The system dynamic study of regional development of Manas Basin Under the constraints of water resources

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Abstract

The arid Manas River Basin, Xinjiang, China, similar to the other arid regions is facing the problem of water constraints. The social, economic and political systems the basin is located in all have to interact with the water resource management. Within the social economic and political systems, growth and expansion has always been the key driving force while it occasionally is forced to slow down or even decline due to the water constraints. To date, the growing populations, industry and agriculture water demand has largely been met by improving and expanding reservoir capacity, by mining fossil groundwater resources, and by improving the water use efficiency. However, bringing future demand in line with available supplies will require increasingly efficient water management practices and greater conservation of water resources. An object-oriented system dynamics approach has been used to develop a model to evaluate the sustainability of the water resource system in the Manas River basin. The study shows that the technical solutions on the improvement of water supply and the improvement of water use efficiency are not the fundamental solutions. Acknowledging the water capacity and changing a growth orientated value system is crucial in the sustainability of Manas River Basin.

Key works: water resource, sustainable development, system dynamics modeling, Xinjiang, Manas basin, arid/semi-arid river basin

1. Introduction

Water resource management is an complicated and delicate issues in regional planning and development, especially in arid river basin where evaporation is much higher then precipitation. Arid water problem is not limited to the technological solution but also has to be addressed within the social-economic system, since the fundamental problem of the sustainable development in the arid area is to manage the social-economic growth with the acknowledgement of the carrying capacity from the limited water resources（Syme and Hatfield- Dodds 2007.）

In a society focus on economic growth in many areas of China, the scarcity and the carrying capacity of the water resources on the regional development are often ignored or not noticed. The issues of the water resources stress keeps being solved through engineering solutions. Various technical solutions are proposed and implemented to deal with the water shortage problems while the other social, economic and political sectors are still striving to show the continuous growth in align with the other. Many water conservation projects are focus on increase the surface water efficiency, such as to improve evaporation and seepage rate of channels and reservoirs, to reduce water demand per area of cultivated land by dripping irrigation.

However, under the limitation of water carrying capacity, there are many questions to ask: a) up to which point, the economic development is sustained? b) Is there any feedback from economic development to hydrological process in short term and long term? c) what is the future of the arid regional if the development process keep going? d) is there any other options or better strategies.

With this in mind, we need to find: a) the key elements in the water-social- economic system, b) main feedbacks of the system, c) changing interrelationships amongst themselves and integration with their environment.

A systematic approach provides a proper solution (Gastelum et al, 2006, 2010; Simonovic and Fahmy, 1999; Xu, et al 2002; Tidwell, 2004; Sanchez-Roman, et al, 2010;): A)linking the hydrological process of the water resources which requires sustainable management of both supply and demand issue with the social-economic structure(Rauch et al 2005). b）The system is a description of the reality, addressing both systemic and non-linear relationships (Ohlsson and Turton 1999). c) changes happening along the time. d) different scenarios can be simulated to measure the efficiencies of polices. (Gastelum, 2006)

However, a systematic approach is not only difficult to be applied in the society, but even in the academic world, the system approach in which linking the hydrological process of the water resources and the social-economic structure is seldom applied. The key reason for this lacking of linkage is due to the accuracy expectation in the hydrological engineering studies and the uncertainty of the relationships and the parameters associated with the social and economic sector. Recently, a SD model being build to explore the among water stress with water offer and water demand(Sánchez-Román *et al,* 2010), however, the model system is limited in the hydrological process, there are lack of feedbacks between water exploitation and nature river system and between the water allocation and social- economic development.

A system dynamic model (Forrester J.W. 1961, 1980) which links the social-economic development- water allocation-water exploitation-nature river system is developed and run to analyze the history and forecast the future to assess water-social-economic sustainability and simulated different water allocation and utilization scenarios try to find alternative water strategies.

2 Materials and Methods

The system dynamic model is built in a STELLA 9.0 platform and implicated in the Manas River Basin (MRB) which is a arid region, located in the North of Tianshan Mountain, Xinjiang Uygar Autonomous Region, northwestern of P.R. China.

