J. Resour. Ecol. 2010 1(3) 222-230
DOI:10.3969/j.issn.1674-764x.2010.03.005
www.jorae.cn

Water topic

A Distributed Time-Variant Gain Hydrological Model Based on Remote Sensing

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Abstract: A Distributed Time-Variant Gain Hydrological Model (DTVGM) based on remote sensing (RS) is proposed. The model contains several sub-models, such as snowmelt model, runoff model. It produces outputs including snow cover, evaporation, runoff, etc. All inputs for the model are derived from remote sensing data. Data from the Lhasa River basin is used in this study, including USGS-SRTM DEM, TRMM precipitation and Modis-LST. More than eight years (2001-2008) of daily hydrological data set was selected to calibrate the model. Based on the comparison of the observed and estimated runoff, the model's averaged efficiency of daily runoff simulation is over 0.6. The error of water balance was less than 5%. Distributed modeling results are quite satisfactory. This study provided a promising approach to resolve hydrology and water resources problems in ungauged or sparsely gauged basins.

Key words: remote sensing; Distributed Time-Variant Gain Hydrological Model; TRMM; Modis-LST

1 Introduction

Remote sensing (RS) data has been used widely in hydrologic modeling studies. Most of the applications involve the use of vegetative covers, land use patterns, digital terrain derived from RS data. Cermak (1979) studied how to estimate hydrological parameters by using Landsat-derived land use data. In similar studies, Wei *et al*. (1992) and Liu *et al*. (2005) utilized RS based land use and soil type data to run SCS (Soil Conservation Services) model and obtained improved hydrologic simulation results. There were numerous applications using RS data to get better simulations of snow cover and snow depth, and consequently improve snowmelt- induced runoff (Martinec 1986; Seidel 2004; Kaya 1999; Ferguson 1999; Wang 2001; Tekelia 2005).

Tropical Rainfall Measuring Mission (TRMM) data became available since 1998. The spatial resolution of TRMM data is 0.25° by 0.25°, and the temporal resolution is 3 hours. The data has been applied in many basins in the world, including Huaihe River Basin (Yang *et al*. 2009), and Amazon basin (Collischonn 2008). These results indicated that the precision of TRMM data is similar to the observed raingauge data.

How to use RS data to compute evaporation has always been a hot topic in hydrologic modeling. Immerzeel (2008) found that the simulation of spatial distribution of hydrologic cycle by SWAT model was more creditable by using RS derived evaporation.

Much progress has been made by using RS data to study various hydrologic phenomena. However, few previous studies depend exclusively on RS data as the only source of data to conduct hydrologic modeling. This study shows how to make exclusive use of RS data for the Distributed Time-Variant Gain Hydrological Model (DTVGM). The RS data used include USGS-SRTM DEM, TRMM precipitation and Modis-LST. DTVGHM simulates the entire hydrologic process and generates runoff, soil moisture, and snow depth outputs. The Lhasa basin in Tibet is used as a case study.

The paper is organized as follows. Section 2 describes DTVGM. Section 3 discusses the RS data sets used and the preprocessing methods. In Section 4, we present the simulation results. Section 5 provides summary and con-

Received: 2010-08-24 **Accepted:** 2010-09-01
Foundation: National Basic Research Program of China (973 Program) (No. 2010CB428402); Natural Science Key Foundation of China (No. 40730632).
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clusions.

2 A brief description of the Distributed Time-variant Gain Hydrological Model (DTVGM)

Time-Variant Gain Hydrological Model (TVGM) is a rainfall-runoff modeling system developed based on nonlinear Volterra functional series and a conceptual hydrological modeling approach (Xia 1989; 1995). With the adoption of GIS technology, TVGM is extended to include a distributed hydrologic modeling capability (DTVGM). DTVGM was applied to two cases: the Heihe River Basin located in the arid and semiarid region of northwestern China and the Chaobai River basin located in the semi-humid region of northern China (Xia *et al*. 2002). DTVGM, combining the advantages of both nonlinear and distributed hydrologic models, can simulate various hydrologic processes under different environmental conditions. Promising results were obtained in forecasting the time-space variations of hydrologic processes and the relationships between land use/land cover change and surface runoff variation.

In this study, snowmelt and RS driver modules were incorporated to DTVGM. The new model structure is shown in Fig. 1.

2.1 Snow cover and snowmelt module

The main object of snowmelt module is to simulate amount of water from snowmelt. The module can output areal coverage of snow, snow depth and snow melt. It is based on dynamical balance of snow accumulation and snowmelt.

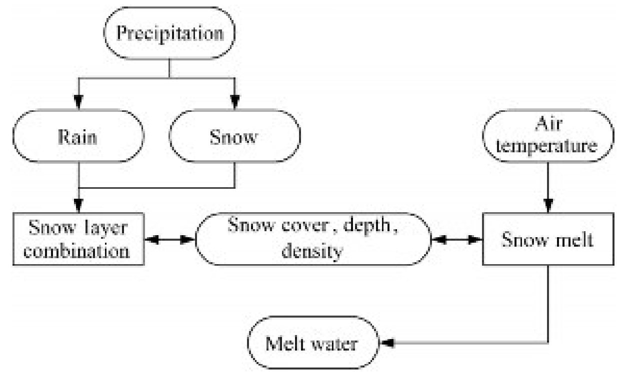

Fig.2 Flow chart of precipitation and snow melt module.

