

REMOTE SENSING BASED SNOWMELT RUNOFF MODEL COUPLED WITH DISTRIBUTED HYDROLOGICAL MODEL IN UPPER YELLOW RIVER BASIN

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This paper introduces a remote sensing based snowmelt model and its coupling with a metrological based distributed hydrological model in the Upper Yellow River Basin in China. Until the availability of earth resources satellites, no really efficient way of obtaining snow-covered area existed. This situation is more severe in inaccessible rugged mountainous regions. Snowcover is important hydrological phenomenon and it is clearly discernible using satellite-obtained optical data because of high albedo of snow. Present study is to estimate snow cover quantitatively on a catchment scale from satellite remote sensing data along with ground-based metrological and hydrological data. Its suitability to snowmelt runoff forecasting has been investigated. This may contribute to management and utilization of water resources in remote and less developed areas.

Key Words: *Distributed Hydrological Model, Inaccessible mountainous, Satellite Remote Sensing, Runoff forecasting*

1. INTRODUCTION

Water in the frozen state accounts for more than 80% of the total fresh water on the earth¹⁾. About 30% of the earth's land surface is seasonally covered by snow and contributes the largest proportion of river discharge over major portions of middle and high latitudes. Snowmelt accounts for 50-80% of the annual stream flow in many areas of the world, including the Sierra Nevada, the Rockies, the Alps, the Andes and the Himalayan Mountains²⁾.

The snowmelt runoff water resource plays an important role in ecosystem activity in the west of China. Particularly in spring, the inflow coming from the snowmelt process is the main water supply for industry and irrigation in this region, accounting for an average of approximately 75% of total annual river runoff. In the headwaters of the Yellow River, much of the water stored in the reservoirs for electricity production originates from

melting of snow and glaciers. So, in the west of China, forecasting snowmelt runoff (including glaciers) is an important subject and activity.

Snowmelt runoff models³⁾ use snows cover area and its variation during ablation periods along with meteorological data as an important input.

In high mountainous terrain with an extreme climate, where rugged land surfaces provide limited accessibility and little ground control, it is very difficult to monitor metrological data and snow cover information accurately on a continuous basis. The ruggedness further complicates the definition of snow line owing to the occurrence of snow in patches. Ground monitoring of snow is normally based on point measurement, which is subjected to numerous problems especially in inaccessible mountainous regions. In addition, ground-based monitoring stations constitute an insufficient network of point observations, which are not necessarily indicative of the entire watershed.

Therefore, satellite data could be a useful

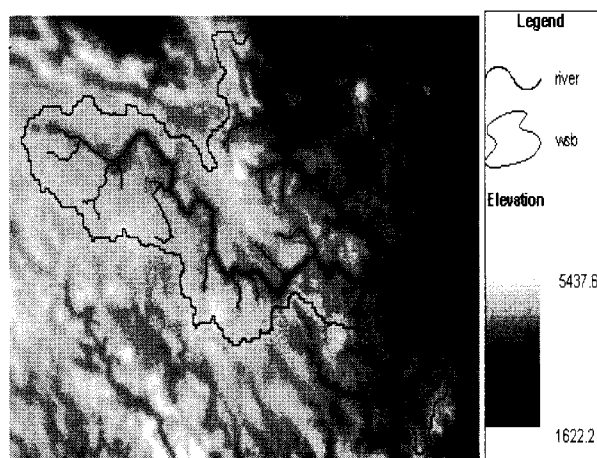


Fig.1 Digital Elevation Model

alternative for snow monitoring and snow cover mapping. Until the availability of earth resources satellites, no really efficient way of obtaining snow-covered area existed. Integrated approaches based on satellite remote sensing data and ground information were developed recently for snowmelt runoff forecasting. Satellites with optical (visible and infrared) and microwave (passive and active) sensors on board are able to perform real-time mapping of certain hydrological parameters like snow cover for numerous mountain basins in the world. This is very useful in remote areas like Upper Yellow River where observed snow data is not available and meteorological data is either insufficient or in daily time scale. The objective of the present study is to estimate snow cover quantitatively on a catchment scale from satellite remote sensing data, along with ground-based meteorological and hydrological data and its applicability to forecast snowmelt runoff is investigated. This may contribute to the management and utilization of water resources in less developed areas. Moreover, models for meteorological data were developed to convert daily time scale into hourly time scale.