2.1 Study Area Characterization

MBR lies immediately to south of Dzungarian Desert, with a drainage area of 2.29×10^4 km^2 and is consisted by 6 rivers, is composed by three parts: mountain area is at the edge of the basin and covered by perennial snow which provide water resource to the basin, oasis where the main human activities take place is at the foot of the mountain, and desert is in the downstream of the rivers following Oasis. The mountain area is about $7650.91km^2$. Almost all oasis area grew from desert. Manas River which is supplied by the melting snow from the mountain is the most important tributary supplying over 50% of Basin’s water volume.(Cited from: Shihezi Water Conservancy)

Human beings’ activities have been found from three or four thousands years ago, but most of them was living a nomadic life according to the availability of water resource from the natural system. MRB developed slowly and the population stayed at a low level, since there were seldom water conservancies before 1949 to increase the availability of the water for the human being.

After 1949, the opening of the new land for cultivation was implemented as a regional development strategy especially at the marginalized area and a special public organization was established. A national land reclamation corporation was setup with people organized from the east and to migrate to Manas River Basin to reclaim the land from dessert by using the water from the rivers. This Corporation made efforts to build the canals and the reservoirs to increase the available water. With the increased available water, land was reclaimed and cultivated, new oasis has been forming.

2.2 model development

The model behavior is governed by model structure. Figure 1 is the causal diagram There are four feedbacks. two are balance feedback loops from water stress to water utilization and water allocation. Water stress would be in a balance position if Economic development is just governed by water stress. However, other two reinforce feedbacks from groundwater to water utilization and from development expectation to economic development worse the situation.

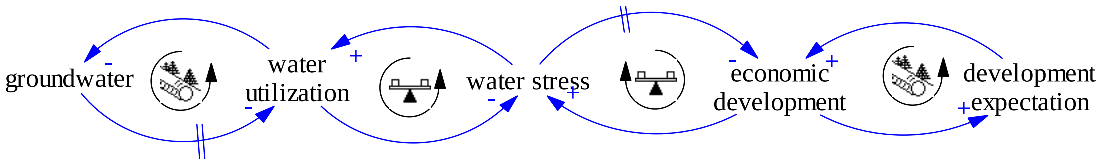


Fig. 1 the causal diagram

Information collection integrate both quantitative and qualitative methods. Data were collected from four sources: published government documents, journals, information from informal/semi-structured interviews and field observations. The most important government documents used in this study are the Shihezi County Gazetteer (Shihezi xianzhi) and Shihezi Water Conservancy (Shihezi Shui Li zhi)， Manas River Basin Development Planning 1990 which provide details of the major changes and historical events of the implementation of irrigated land exploring, industry development, urban expansion in MRB, and major early-period quantitative data, especially demographic and agricultural data. And most recent quantitative data were derived from officially published statistics, xinjiang Statistical Yearbooks 1990-2007 and Xinjiang Corps Yearbook 1990-2007.

The basic structure of the model is the dynamic water budget. Specifically, each supply and demand component is treated as a spatially aggregated, temporally dynamic variable. Temporally, the model operates on an annual time step encompassing the period 1949–2050 which includes a 58-year calibration period (1949–2006) and the prescribed 44-year planning horizon (2007–2050). An annual time step was used because it matched the annual basis of calculation for key metrics in regional water planning (i.e. river flows, irrigation, population water demand and groundwater pumping). In order to find the interrelationships among water, economic and social sectors, observation and semi-structured interviews are also conducted during the early of 2010 Spring. There also many information come from former researches, such as Tang etc.(1992), Han et al.(2001) explored the land use change due to the water use change from the period from 1950 to 1977, Yuan et al.(1995) and Cheng *et al.*(2005) provided the historical patterns of the land use and water resources over the past 50 years history of oasis development. Yet, still these studies all attempt to find the technological solutions to this complicated social-economic system. The lack of effective and precise information on these topics, such as the feedback from water pumping and economic develop plan to water stress, created some uncertainties during the simulations. As a business-as-usual scenario, the continuation of current trends is assumed for forecasting.

