A Distributed Time-Variant Gain Model Applied to the Yellow River

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Abstract: A Distributed Time-Variant Gain Model (DTVGM) was developed to analyze the impact of climate changes and human activities on the flow regimes in the Yellow River. The large-scale DTVGM was a monthly water balance model, consisted of many modules: (a) natural runoff generation module based on the concept of TVGM, a nonlinear system approach; (b) evapotranspiration estimation module related to land use types; (c) water loss module due to the Water-Soil Conservation Projects (WSCPs); (d) water use module due to human activities; (e) reservoir regulation module.

Key words: Distributed Time-Variant Gain Model; climate changes; human activities; the Yellow River

1. Introduction

Due to global change and the development of social economy, the problem of water resources is becoming more and more significant, which brings new challenge to the hydrology, i.e., how to deal with the problems of forming and evolving of water resources under variational environment.

The distributed hydrological model is the foreland and direction of hydrological scientific development, it have got considerable development already since 1970s. It research four different kinds of questions which are surface flow simulation; Simulating how human activities impacts on surface flow (such as: Deforestation, collecting the groundwater and irrigation); the water quality and soil corrode simulation; Researching the physics mechanism course of hydrology. There are many classical distributed models such as SHE, MIKE-SHE model and Topmodel are net yardstick, SWAT calculates in sub basin and VIC is a great net yardstick model. Every model has excellence as its shortcoming. Different model is suitable for different yardstick.

The Yellow River is the second largest river of China. But, the Yellow River has twenty phenomena of course drying-up of lower Yellow River since it appeared the first natural blanking phenomenon in 1972 among 1972-2002 according to hydrological data set from Shandong. Especially after entering the 1990s last century, number of blanking rise sharply every year, up to 226 days in 1997 at most. It must study the following question at first to solve the serious water problem that the Yellow River faces: How to quantize that climatic change and human activities influence the water resource and water circulation? This is the main science problem which modern water science faces too. The water problem of the Yellow River can not clear according to research typical basin among it, it need to research and analyze its water circulation in terms of the whole basin of the Yellow River.

The Yellow River has more sand and little water. it is very violent that the human activities influences water circulation. A large number of Water-Soil Conservation Projects and reservoirs have changed the law of natural runoff by rainfall. There is little hydrological data in the upper Yellow River in addition, remarkable PUB question exists. The classical distributed hydrology models are unable to receive very kind result in the Yellow River basin; simulation is not high in precision. This paper set up a Yellow River Distributed Time-Variant Gain Model (DTVGM) from characteristic of the Yellow River Basin and advantage of Time-Variant Gain Model. The purpose of the model is to quantize that climatic change and human activities influence the water resource and water circulation by imitating course of water circulation. Face to so complicated the Yellow River, the paper attempts to solve the following problems:

1) The traditional distributed model is a model of the pure physics mechanism. The model complexity of the pure physics mechanism is very high, so the precision of simulation is very difficult to improve. Take a method which combines systematic theory and physics mechanism among the Yellow River month distributed model. Runoff is calculated by systematic theory of Time-Variant Gain model in each hydrological unit, it can given play to the advantage of the distributed model and reduce the complexity of the model.
2) One of main reasons that water is indigence is Water-Soil Conservation Projects reduces Water of the Yellow River Basin. The Water-Soil Conservation Projects (WSCPs) model is set up in DTVGM which can simulate how to reduce water resource by Water-Soil Conservation Projects and which need any data set such as terraced fields area, forest area, meadow area, dam area, etc.
3) It is 57% that human activities reduces water among all consuming water, among them a big chunk is irrigation water of agriculture. Water use module due to agriculture is set up in DTVGM which can get the amount of irrigation water. The module thinks some factors such as the area of the cultivated land, type of the crop, etc. which are leading factors of the agricultural water consumption.
4) There is a reservoir dispatcher's module in DTVGM which can simulate reservoir run according to the rules of dispatcher in the reservoir. The ultra large-scale reservoirs in the mainstream of the Yellow River main consider Longyangxia, Liujiaxia and Sanmenxia reservoir. It is tremendous that reservoirs influence the Yellow River. Main function of reservoirs is what redistributes water within the year; the influence of reducing water is relatively small in the Yellow River.