2. AREA OF INVESTIGATION

(1) Physiography

The Upper Yellow River is situated in the northeast of the Qinghai-Xiezang plateau. The elevation ranges between 5437.6 and 1622.2 m as shown in **Fig. 1**. The study area was selected from the source of Yellow River to Tangnaihai hydrological station as shown in **Fig. 2** with an area of 121,972 km². Because of the abundant precipitation (300-750 mm/yr), low annual mean temperature and weak evaporation of the ground, surface runoff per unit area in this area is about three times high than the mean value of the whole Yellow River basin, so the study area is one of the

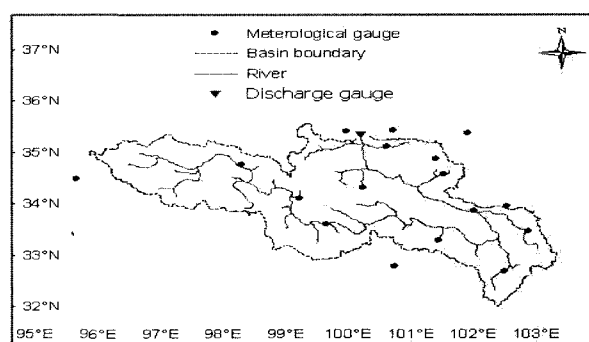


Fig.2 Map & metrological station locations in the Upper Yellow River basin

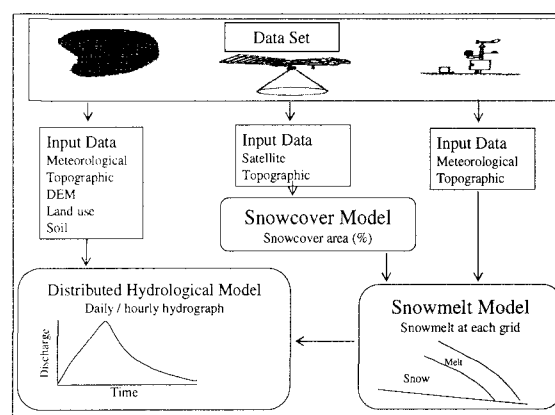


Fig.3 Flowchart of snowcover, snowmelt & distributed Hydrological model

main runoff producing areas. In addition, the snow and glaciers are distributed widely and 57 glaciers developed around Maqengangri peak with an area of 120.75 km². The melt water from glaciers and snow is the main supply sources of spring runoff in the upper reaches of the Yellow River and accounts for about 72.6% of the surface runoff in the same period⁴⁾.

(2) Meteorological and Hydrological Data

There are 17 well-equipped hydro-meteorological observatories in the upper Yellow River (**Fig. 2**). At all of these observatories precipitation, wind speed, wind direction, air temperature and relative humidity are monitored on daily basis.

The entire surface and subsurface runoff that contributes to the discharge of Upper Yellow River Basin enters into lake situated in the downstream part of the catchment and it is measured at Tangnaihai.

3. METHODOLOGY

Fig. 3 shows the general outline of the present

study. First of all, snowcover is calculated from satellite data of National Oceanic & Atmospheric Administration / Advance Very High Resolution Radiometer (NOAA/AVHRR). This snowcover area integrated with metrological and topographic data is input into the snowmelt model which calculates basin wide snowmelt. Snowmelt runoff simulations were carried out by coupling a snowmelt model with a distributed hydrological model. Distributed hydrological model employed here is the Geomorphologic Based Hydrological Model (GBHM) developed by Professor Dawen Yang⁵⁾. After coupling GBHM with a remote sensing based snowmelt model, it is termed as coupled_GBHM.

GBHM developed by Professor Dawen Yang is termed as original_GBHM in the present study. Snowmelt calculations are carried out by a temperature index approach in original_GBHM. If the temperature is equal or greater than the threshold value, then the precipitation is considered as snow. This model does not require snowcover.