The model is composed by nine sectors. The main sector Water Stress serves as an indicator for water sustainability. The feedback between land reclamation, population, industry and the urban water demand which comprises irrigation, population water demand and industry water demand is the first reinforce feedback. Generally, water stress infects land reclamation and pumping directly and immediately. Water utilization sectors describe the engineering solutions to the water supply, pumping and reservoir building. The other reinforce feedback is from the ground water resource and pump.

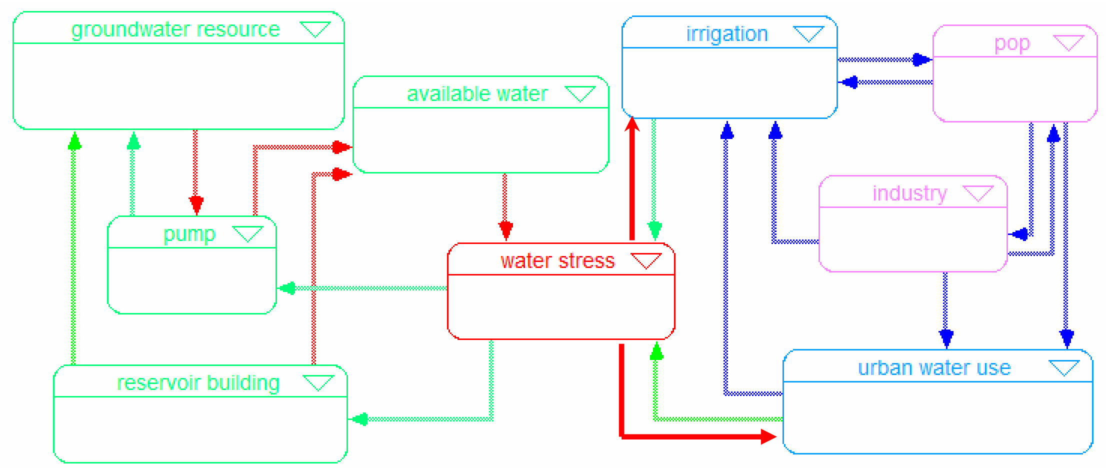


Fig. 2 conceptual model

In the hydrology aspect, water stress demand modern water conservancy which would increase the available water, then impact the natural river system and deep aquifer system in long-term. In the economy aspect, the available water boosts the cultivation and settlements process. But economic developments prick up water stress. In the society aspect, the economic development promote urbanization the establishment of the municipal structures and attract immigrates, and then enhance the economic development expectation.

2.3 Model structures

Systems are modeled as a network of stocks and flows.

2.3.1 Natural river system:

1) Surface water

Surface water originating from the runoff form in the mountain, is an exterior variable. The mainstream and tributary flows for the period 1956–2007 are based on historic data from Kensiwate Hydrologic Stations in the upstream of Manasi river. Manas River is the largest river in MRB. Since the first Hydrologic Stations, Kensiwate, located at the upstream of Manas River, was built in 1956, the runoff data from 1956 can be obtained (Figure 3). The average runoff was 1172 Mm^3/y for the years from 1956 to 1996, accounting for about 52% of the total water resource in MRB. It can be observed that minimum runoff with 935 Mm^3 happened in 1992, maximum runoff with 1470 Mm^3 in 1966. Ex-1956 mainstream/tributary flows are generated stochastically and based on 1989–1995 data, and Post-2007 flows are generated on 1956-1996 data.

The inflow in reservoirs is constrained by reservoirs capacity and the surface water availability. Usually, the reservoir capacity wouldn't exceed the surface water availability. When storage exceeds reservoir capacity, spillover happens.

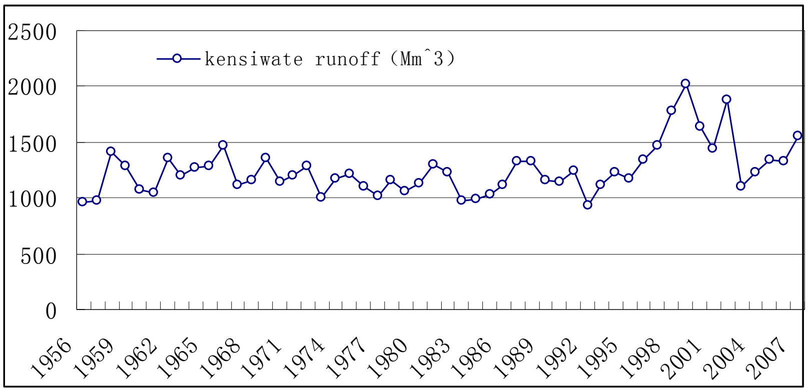


Fig. 3 Runoff Change of Kensiwate Hydrologic Stations on Manas River

(Resource：Kensiwate Hydrologic Stations)