2. Distributed Time-Variant Gain Model (DTVGM)

The whole structure of DTVGM is runoff in sub basin and routing in stream. Some initial data of the model need be prepared such as: rainfall, runoff, temperature, DEM, industry and agriculture water, Water-Soil Conservation Projects area, reservoir position, characteristic capacity of reservoir and power plant parameter, etc. The whole basin is divided three grades in DTVGM. When we face to a large basin, at first, we can divide it to several function sections, then get little sub basins. It is correspond to reality, and it is a kind of effective method to solve the problem too. The function sections lie in considering the part with same function synthetically, reduce the redundant calculation amount. But it can give play to the advantage of the distributed model, provides the space information on the whole in the basin. DTVGM have two major modules which is runoff generation module under the natural situation and human activities influence module.

2.1. Runoff generation module under the natural situation

2.1.1. Snowmelt model

The source in the Yellow River Basin belongs to high and cold mountain area. In such region, the some parts of runoff formed by ice-snow-melt water, so it is important to consider Snowmelt to study the Yellow River question.

The amount of snowmelt water can be calculated by:

$$S_M = MF \cdot \left(\frac{T_{snow} + T_{\max}}{2} - T_{mlt} \right), \quad \text{or} \quad S_M = MF \cdot \left(T_{av} - T_{mlt} \right) \tag{1}$$

where SM is the amount of snow melt on a given month (mm mon^{-1}); MF is the melt factor for the month (mm ℃$^{-1}$ mon^{-1}), which varies with season and elevation; T_{snow} is temperature of the snow surface (℃); T_{max} is the highest temperature of month(℃); T_{mlt} is snowmelt critical temperature(℃), which is usually chosen as T_{mlt}=0.0℃. T_{av} is monthly average temperature(℃).

2.1.2. Time-Variant Gain Model (TVGM)

The Yellow River Basin belongs to half arid and semi-humid region, Runoff is produced by excess rain, and the rain-runoff is nonlinear hydrological systems. In order to catch its non-linear essence from the system theory, DTVGM adopts non-linear Time Variant Gain Model (TVGM). The basic concept is: the system relation of precipitation runoff is nonlinear because the change of runoff generation quantity is caused by different soil moistures during the process of runoff generation. The TVGM is very simple about its runoff calculation, which prevent Richard equation complicated calculate, but can get good result and replace the complex Volterra nonlinear formulation.

P (rainfall) is sum of rain and snow melt water, the surface runoff (RS) of sub basin as follows:

$$RS = g_1 \cdot \left(\frac{AW}{AWC} \right)^{g_2} \cdot P \tag{2}$$

where AW is soil moisture, AWC is saturation soil moisture, g1 and g2 are parameters of runoff.

References【5 】【10 】detailed recommends TVGM.

2.1.3. evaporation

Generally, evaporation can be divided two aspects: potential evaporation and actual evaporation. Potential evaporation data can be observed by evaporation station, the paper use observation data set. Actual evaporation is determined by evaporation capability and water movement characteristics of soil. In hydrological model coupled with Bagrov model.

The relationship of precipitation (P), potential evaporation (ET_p) and actual evaporation (ET_a) can be assumed that:

$$\frac{dET_a}{dP} = 1 - \left(\frac{ET_a}{ET_p}\right)^N \tag{3}$$

Where N is a parameter which can reflect soil type and land use pattern. The equation can be solved by figure method.

$$d\left(\frac{ET_a}{ET_p}\right) = \left(1 - \left(\frac{ET_a}{ET_p}\right)^N\right) \cdot d\left(\frac{P}{ET_p}\right) \tag{4}$$