(1) Snowcover Model

A snowcover model is used for the estimation of snowcover area from remote sensing data. Snowmelt is calculated from snow cover area but not from snow amount, which is input into the coupled_GBHM.

a) Digital Elevation Model

The elevation, slope and aspect are the most obvious components of the landscape. In high mountain areas, snow distribution is not homogeneous owing to high variation of these parameters. In addition, the ruggedness of the terrain complicates interpretation of the satellite scene⁶⁾. Significant variation occurs in remotely sensed images acquired under visible and near-infrared wavelengths, owing to local topographic effects which cause variation in illumination angle and shadowing from local horizons^{7 8 9 10)}. Snow in the shadows can be darker than soil or vegetation in the sunlight, so that snow mapping in the mountains is not easily accomplished and the problems of correct interpretation of the satellite signal are severe.

The DEM was used as a binary mask for extracting the exact watershed surface actually contributing to the water balance of the basin.

b) Image Processing

The snowpack parameter most frequently estimated using remote sensing is the amount of snow-covered area of a basin under snow cover¹¹⁾. The nature of the snow cover must be characterized adequately if distributed models are to improve hydrological modelling through improved representation of the state variables¹²⁾. Knowledge

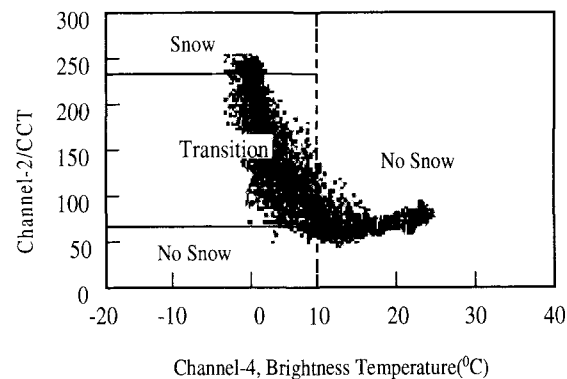


Fig.4 Channel-2/CCT versus Channel-4 Brightness Temperature

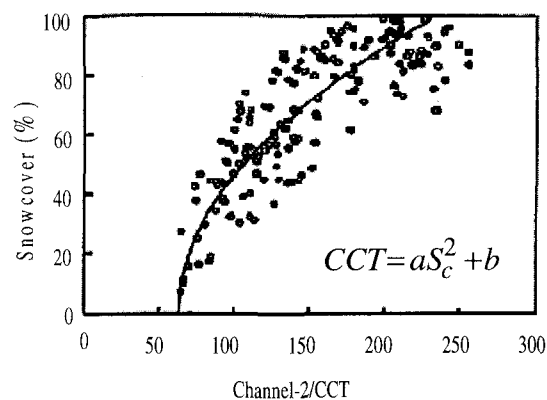


Fig.5 Snowcover area versus Channel-2/CCT

of the areal distribution of the snow within catchment is required in order to make reasonable estimates of the total water available in the snow cover of a watershed¹³⁾. In the present study, data sets of 1.1 km (NOAA/AVHRR) polar orbiting satellite, Channel-2 (0.75-1.1 μ m) and Channel-4 (10.3-11.3 μ m) ten days composite images from 1998-1999, from a data base of Institute of Industrial Sciences (IIS), Tokyo University was used. Nine images for 1998 and eleven for 1999 were selected and analyzed using digital image processing techniques. These images were selected as they are almost cloud free and cover mostly February-July period when snow depletion occurs. The data were fully examined by employing digital image processing and classification methodologies. Images of Channel-2 & Channel-4 were combined and imported into Erdas Imagine Software. All the images were converted into Lambert Azimuthal equal area projection. For perfect snow, Channel-2/CCT would be higher and Channel-4/Brightness Temperature would be low. By plotting Channel-2/CCT and Channel-4/ Brightness Temperature as shown in **Fig. 4**, snowcover area (%) was calculated as shown in **Fig. 5**.

Snow-covered area was estimated pixel by pixel

according to **Fig. 5** for cloud free days. Snowcover area for the cloudy days was estimated by linear interpolation and extrapolation from the data on the cloud free days.