2) Underground water

Underground water resource which is a stock, increased by the recharge rate and decreased by drainage and the pumping.

Groundwater recharge

The annual ground water runoff in plain area is about 1197 Mm^3/y, and 945 Mm^3 is recharged from surface water over the period of 1956–1996. Groundwater inflow is about 50 Mm3/y from reservoir seepage, 1000 Mm3/y from mountain recharge, and 9680 Mm3/y from canal seepage, and 27 Mm3/y from municipal water recycling and precipitation in 1990. Another important inflow to the aquifer system is irrigation leakage from irrigation system and flood interflow seepage. In order to simplify the model, flood interflow seepage is included in irrigation leakage. In conclusion, the recharge is from the reservoirs leakage, canal leakage, mountain recharge and the leakage from the irrigated land.

After 1949, water distribution began to dependent on canal construction, canal always be built before the unused land been explored. Almost all surface water run into irrigation canals just out of Mountain. Therefore, the volume of surface water recharge for ground water is according to the canal seepage coefficient. That is to say, the surface water recharge is equal to volume of surface water multiple canal seepage coefficient. Recent several decades, due to the continuous improvement of channel anti-seepage technology, the coefficient is getting a trend to decline to 0 while the ground water demand is kept rising. In 1990, the canal seepage coefficient is among 0.38 to 0.42.On the irrigation aspect, flood irrigation gradually changed to dripping irrigation in order to enhance water resource utility with the increase in cultivated land. Mountain recharge ratio and reservoir leakage ratio is fixed as 0.043 and 0.13 respectively according to historical records (General Report on the Manas River basin planning, 1997).