After N is confirmed, the relationship between $\frac{ET_a}{ET_p}$ and $\frac{P}{ET_p}$ can be confirmed. $\frac{P}{ET_p}$ can be get from observation data, N can be confirmed by the earth's surface and soil situation, then it can calculate out actual evaporation. The Bagrov model neglects antecedent precipitation, it does not consider the influence of the soil moisture. But, at fact, the influence of the soil moisture is very heavy to evaporate. So we make improve Bagrov model:

$$\frac{ETa}{ETp} = f\left(\frac{AW}{AWC}, KET_{Bagrov}\right) \tag{5}$$

$$\frac{ETa}{ETp} = \left[(1 - KAW) \cdot KET_{Bagrov} + KAW \cdot \frac{AW}{AWC}\right] \tag{6}$$

Where KET_{Bagrov} is ratio between potential evaporation and actual evaporation which is calculated by Bagrov model, it shows the influence of rainfall. If *f(AW/AWC, KETBagrov)*>1 then *f(AW/AWC, KETBagrov)*=1. *KAW* is the weight coefficient.

2.1.4. Subsurface Interflow

For soil layer, the following equation can be got based on water balance equation:

$$AW_{t+1} = \left[P_t - RS_t - ETa_t + \left(1 - \frac{Kr}{2}\right) \cdot AW_t\right] \Big/ \left(1 + \frac{Kr}{2}\right) \tag{7}$$

$$RSS_t = Kr \cdot \overline{AW_t} = Kr \cdot \frac{AW_t + AW_{t+1}}{2} \tag{8}$$

Where AW_t and AW_{t+1} is soil moisture at the start of t time period and at the end of t time period, Kr is outflow efficient of soil moisture, RSS_t is amount of soil moisture outflow.

Where $0 \le AW_{t+1} \le AWC$, AWC is saturation soil moisture.

2.1.5. Total runoff

The total amount of runoff generation per unit grid is the sum of the amount of surface runoff generation and soil runoff generation, that is:

$$R = RS + RSS \tag{9}$$

where R is Total runoff, RS is surface runoff. RSS is soil runoff.

2.2. The human activities influences module

The above model can describe the course of natural situation runoff, which does not consider land use, cover change and human activities. It is feasible to apply in less human activities basin. But, it can not get good result in violent human activities area, so we must improve it. The influence of the human activities will be analyzed as flow.

2.2.1. the Water-Soil Conservation Projects

In order to content mankind request, human always conquers nature, transforms nature, and even destroy nature. After being punished by nature, human begins to protect nature. All these activities have changed the mode of natural rainfall-runoff. Here will explain the influence of land use and cover change.

We can get vegetation data set is its area, the type number of vegetation is 25 from vegetation map, the hydrological model mainly considers 5 types, which are plantation, forest, pastures, water area, desert. The Water-Soil Conservation Projects mainly have terrace, tree planting, annual pasture and alluvial dams. The influence ability is difference on different vegetation. The influence of water-Soil conservation projects can be given by

$$R' = R(1 - \sum_{i=1}^{n} \frac{\gamma_i S_i}{S}) \tag{10}$$

where S_i is vegetation area, S is sub basin area, R is natural runoff, R' is runoff after interception, i is vegetation type, n is the number of vegetation type, γ_i is the influence ability of vegetation. Definition of γ_i is interception loss of one unit runoff (or rainfall) if only one type vegetation lives in a basin and it covers whole basin.

The interception loss of rainfall can be given by

$$P' = (1 - \sum_{i=1}^{n} \frac{\gamma_i' S_i}{S}) \cdot P \tag{11}$$

where γ_i' is the influence ability of vegetation.

$\gamma_i\,(\gamma_i')$ is difference in different period and different rainfall intensity. It is equal to 1 in drought period, but it is possibility very small in flood period. It will increase when rainfall intensity strengthens. So $\gamma_i\,(\gamma_i')$ is a function of rainfall intensity, time of rainfall and soil moisture (or API).

$$\gamma_i = f(I, t, Aw) \tag{12}$$

where *I* is rainfall intensity, *t* is time of rainfall, *Aw* is soil moisture.