Model sub-steps are presented as follows (Fig. 2):

(1) Initialize the snowmelt module to obtain initial snow cover area and snow depth for each sub-basin

In a basin, air temperature and precipitation determine the areal coverage of snow and snow depth. Under the same amount of precipitation, lower temperature will lead to thicker snow cover. Therefore, initial snow depth can be written as a function of temperature:

$$H_{s0} = H_0 \cdot \exp(-T/T_0) \qquad (1)$$

where H_{s0} is initial snow depth (mm), T is air temperature (℃), H_0, T_0 are parameters.

From E_q. 1, assuming H_0=1 and T_0=8, the H_{s0}-T relationship is shown in Fig. 3:

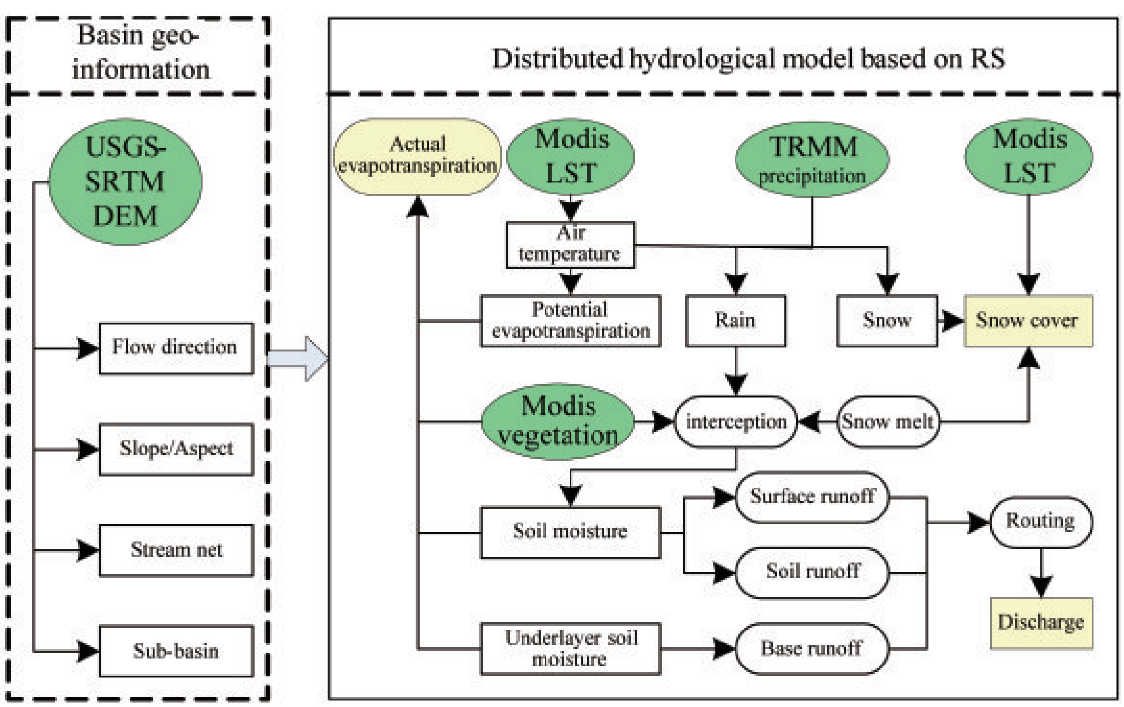

Fig.1 Framework of distributed hydrological model based on RS.

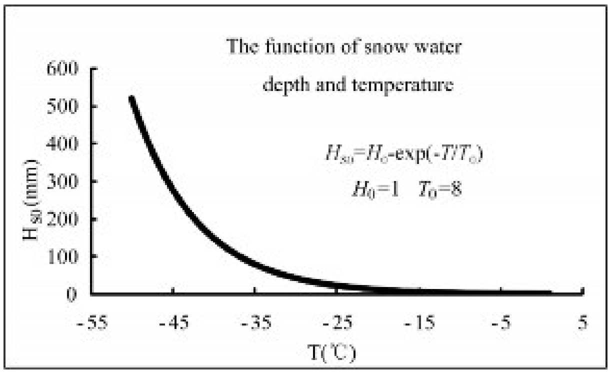

Fig.3 The relationship between initial snow depth and air temperature.

Snow depth is calculated as snow water equivalent. When air temperature is less than 0 ℃, precipitation is regarded as snow, and adds to snow depth.

(2) Snowmelt

Snowmelt is computed according to day degree factor (DDF) method (Li 2008; Liu 2006). The melted water can be calculated according to the following equation:

$$S=\begin{cases}\alpha\cdot(T_{av}-T_{mlt}) & T_{av}>T_{mlt} \quad and \quad \alpha\cdot(T_{av}-T_{mlt})<H_s\\ H_s & T_{av}>T_{mlt} \quad and \quad \alpha\cdot(T_{av}-T_{mlt})>H_s\\ 0 & T_{av}\le T_{mlt}\end{cases} \tag{2}$$

$$\alpha = 11\cdot\frac{\rho_s}{\rho_w} \tag{3}$$

where S is melted water (mm), α is DDF (mm ℃$^{-1}$ d^{-1}), Tav is average air temperature (℃), T_{mlt} is the critical temperature of snowmelt, ρ_s is snow density, ρ_w is water density, H_s is snow cover depth.