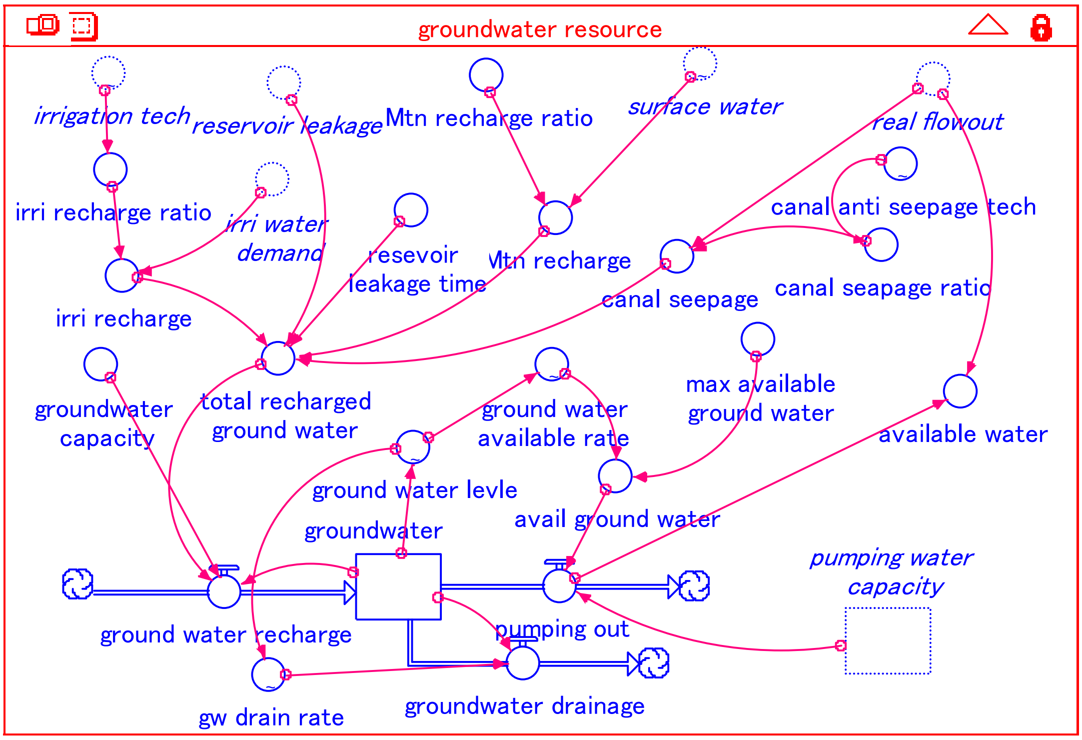


Fig 4 dynamic model for groundwater sector

Groundwater drainage

The ground water drainage is modeled as a function of ground water level which is decided by groundwater volume and is the determinant of the ground water availability. When the ground water level decreased to some critical points, there were no water can be drained out or pumping out.

3) Impact of Pumping on groundwater

The increasing groundwater pumping would result in significant groundwater level declines and limited ground subsidence. The recent situation of groundwater is no accurate figures due to the feedbacks from declined groundwater level to the available groundwater seldom been researched in this basin. But, in fact, scarcity of surface ground water has been observed in some downstream area. From 1964 to 1993, due to the long-term exploitation of groundwater, the groundwater level dropped about 12.58m to 17.06m in Shihezi County, and there is an average annual decreasing rate of 0.17m in the west of Manas County (Cheng, 2003). Some areas began to explore deep groundwater. At present, it is still not easy to control the use of groundwater. In the downstream area, the situation is getting worse.

The observation is various in discrepant points. Therefore, a graph function is used to measure the impacts of ground water subsidence on available groundwater. The initial groundwater reserve is defined subjectively as 40000 Mm^3. There is a maximal available groundwater used to constrain the groundwater availability. The available groundwater would decrease sharply when groundwater reserve begins to reduce. And no more water can be pumped out when groundwater reserve diminished to about 32000 Mm^3.

As for the groundwater distribution, available ground water would first satisfy human and urban development, and available groundwater for irrigation is constrained by industry development and urbanization process mainly because that the majority of arable land in the basin is in the middle and downstream. Nevertheless, it is still dependent on policy, how the industrial composition is adjusted.

2.3.2 Water utilization

1) Reservoir

The reservoir is presented by a stock. The water in the reservoir is increased by the inflow from the runoff from the mountain and is a fixed amount given by histrical data. There are three outflows, the reservoir leakage, outflow for irrigation and the reservoir evaporation. Surface water is stored in reservoir first, and then divided to irrigated land. Water flow out just since surface water not in reservoir is not enough for irrigation.

Outflows

Most reservoirs were built in oasis area. Evaporation rate is much higher than precipitation. Reservoir evaporation rate is set to have a positive relationship with reservoir water volume and affected by its location. The evaporation coefficient is based on 1990 data what average evaporation losses are equal to the water in reservoir multiple 0.1. The reservoir seepage rate can be reduced by technology development represented by a graph function.