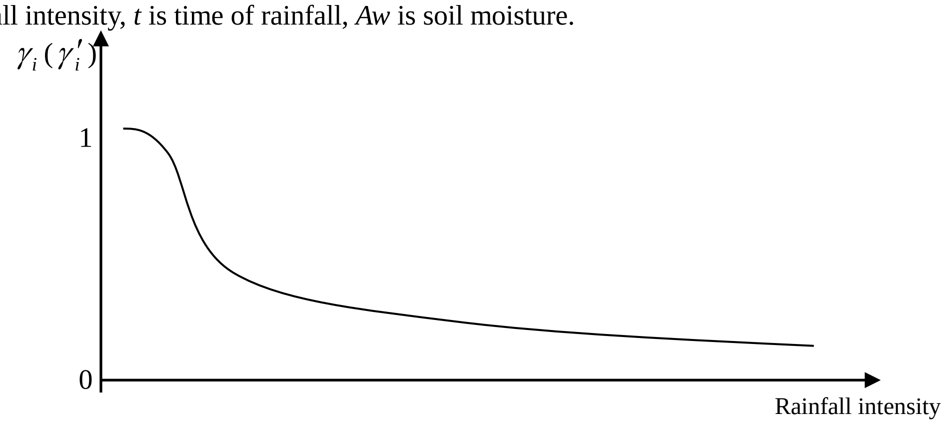

Fig.1 relationship between $\gamma_i\,(\gamma_i')$ and rainfall intensity

Interception loss always is evaporated, so the evaporation of DTVGM becomes:

$$ETa' = ETa + R' - R \tag{13}$$

2.2.2. Human water use model

Human water use includes irrigation water, industrial use water and domestic water, etc. The proportion of human water use has become more and more heavy, even 100% in arid and semi-arid region. Especially irrigation water, the flood irrigation of the large area causes the blanking of the river. So distributed hydrology model must consider the influence of human water use.

Main part of human water use is irrigation water. The count of irrigation water is decided by the area and the kinds of crop. In order to the feasibility and practicability of hydrology model, the following equation is applied to human water use:

$$Ir = \alpha_j \beta S_1 / S \tag{14}$$

where α_j is month distribution of irrigation water, it can be confirmed by irrigation period(j=1,2,…12). β is count of irrigation water in unit area, it can be confirmed by the type of the crop and irrigation way, we can get data set by experimentation. S_1 is area of Cultivated land. α_j、β is time-variant in theory, and climate change, human demand and advanced irrigation technique all can change its value. But within short time, the change is not very great.

A little part of irrigation water can come back basin, majority of it is evaporated. β is count of irrigation water which has deducted regressive water. These water is calculated in evaporation in DTVGM.

Except agricultural water, industrial use water and domestic water are function of industrial production (*In*), population (*Po*) and urban and rural areas (S_5).

$$W = f(In, Po, S_5) \tag{15}$$

W is to increase fast with the improvement of industrial production and human living standard, so its influence degree is greater and greater.

The influence of human water use can be given by

$$R'' = R' - \alpha_j \beta S_1 / S - W \tag{16}$$

and actual evaporation turns into:

$$ETa' = ETa + R'' - R \tag{17}$$

2.2.3. Reservoir operation

Human has built a large number of reservoirs on the river in order to flood prevention. The main function of the reservoir is flood prevention and generating electricity. Reservoir redistributes space-time apportion of water in hydrology circulation, the influence of reducing water is relatively small. A simple reservoir dispatcher's scheme is provided:

In a basin, reservoirs must be calculated step by step from upper to low. The following picture is dispatcher's model in the individual reservoir.

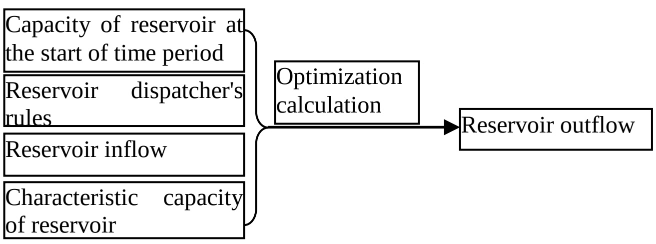

Fig.2 dispatcher's model in the individual reservoir

Reservoir inflow can be getting from rainfall-runoff hydrology model. The following several respects are considered to the dispatcher of each period:

- The minimum capacity of the reservoir: Guarantee that the reservoir water level can't be lower than the minimum water level of the reservoir;
- Limit water level in flood period: the reservoir water level can't exceed the limit water level;
- Minimum flow for ecology need: the outflow of reservoir must be greater than the minimum flow;
- Benefit is maximized to generate electricity: Benefit of generating electricity must fully consider after meeting the request of preventing flood.