Strictly speaking, DDF varies with snow density. Snow density varies in time. In order to simplify the calculation, snow density is pre-specified for different months (Table 1; Li *et al*. 2008).

(3) Snow cover and depth change

In the distributed model, the basin is divided into several sub-basins. Snowmelt calculation is done for each sub-basin. The snow depth is likely to change because of precipitation and snowmelt in each sub-basin in each time period.

2.2 Potential evaporation method

Potential evaporation is computed based on the method of Hargreaves & Samani (1985):

$$E_p = aQ_0\left(T+17.8\right)\left(T_{\max}-T_{\min}\right)^b \tag{4}$$

where a, b are parameters, a ranges between 0.0023 and 0.0032, b varies between 0.5 and 0.6, Q_0 is solar radiation (mm day^{-1}). T, $T_{\max}$, $T_{\min}$ are daily average, maximum and minimum temperature (℃).

2.3 Runoff method

Runoff is calculated for each hydrologic unit (i.e., sub-basin or grid). There are three layers in the model: vegetation layer, surface soil layer and deep soil layer (Fig. 4). There are three runoff components: surface runoff on land surface, sub-surface runoff from the surface soil layer, and base flow from the deep soil layer.

DTVGM is basically a water balance model. Evaporation, soil moisture and runoff are computed iteratively. Water balance equation is:

$$P_i+W_i=W_{i+1}+Rs_i+E_i+Rss_i+Rg_i \tag{5}$$

where P is precipitation, W is soil moisture, E is evaporation, Rs is surface runoff, Rss is sub-surface runoff, Rg is ground water runoff, i is period of time.

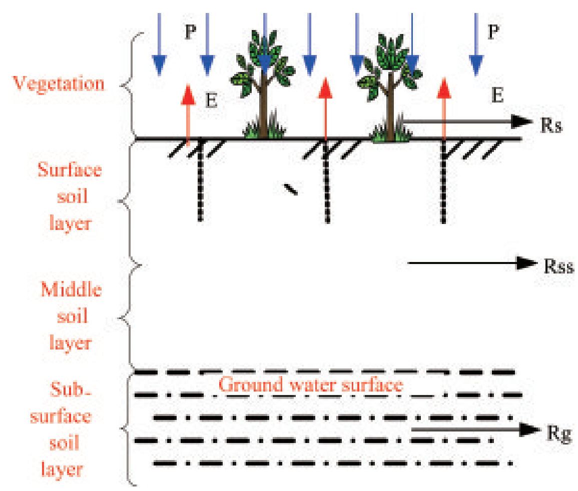

Fig. 4 The runoff model.

Inserting current evaporation, surface runoff, sub-surface runoff and base flow in Eq. 5, we obtain:

$$P_i+AW_i=AW_{i+1}+g_1\left(\frac{AW_{ui}}{WM_u\cdot C_j}\right)^{g_2}P_i+ AW_{ui}\cdot K_r+Ep_i\cdot K_e+AW_{gi}\cdot K_g \tag{6}$$

where AW is soil moisture (mm), AW_u is the upper soil moisture at sub-basin (mm), AW_g is the lower soil mois-

Table 1 Snow density (Li *et al*. 2008).

Month	1	2	3	4	5	6	7	8	9	10	11	12
Snow density (g cm^{-3})	0.136	0.1	0.1	0.155	0.15	0.167	0.2	0.2	0.133	0.1	0.134	0.173

ture at sub-basin (mm), WM_u is the upper saturated soil moisture (mm), u is "upper", it mean upper soil, g_1 and g_2 are parameters ($0<g_1<1$, $0<g_2$), g_1 is runoff coefficient when soil is saturated, g_2 is the parameter about soil water, C is land cover parameter, K_r is the sub-surface runoff coefficient, K_g is the groundwater runoff coefficient, K_e is the evaporation coefficient.

2.4 Routing model

The routing model used is the kinematic wave model. In order to simplify the model, the friction term in momentum equation is ignored. Assuming that friction slope (*Sf*) is equal to slope (*S0*) and river flow is unsteady open channel gradual change flow (Ye *et al.* 2006), the continuity equation is written as:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{7}$$

where A is river cross section area (m^2), t is time(s), Q is discharge (m^3 s^{-1}), x is flow path (m), q is lateral inflow (m^3 s^{-1}).

Flow velocity v (m/s) is calculated based on Manning formula:

$$v = \frac{1}{n}\cdot h^{\frac{2}{3}} S_0^{\frac{1}{2}} \tag{8}$$

where n is Manning roughness coefficient (Huggins 1996), S_0 is slope.