The inflow is from the mountain

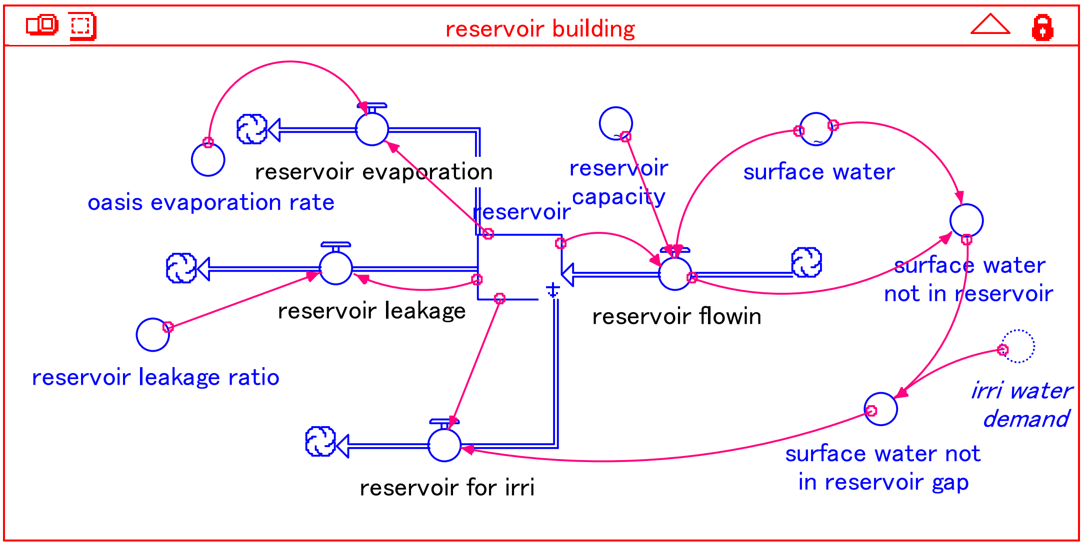


Fig 5 dynamic model for reservoir sector

2)Pumping

pumping capacity is influenced by two main factors, municipal water demand and irrigation water demand on pumping and is constrained by the perceived groundwater stress. If they perceived goundwater stress which means they know that the chance they get pump water out is very small, some of them would stop pumping activities even them encounter the water using stress. The perceived ground water shortage is measured by the observed depreciated pumping facilities due to the ground water subsidence which is influenced be the volume of groundwater.

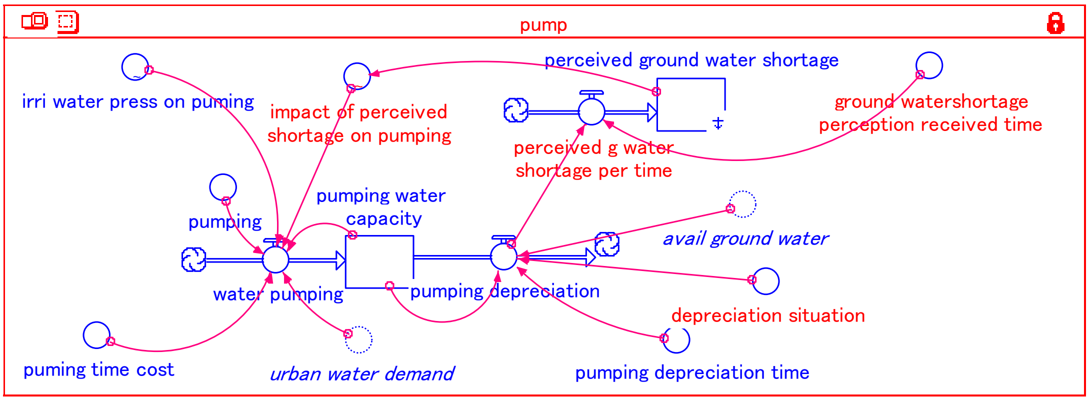


Fig 6 dynamic model for water pumping sector

2.3.3 water demand

1) Land reclamation and irrigation demand

The biggest demand for water is from the irrigation demand. The irrigated land is a stock which is increased through the land reclamation and decreased through the transformation to the settlements and the return to the unused land due to lack of water. (Fig. 7)

