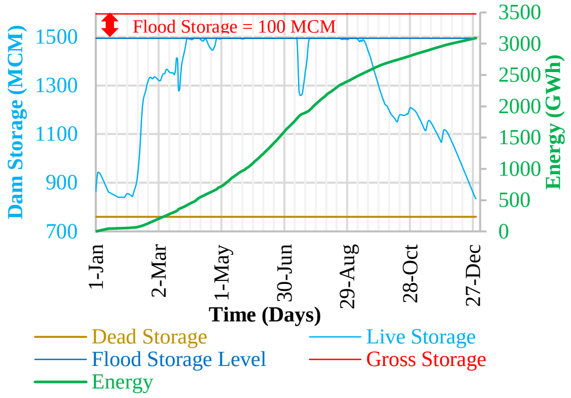


Figure 9. Reservoir Storage and Energy

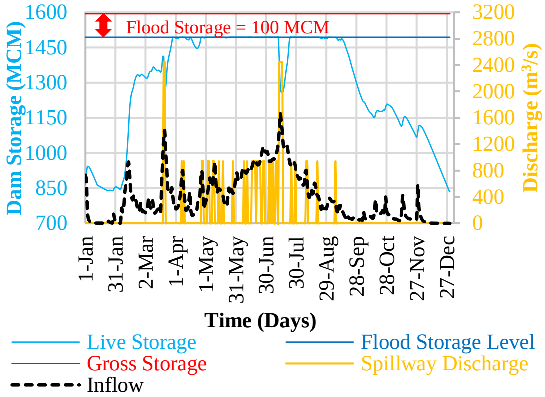


Figure 10. Spillway Operation

The module ensure that no extra spillage occurs during and after flood mitigation which may decrease the reservoir storage to unacceptable limits. To ensure this, the spillway operation does not start if the storage in reservoir is less than 60% of total live storage, i.e. 1,260 MCM.
Besides socio-economic uplift of the area, water conservation, forestry and fishery industries development; the major benefits considered for economic evaluation are irrigated agriculture development, municipal water supply, hydropower generation along with allied Clean Development Mechanism (CDM) benefits and most importantly the flood alleviation benefits. The results and expected economic benefits based on normal and flood control operation are presented in Table 1.

Table 1: Economic benefits of flood alternative plans

S. No.	Flood Discharge (m^3/s)	Agriculture	Water Supply	Power Generation	CDM	Flood Alleviation	Total Revenue
1	No Flood	-	-	57,924.000	8,362.024	-	**66,286.024**
2	Normal Flood	2,589.430	1,075.640	37,164.000	5,365.069	1,104.87	**47,299.004**
3	100 Years R.P. Flood	2,589.430	1,075.640	37,860.000	5,465.545	1,104.87	**48,095.480**

CONCLUSIONS

By incorporating the variable lapse rate and degree day factor in RRI-Snow, the performance and level of accuracy of model improved from 41 to 85%. Snowmelt is a major contributor of water resources in Swat River Basin analogous to Indus River Basin as it contributes approximately 56% of the total

inflows. Efficient spillway operation during floods can altogether change the project economics especially when hydropower generation is involved in a multipurpose dam. Water conserved by efficient reservoir operation during flood times may become a blessing during agricultural drought season. The spillway operation during flood plays a vital role for project economics and it's a trade-off between flood and drought mitigation and harnessing the maximum benefits from hydropower generation.
For improving water availability for various sectors like agriculture, domestics, commercial, industrial etc., storage capacity of Pakistan must be increased which is currently only 13% of its average annual inflow. So the construction of multipurpose dams comprising storage and hydropower generation facility is inevitable for coping with water scarcity and energy crisis of the country.

RECOMMENDATIONS

The snow module needs to be modified by incorporating the snow budget instead of taking 8 days' composite snow data which remains constant throughout the simulation period. For better results, utilization of hourly temperature and precipitation data is recommended for bifurcating the rainfall and snowfall. Analytical relation for DDF and TLR in context with air temperature, humidity, solar radiation, dew point temperature are recommended for incorporation for model improvement from empirical to semi-empirical or analytical. Agricultural module consisting of crop water requirement, crop maturity and computation of approximate agricultural production may be added into RRI to integrate the agricultural and irrigation together for efficient water resources management. Most importantly, RRI model needs to be coupled with some Weather Forecast Model for incorporating the self-running capability in real time reservoir operation and facilitate decision making for spillway operation which would enable the dam engineers to manage the storage accordingly to attenuate more flood peaks.

The adaptation and implementation of Integrated Water Resource Management policies remain the final solution to overcome the challenges of water scarcity, floods, droughts and energy crisis in the country. Considerations have to be given for water conservation, crop substitution, rainwater harvesting, adaptation of high efficiency irrigation systems, recycling of effluents and desalination of sea water to reduce pressure on surface and fresh water resources.

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REFERENCE

Afzal. M., Sagiura, A., Sayama, T., Hasegawa, A., (2014), "Estimation of snowmelt contribution to discharge in upper Indus basin in Pakistan using degree day method", International Center for Water Hazard and Risk Management, Public Works Research Institute, Tsukuba, Japan

JICA (2000), "Feasibility Study on the development of Munda Dam Multipurpose Project in Islamic Republic of Pakistan", *Nippon Koei Co. LTD. Nippon Giken Inc.* MPN JR 00-016.

National Snow and Ice Data Center, MOD10A2 Scientific Data Sets and Description, https://nsidc.org/data/mod10a2

Sayama, T. (2015), Rainfall-Runoff-Inundation (RRI) Model Version 1.4.2, International Center for Water Hazard and Risk Management, Public Works Research Institute, Tsukuba, Japan.

Sufi, A.B., Hussain, Z., Sultan, S.J., Tariq, I. (2011), "Integrated Water Resource Management in Pakistan", Changing Environmental Pattern and its impact with Special Focus on Pakistan, Pakistan Engineering Congress Symposium, Lahore, Pakistan, Vol 33, pp 36-48.

United Stated Geological Survey: HydroSHEDS https://hydrosheds.cr.usgs.gov/dataavail.php

Young, G.J., and Hewitt, K., (1990), "Hydrology Research in the upper Indus basin, Karakoram Himalaya, Pakistan.". Hydrology of mountainous areas. IAHS Publ. No. 190, pp 139-152.