The discharge at the river cross section is:

$$Q = A\cdot v \tag{9}$$

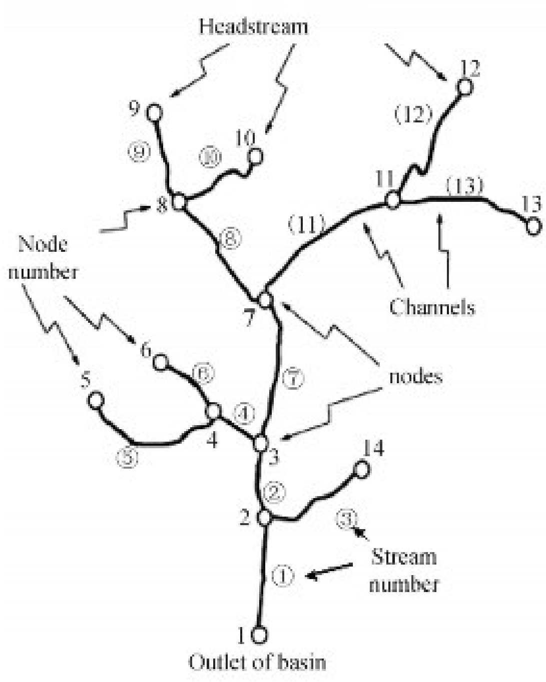

Fig. 5 Sketch map of stream network definition.

The river stream network is encoded from the outlet of basin to upstream (Fig.5) (Ye *et al*. 2005). The routing is calculated from upstream to the basin outlet, namely.

3 The RS data and preprocess method

3.1 TRMM

TRMM is a joint mission between US and Japan. It is the first satellite Earth observation mission to monitor tropical rainfall, which exerts significant influences over global climate and environmental change. The temporal resolution of TRMM is 3 hours. The spatial resolution is 0.25 degree. Daily data is obtained by summing 3-hour data over a 24-hour period. The hydrologic unit is a sub-basin. Daily precipitation over a sub-basin can be obtained using a spatial interpolation method.

3.2 Modis LST and preprocess method

Land surface temperature (LST) is one of the Modis data products (i.e., MOD11A1) (https://wist.echo.nasa.gov/). It has a daily temporal resolution and 1 km spatial resolution. The data preprocessing includes the following steps: (i) the data was first downloaded from NASA website for the designated area; (ii) the data is merged and consolidate; (iii) the matrix coordinates of the sub-basins are translated into a Sinusoidal projection coordinate system, consistent with the Modis data; (iv) convert the Modis 1 km data into areal average for each sub-basin; and (v) fill in the missing values in the Modis data by interpolation method. Modis day LST and night LST are used, and the average LST is the average of day and night LST.

3.3 Modis LST to 2m air temperature

Statistics shows that correlation coefficient of LST and 2m air temperature (T_{2m}) is more than 0.95. In order to simplify calculation and reduce data requirements, T_{2m} is obtained using the relationship between LST and T_{2m} through regression analysis. The relationship is different for different areas. Thus the regression parameter should be calibrated for each sub-basin:

$$T_{2m}=a\cdot LST+b \tag{10}$$

where a and b is regression parameters.

3.4 Modis snow cover data process

Modis snow cover data has a 500m by 500m spatial resolution. The data is available every 8 days. The preprocess method is as same as LST. Snow cover data is used for model verification.

4 Results for Lhasa River Basin

4.1 Lhasa River Basin

Lhasa River is the largest tributary of the Yarlung Zangbo river in Tibet (Huggin *et al*. 1995). The basin drainage area is 32 471 km^2, equal to about 13.5 % of Yarlung Zangbo basin area. The Lhasa River length is 551 km, elevation drop is 1620 m, and average gradient is 2.9%. Lhasa River has many tributaries, including Maiqu, Sangqu, Laqu, Xuerongzangbu, Mojumaqu, Yunianqu and Duilong (Fig. 6). The largest tributary is Duilong which has a river length of 137 km and area of 4988 km^2. The annual precipitation is about 500mm. The distribution of precipitation is uneven during the year. About 90% precipitation is concentrated from June to September. The annual evaporation is about 1300mm. The annual runoff is about 300mm.

4.2 The RS data in Lhasa River Basin

The annual precipitation from TRMM is 558mm in the Lhasa River in 2001. The spatial distribution of precipitation is consistent with the ground based observations (Fig. 7). The error of total precipitation is less than 20%. The spatial resolution is higher than interpolation data from limited meteorological stations (Table 2 and Fig. 8). Because there are no meteorological stations when the elevation is higher than 5000m (Fig. 8), the RS data is more reasonable.

Table 2 The observed annual precipitation at meteorological stations in 2001.

Station	Lhasa	Dangxiong	Mojugongka
Annual precipitation /mm	492.3	655.0	725.5

Since Modis can provide LST with a mean error of less than 1K°, Modis LST can be used reasonably for hydrologic modeling. Potential evaporation calculation needs T2m, which can be calculated from LST according to Eq. 10. The statistical results between observed LST and T_{2m} for 1956–2000 are shown in Table 3 and Figs. 9 and 10:

Fig. 11 displays the annual average temperature for the entire study area based on data from 2001 to 2008.

Potential evaporation calculated based on T_{2m} for 2001–2008 is shown in Fig. 12:

4.3 The hydrological simulation in Lhasa River Basin

Based on USGS-SRTM 3-second DEM, the Lhasa river

Table 3 The relation between LST and T_{2m} at meteorological stations.