(2) Meteorological Data Preparation and its Downscaling

Hourly rainfall, air temperature, evaporation and sunshine duration data converted from the daily available data was used in hydrological simulation.

The daily precipitation was uniformly distributed for the rainfall duration. The rainfall time in a day was determined randomly and considered as half in night and half in daytime¹⁴⁾.

The hourly air temperature is linear interpolated from the minimum and maximum temperatures, which assumes the maximum temperature at daytime 13:00 and the minimum at night 1:00. The daily potential evaporation is uniformly distributed in the daytime from 7:00am to 7:00pm of the local time.

Hourly sunshine is calculated from daily sunshine hours, equally distributed from mid day (1200) in both directions (morning and evening).

(3) Snowmelt Model

The snowmelt runoff model should be able to simulate the contribution owing to the snow depletion in the basin to the total river discharge, during the melting season. Snowmelt runoff simulation models generally consist of a snowmelt model and a transformation model. The snowmelt model generates liquid water from the snowpack that is available for runoff, and the transformation model is an algorithm that transfers the liquid output at the ground surface to runoff at the basin outlet. The snowmelt and transformation model can be lumped or distributed in nature. Lumped models use one set of parameter to define the physical and hydrological characteristics of a watershed. Distributed models attempt to account for the spatial variability by dividing the basin into subareas and computing runoff for each subarea independently, with a set of parameters corresponding to each of the subareas. Melting of snow is caused by input of energy (or heat) into the snow pack. A net energy input may come from a variety of sources: shortwave and longwave net radiation, convection from the air (or sensible heat exchange with the atmosphere), condensation of water vapour (or latent heat exchange), heat input by precipitation, and conduction of heat from ground. In most environments, the ground heat flux is a very small component in the daily energy balance of a melting snowpack compared with other components and its effects on total snowmelt can safely be ignored. Snowmelt model used in this study has three main

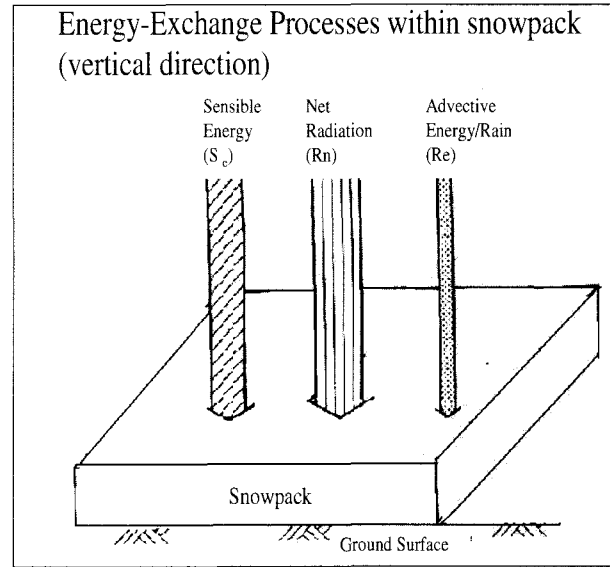


Fig.6 Snowmelt Model

components¹⁵⁾: the net radiation, R_n ; sensible energy S_e ; and condensation and rainmelt, R_e as shown in **Fig. 6**.

Net radiation component R_n is composed of shortwave, downward & upward longwave radiation¹⁶⁾:

$$R_n = M_{sw} + M_{lw\downarrow} + M_{lw\uparrow} \quad (1)$$

$$M_{sw} = S_c \{ (1 - \alpha) I \} / L_m \quad (1a)$$

$$M_{lw\downarrow} = S_c \{ (1 + n_{\max}(1 - C_c)) (0.51 + 0.066 \sqrt{e}) \alpha (T_a + 273)^4 \} / L_m \quad (1b)$$

$$M_{lw\uparrow} = S_c \varepsilon \sigma (T_s + 273)^4 / L_m \quad (1c)$$

Where, M_{sw} is shortwave radiations ($\text{MJ m}^{-2} \text{ hour}^{-1}$), M_{lw} is longwave radiations ($\text{MJ m}^{-2} \text{ hour}^{-1}$), S_c is snowcover area (%), α is the shortwave albedo or reflection of snow surface, σ is Stefan-Boltzman constant, $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, ε is emissivity, I is insolation on slope surface and it is calculated¹⁵⁾ by:

$$I = I_o S_N / S_o \quad (1d)$$

Where I_o is the observed insolation on a horizontal plane, S_o is the insolation receiving rate on a horizontal plane, S_N is the insolation receiving rate at the slope surface,

Sensible energy component S_e , based on degree-hour method is:

$$S_e = S_c (0.008 d.h.) \quad (2)$$

Where S_e sensible energy and $d.h.$ is degree-hour.