The dispatcher's scheme is as follows in DTVGM:

Flood season (generally April - October):

- If reservoir water level is greater than minimum water level and less than limit water level, outflow is equal to flow of full generating electricity. If inflow is less than outflow, reservoir water level will decrease to minimum water level, if inflow is great than outflow, reservoir water level will increase to limit water level.
- If reservoir water level is greater than limit water level, outflow is equal to inflow.
- If reservoir water level is less than minimum water level, and if inflow is greater than flow of full generating electricity, outflow is equal to flow of full generating electricity, if inflow is less than flow of full generating electricity, outflow is equal to inflow.

Not flood season (other months):

- If reservoir water level is greater than minimum water level and less than normal water level, outflow is equal to minimum flow for ecology need, more water will be kept in reservoir or less water will be supplied by reservoir.
- If reservoir water level is greater than normal water level, outflow is equal to inflow and greater than minimum flow for ecology need.
- If reservoir water level is less than minimum water level, and if inflow is less than minimum flow for ecology need, outflow is equal to inflow, if inflow is greater than minimum flow for ecology need, outflow is equal to minimum flow for ecology need.

To the multistage reservoir in the basin, it is first to calculate the upper reservoir. In order to get the low reservoir inflow, must consider Interzone runoff and upper reservoir.

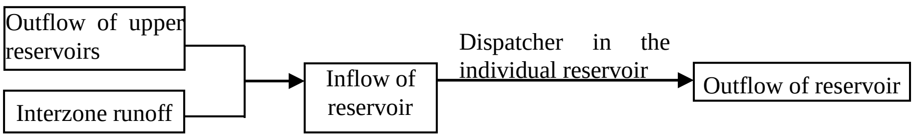

Fig.3 dispatcher's model in several step reservoirs

2.3. Whole frame of the model

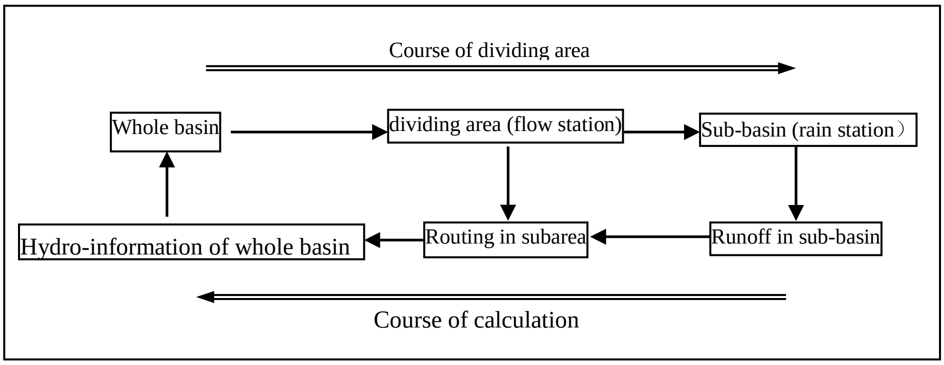

Fig.4 whole flow chart of model

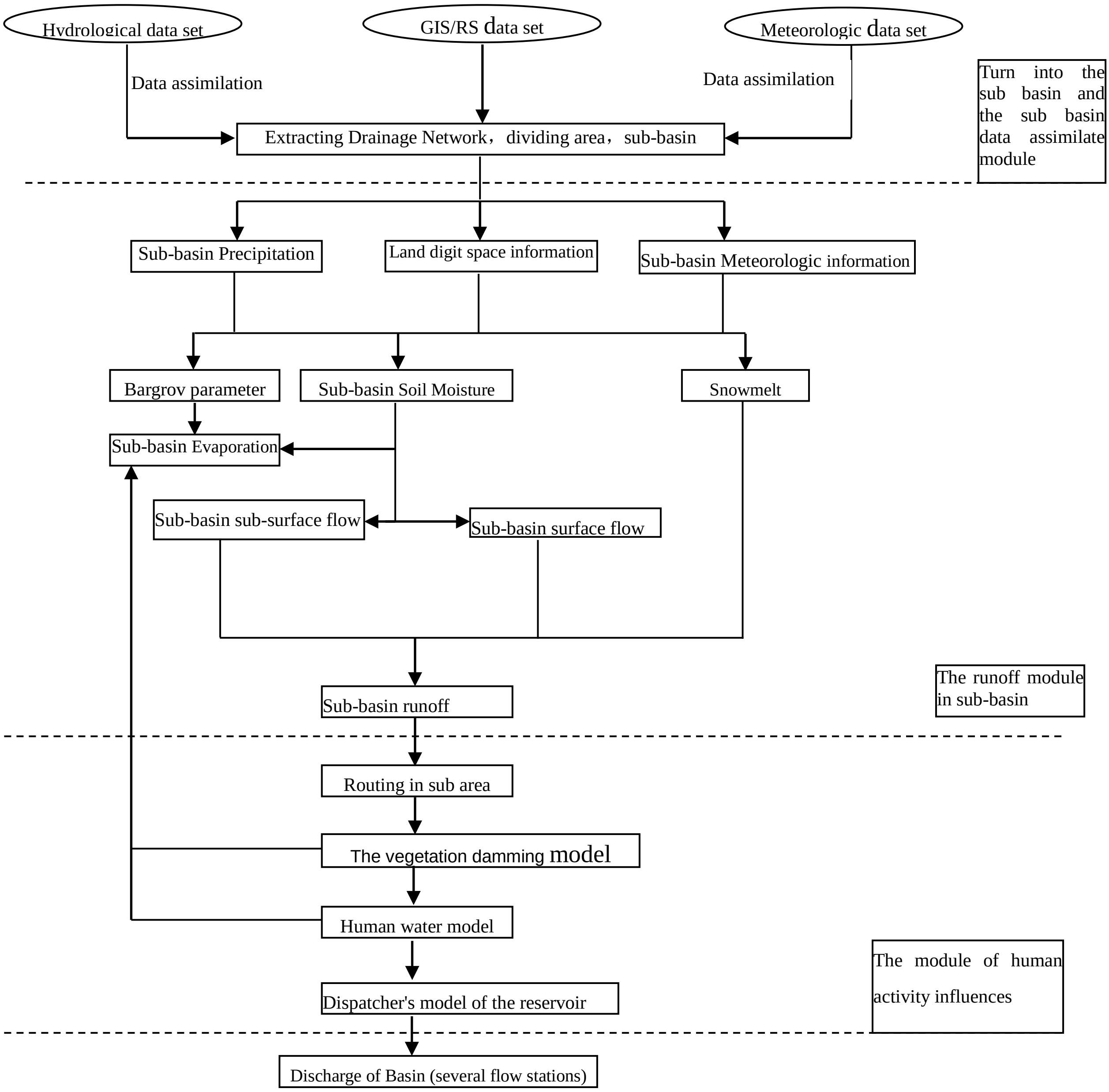

Fig. 5. Scheme of DTVGM

3. Conclusion

The Yellow River area is large, the mainstream of the Yellow River likes Chinese word "几". Because the water and soil run off, there are as many as ten thousand gullies in the basin. It is very violent to influence by human activities in the Yellow River Basin. A large number of reservoirs and irrigation projects have already controlled the flow of the Yellow River. It is very difficulty to set up distributed hydrology model. Take a method which combines systematic theory and physics mechanism among the Yellow River month distributed model. Runoff calculates in sub basin, and considers the influence of land use and cover change. Human activities have made rainfall-runoff regulation change. DTVGM simulates human activities from module of the Water-Soil Conservation Projects, human water use and reservoir.

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