ID	Station No.	Station name	Elevation (m)	Longitude	Latitude	Pa	Pb	R
1	56202	Jiali	4488	93.283	30.66	0.79	–2.714	0.962
2	55593	Mojugongka	3804	91.733	29.851	0.762	–1.045	0.959
3	55591	Lhasa	3648	91.033	29.717	0.725	–0.195	0.958
4	55493	Dangxiong	4200	91.100	30.484	0.809	–2.822	0.962

Note: Pa and Pb: the *a* and *b* in equation (10); R : the relation between LST and T_{2m}.

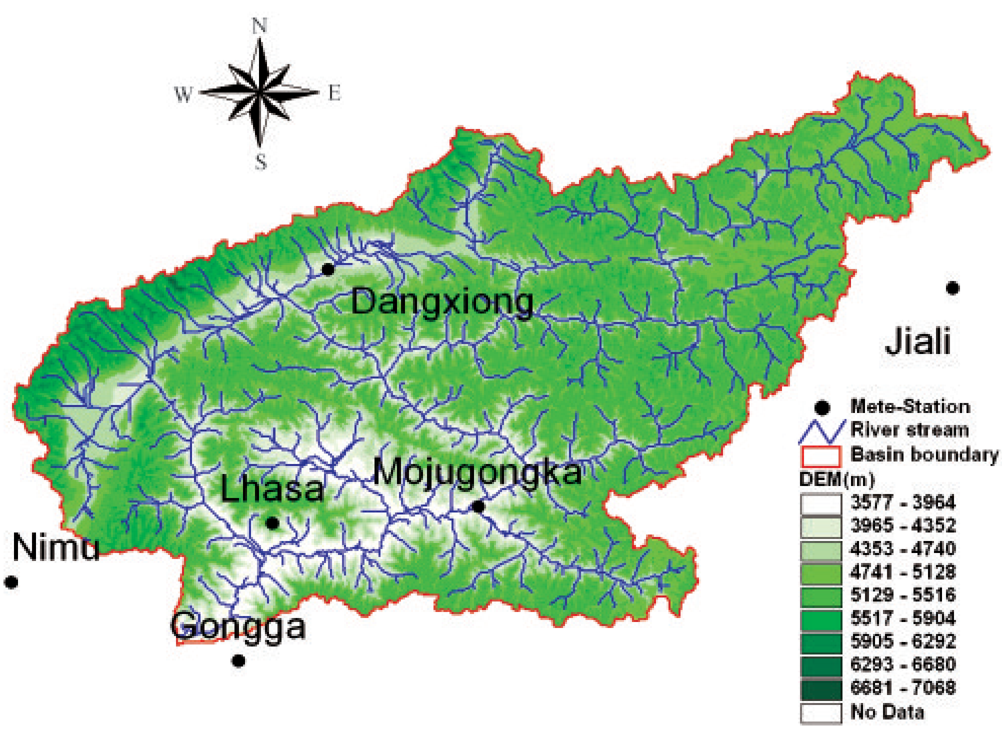

Fig.6 The Lhasa River Basin.

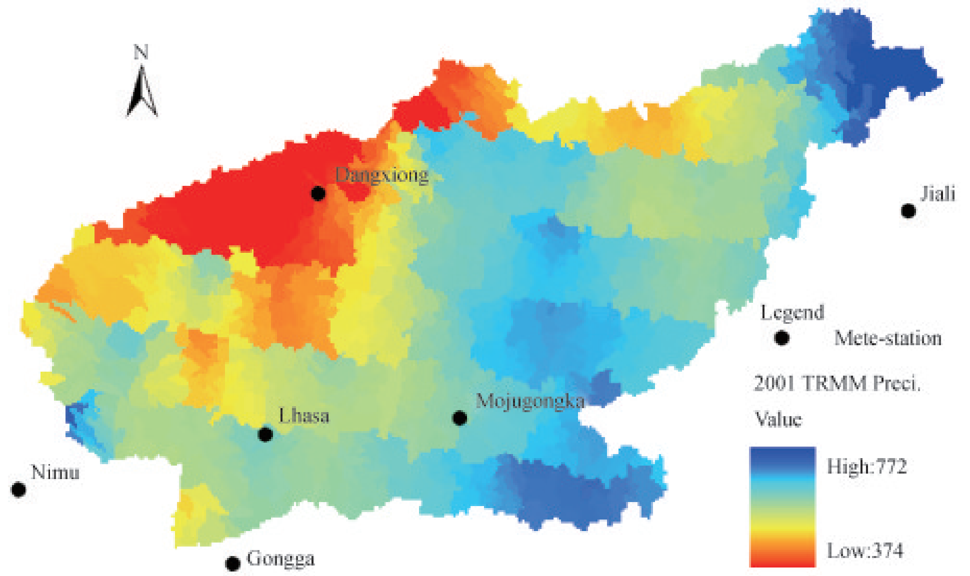

Fig.7 The spatial distribution of TRMM precipitation in 2001.