Condensation and rainmelt component R_e during rainy periods also contribute for snowmelt as:

$$R_e = S_c \{ 10(2.49 \sum (e_{sat} - 6.1) + P T_a / 10) / (238.8 L_m) \} \quad (3)$$

Where, P is rainfall in mm, T_a is air temperature in $^{\circ}\text{C}$ and e_{sat} is saturated vapour pressure of the snow surface, kPa.

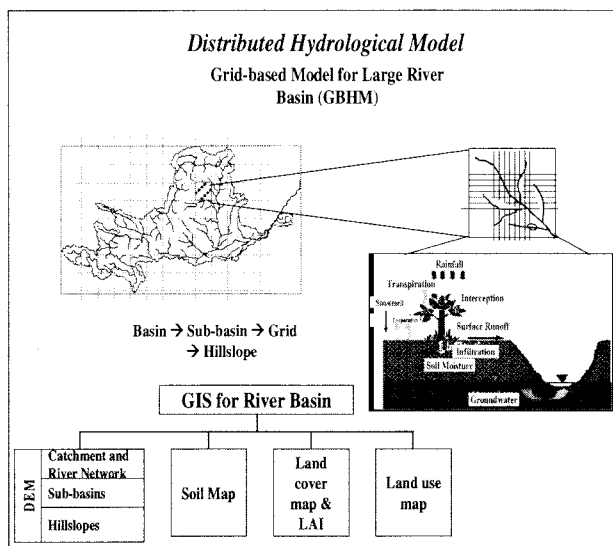


Fig.7 Schematic view of Geomorphologic Based Hydrological Model (GBHM)

(3) Distributed Hydrological Model

The aim of hydrological modelling is to provide a prognosis of the future performance of a hydrological system. Schematic view of the distributed hydrological model is shown in **Fig. 7**. The distributed hydrologic model employed in this study has the following capabilities ¹⁷⁾.

- 1) distributed representation of spatial variations of hydrological variables;
- 2) physical descriptions of hydrologic processes;
- 3) applicability to very large catchments.

This is a Geomorphologic Based Hydrological Model (GBHM). Snowmelt calculations are only based on air temperature. Recent advances in GIS and remote sensing technology allow powerful integration of GIS analytical and visualization tools, remote sensing based hydrological data with physically based hydrologic models.

4. RESULTS & DISCUSSION

(1) Snow Distribution Characteristics of the Basin

According to the analysis of NOAA/AVHRR image for two years it is known that the stable seasonal snow cover begins at the end of September or the beginning of October. The estimated snow covered area extends gradually from high to low elevation and from south to north and reaches the maximum in the first ten days of February of the next year. Then the area begins to contract gradually. The seasonal snow cover melted away in the first ten days of June. **Fig. 8** shows the map of Snowcover for February 1, 1999 and **Fig. 9** show snowcover distribution on May 15, 1999.