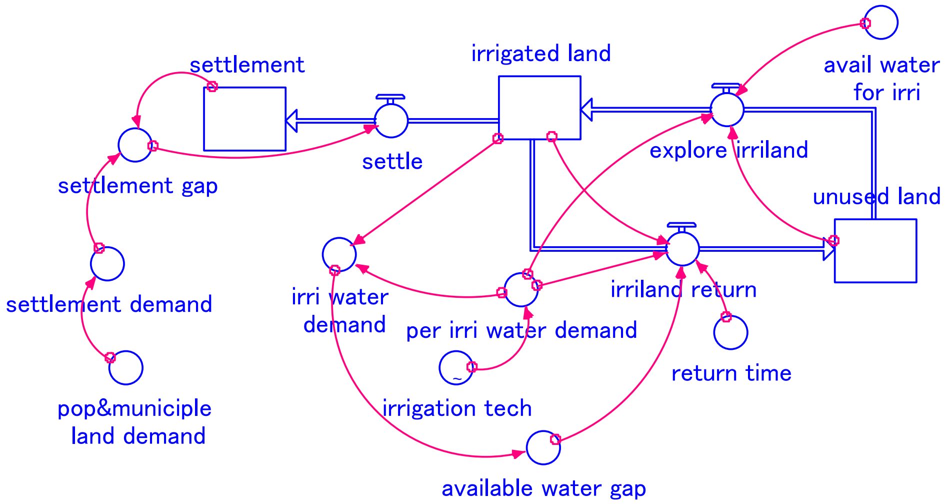


Fig 7 the land usage change process

Water irrigation demand should be impacted by the two other factors. One is the type of the crops; the other is the irrigation technology. A diversity of crops is grown in this region with grains and cottons accounting for most of irrigated land. However, it can be predicated that the percentage of cottons will decrease due to water stress. The second factor is the adoption of the dripping irrigation. Considering the diversity irrigative water demand of crops, the annual average irrigative water demand with an assumption of the same over all crops is about 0.51 Mm^3/km^2 in 1990. And this rate is dynamic according to technology and the components of the plants which are all represented by a technological coefficient.

Available water for irrigation includes three parts, surface water, groundwater and municipal wastewater discharge. The total municipal wastewater discharge was approximately 53 Mm^3 in 1990. The irrigation from surface water and groundwater will be discussed later.

2) Industry water demand

Industry product growth is estimated by Cobb Douglas production function which is dependent upon capital investment, labor force and technology. It was soaring after 1990s. There is an assumption that all investments are autonomous, and all induced investments are used in technology improvement. In other words, the industry technology connotes the development process induced by outsider investment.

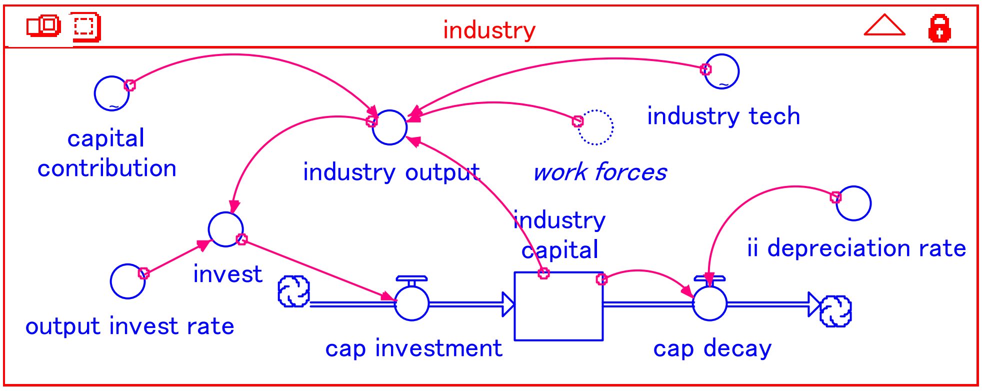


Fig 8 dynamic model for industry sector

Most companies are using public supply water while some big companies are using self-supplied domestic wells now. Therefore there is no accurate data on the water consumption of the industrial sector. It is estimated from the other cities in northwest of China. Assuming that per capital industry water demand has a negative correlation with industry technology.

3) Population water demand

The population is a stock adjusted by the natural growth and the immigration. The migration rate is affected by the job availability, especially industrial job availability for the industry could provide more job opportunities comparing to agriculture. Impact of water resource on immigration is not considered. The rationality is that the water demand by residents would be protected in advance in the scarcity of water resource.