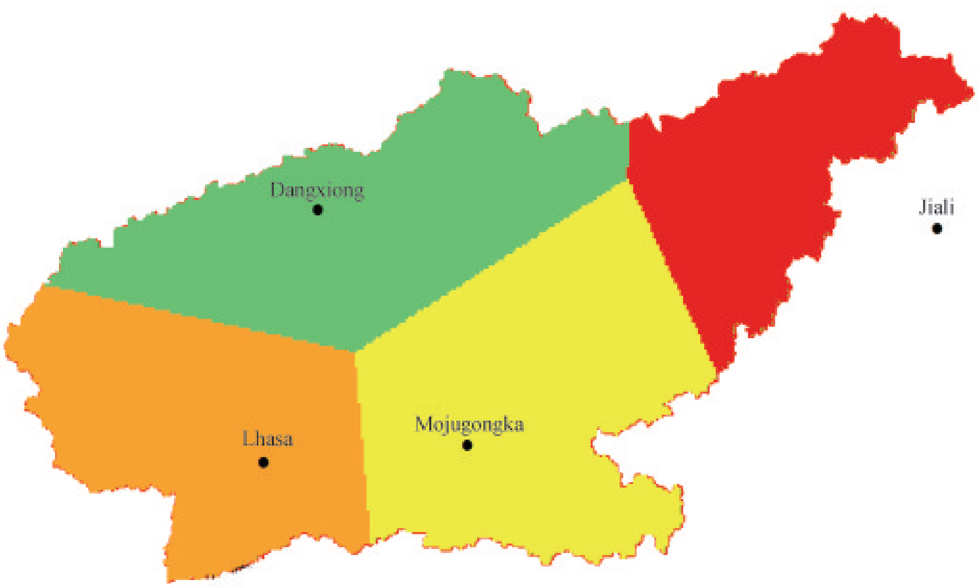

Fig.8 The meteorological stations and their control areas.

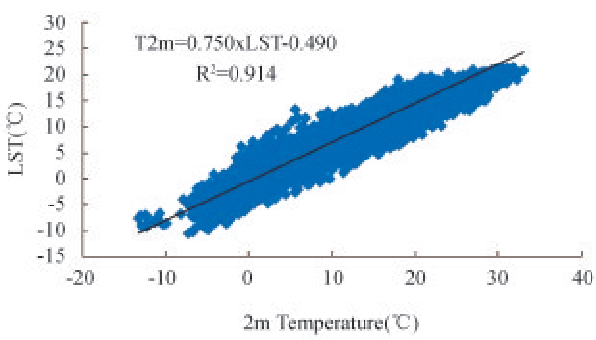

Fig. 9 The relation between LST and T2m at Lhasa.

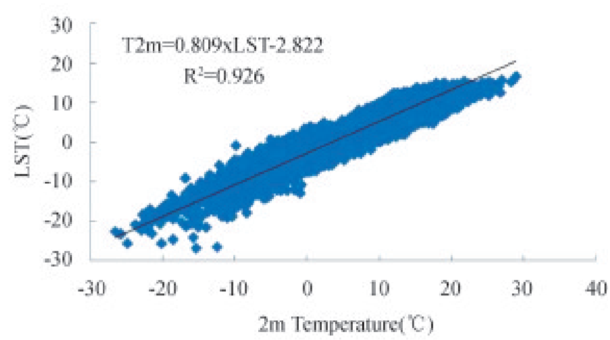

Fig.10 The relation between LST and T2m at Dangxiong.

basin is divided to 1279 sub-basins using GIS. The sub-basin is the minimum hydrologic unit of the model. The hydrologic calculation is performed on each sub-basin.

The study time period is from 2001 to 2008. A daily time step is used for hydrologic simulation. Observed discharge for 2001–2002 at Lhasa hydrologic station is obtained. Table 4 exhibits comparison results between simulated discharge and observed discharge. Following observations can be seen from the results: (i) DTVGM is a fea-

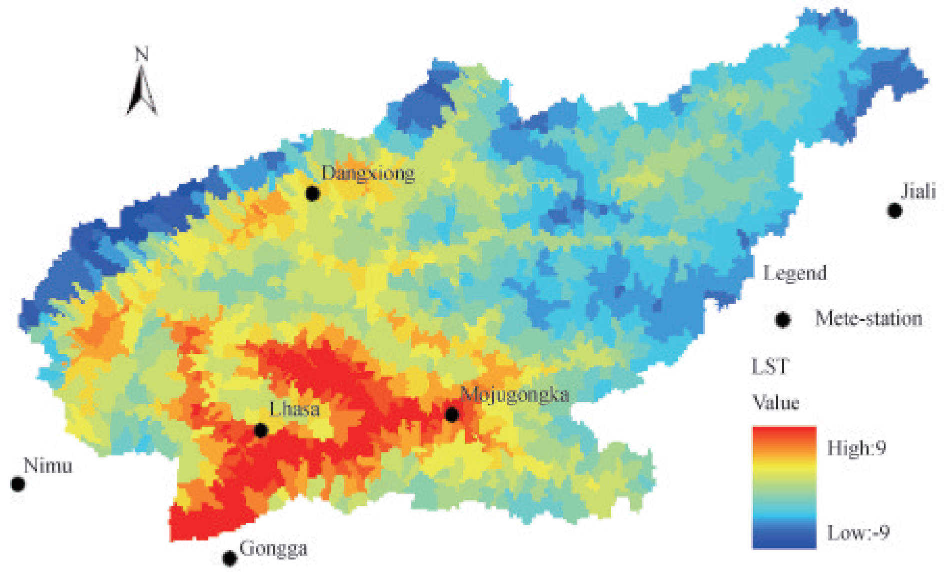

Fig.11 Annual average LST (℃) in 2001–2008.