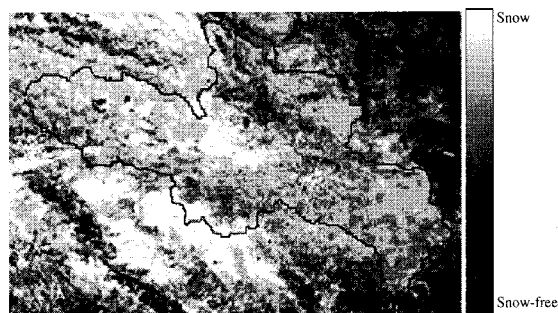


Fig.8 Snowcover on February 1, 1999

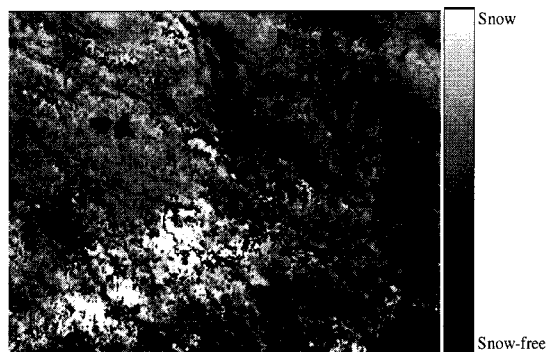


Fig.9 Snowcover on May 15, 1999

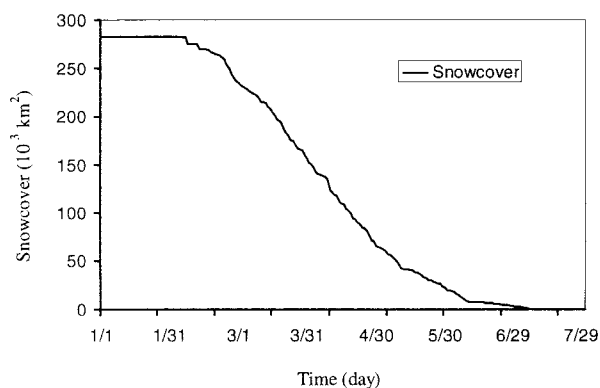


Fig.10 Snowcover depletion curve for 1999

(2) Snow Cover Depletion Curves

The rate of snowmelt during summer months varies from one catchment to another depending on the prevailing meteorological conditions. The spatial distribution of the snow cover is described by snow cover depletion curves (SDCs), which account for the percent areal coverage of the snowpack. SDCs have been developed for, and applied in, hydrological models on a watershed or elevation zone basis.

These SDCs represent the characteristic response of the watershed to snowmelt, which is a function of the land cover and elevation characteristics within the basin. **Fig. 10** shows an example of snowcover depletion curve in 1999.

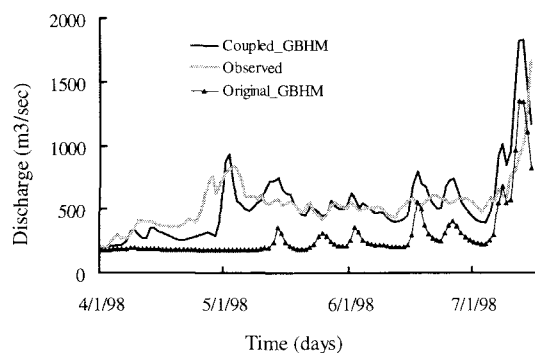


Fig.11 Comparison of Observed and predicted discharges by Coupled_GBHM and original_GBHM for 1998

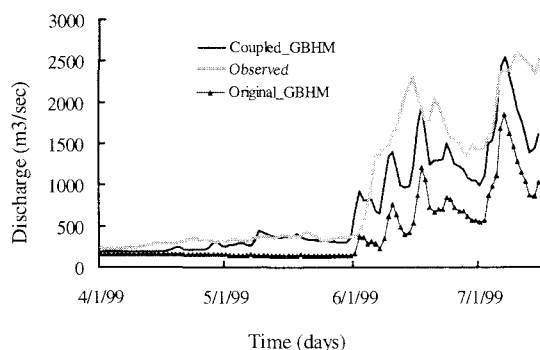


Fig.12 Comparison of Observed and predicted discharges by Coupled_GBHM and original_GBHM for 1999

(3) Runoff Simulation

Fig. 11 & Fig. 12 show the comparison of two models predicted discharges and observed discharge in 1998 and 1999. Coupled_GBHM predicted discharges are closer to the observation. The original_GBHM discharges are well short from observed during snowmelt season.

5. CONCLUSIONS

This analysis utilizes the satellite-data in conjunction with terrain information, air temperature and cloudiness to produce improved snowmelt runoff simulations. The computed discharges by coupled_GBHM are in good agreement with observed discharges. Original_GBHM underestimates the snowmelt runoff considerably.

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