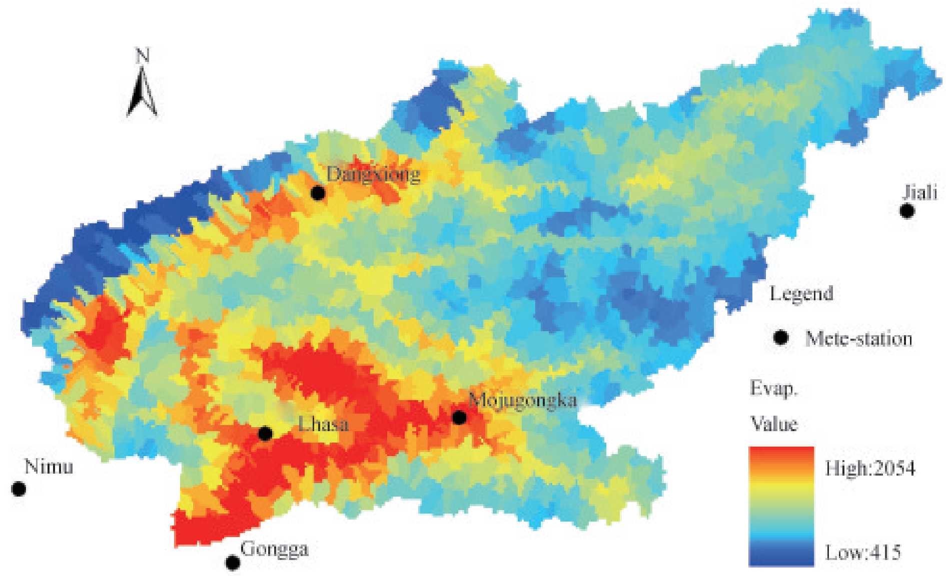

Fig.12 Annual average potential evaporation (mm) in 2001–2008.

sible model, and simulated discharge matches reasonably with the observations (Figs. 13 and 14); (ii) simulated flood peak lags the observed peak. This is due to that fact that TRMM precipitation occurs later than the observed precipitation; and (iii) simulated and observed total water volume are very consistent with a correlation coefficient value of close to 1, and an error of less than 5%.

$$E=\left[1-\frac{\sum(Q_C-Q_O)^2}{\sum\left(Q_O-\overline{Q_O}\right)^2}\right]\times 100\%$$

Table 4 Results of the simulation.

	E	R	B
2001	0.692	0.850	1.01
2001–2002	0.552	0.778	1.02

$$R=\frac{\sum(Q_c-\overline{Q}_c)(Q_o-\overline{Q}_o)}{\sqrt{\sum(Q_c-\overline{Q}_c)^2\sum(Q_o-\overline{Q}_o)^2}}$$

where $Q_O, Q_C, \overline{Q_c}, \overline{Q_O}$ are observed flow, simulated flow and average observed flow; E is Nash efficiency coefficient; R is correlation coefficient; B is balance coefficient.

5 Conclusion

Taking advantage of the advancement in remote sensing technology and theory, this paper proposed a method to utilize RS data to drive DTVGM. This method is suitable for distributed hydrologic modeling in cold mountainous areas or where hydrologic data is scarce. The method is promising for applications in hydrology and water resources. The advantage is that there is no need for any

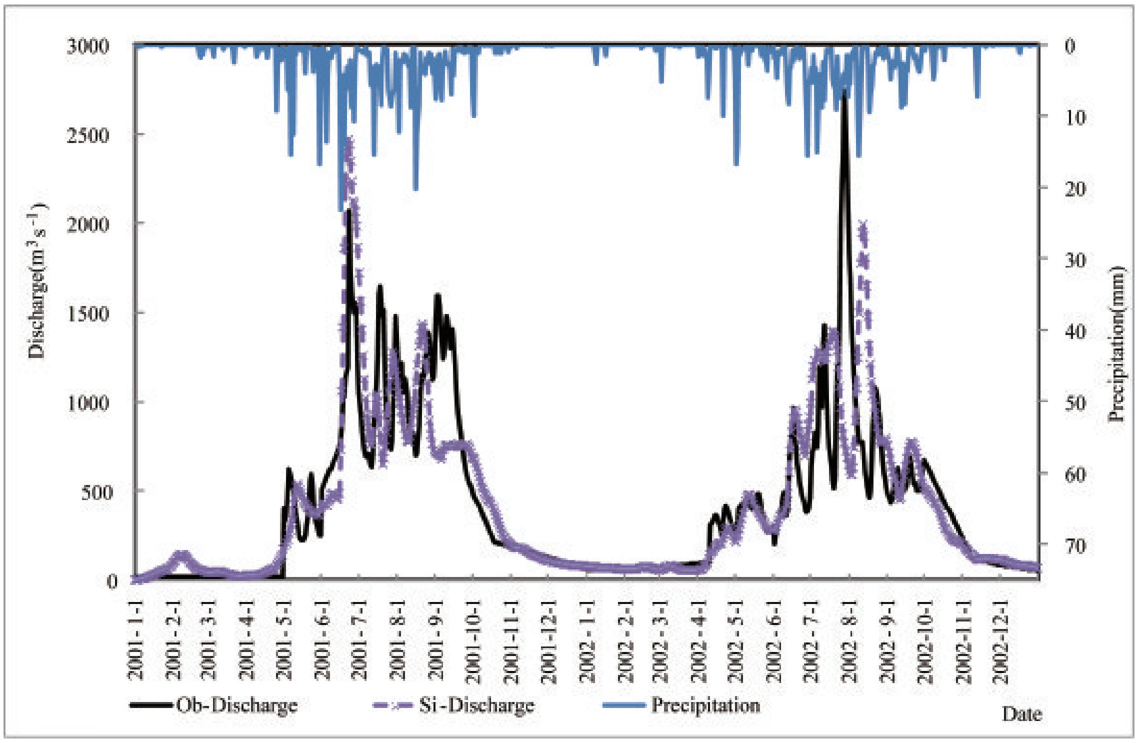

Fig. 13 Simulation and observed discharge for Lhasa in 2001–2002.

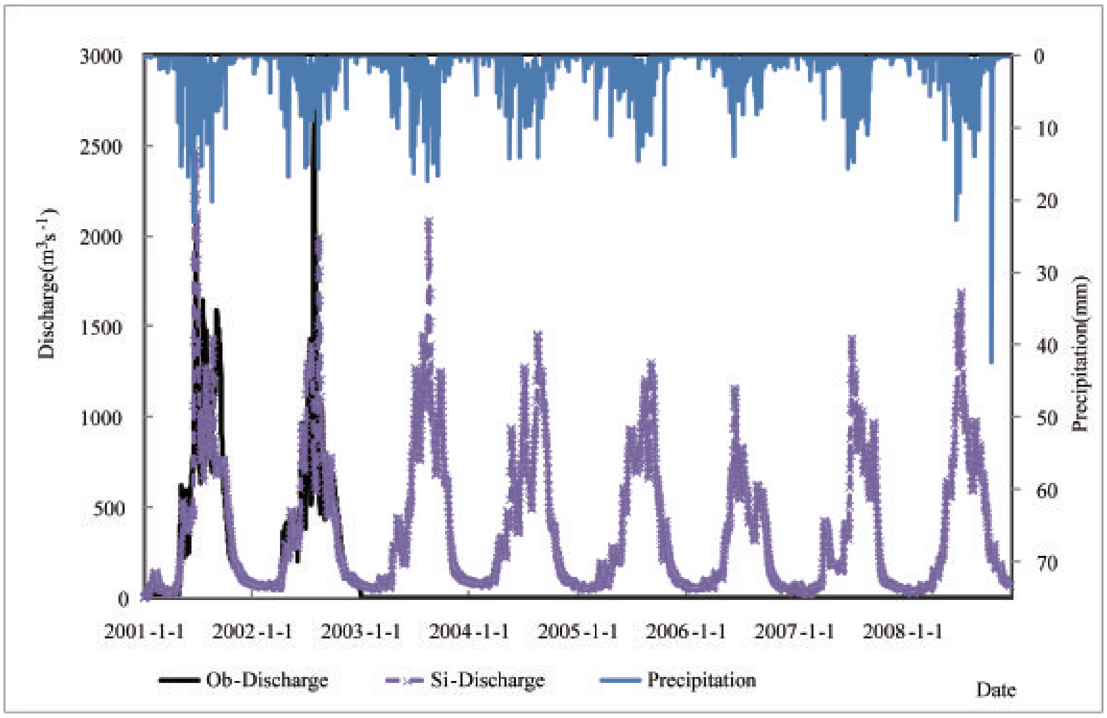

Fig.14 Simulation and observed discharge for Lhasa in 2001–2008.

surface observation data. Only currently available RS data is needed. Therefore, it is an effective tool to for Predictions in Ungauged Basins (PUBs).

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基于遥感驱动分布式时变增益水文模型

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摘要:提出了一个完全采用遥感数据驱动的分布式时变增益水文模型,该模型通过融雪、产汇流等水文过程计算,给出流量的雪盖、蒸散发、径流等水文要素。在拉萨河流域,该模型采用遥感USGS-SRTM的3秒DEM、遥感TRMM(The Tropical Rainfall Measuring Mission)降水、Modis-LST(Land Surface Temperature)数据,建立分布式水文模型,模拟了2001-2008年日水文过程。模拟结果效率系数接近0.7,相关系数接近0.8,水量平衡误差5%以内。说明完全依靠遥感驱动水文模型进行水文水资源模拟可行。该模型为解决高寒山区无资料或缺资料地区水文水资源问题提供了一个新方法。

关键词:遥感;分布式时变增益;水文模型;TRMM;Modis-LST