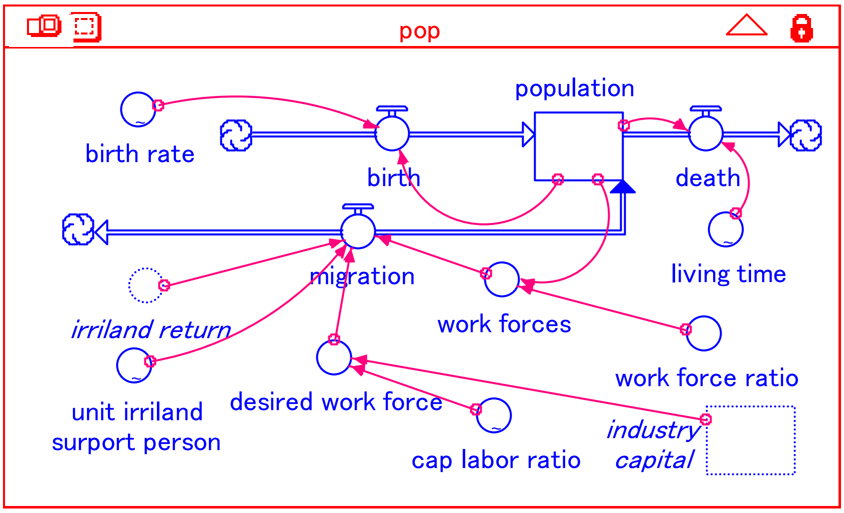


Fig 9 dynamic model for population sector

The water consumptions of the population include two kinds of water usage, household water consumption and urban facilities water demand which account to roughly 30% of the total municipal water use. It is calculated by the population multiplying the corresponding per capita water use which has been increasing through the years. It is 54 liter per capita in year 1978 and 160.5 in year 1999 (Xinjiang brilliant fifty years, 2005; Xinjiang Year Book, 1999). Population water use is protected in advance when water scarcity happened.

2.3.4 Water stress

Water scarcity comes in two flavors. On the one hand, scarcity can be absolute, such as in environments of low precipitation and large evaportranspiration rates. On the other hand, scarcity can be induced by economic constraints, which do not permit the adequate development of water resources. In arid region, both problems are acute.

The perceived water stress which is the interaction between water demand and water supply equals to water demand divided available water. Due to the water demand from municipal water use is relative small (just account for about 0.5%), the water stress mainly come from irrigation. Stress is getting higher when irrigated water demand is reaching the available water for irrigation, and it is soaring when water demand exceed the available amount. The main impact from water stress is on groundwater pumping when reservoirs and canals building domain by government planning.

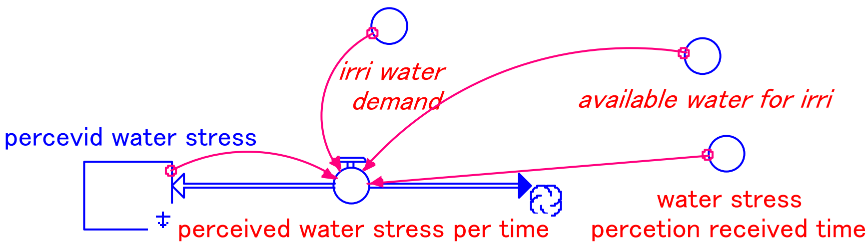


Fig. 10 dynamic model for water stress sector

2.4 model calibration and validation

Model validation has to consider model's behavior and structure (Ruth and Hannon, 994). Tests of model structure it is necessary that its conceptions are correct which means its internal logic should be rational. Tests of model behavior evaluates adequacy of behavior generated by the structure. (Forrester 1961; Sterman, 2005), include behavior reproduction, behavior prediction, *et al*. the family of behavior reproduction tests examines how well model generated behavior matches observed behavior of the real system. Point by point comparisons of model generated and observed behaviors is one widespread accepted symptom generation test (Naylor and Finger, 1967).

Model calibration is the evaluation and adjustment of model's parameters and constants to fit the simulated results with real data for all state variables. (Rykiel 1996). Parameters are selected from a range of feasible values, then tested in the model, and adjusted until satisfactory agreement between predicted and observed variables is obtained.(Li et al. 1998)

Figures 10 and 11 show the simulated trends of irrigated land, demographic and industry development. The results demonstrate that the simulated data fits historical data quite well. In the future simulation for the forecast period of 2010-2030, the irrigated land will have a slight decreasing trend with some fluctuation. Population growth includes natural population growth trend and migration which depends on economic development and the perception of stress from available water. It can be seen that population experiences a S-shape growth. The population in 2050 is four times than that in the 1949. Industry output growth will continue at the exponential rate. The Manas river dried out in year 1974.(Figure 12).

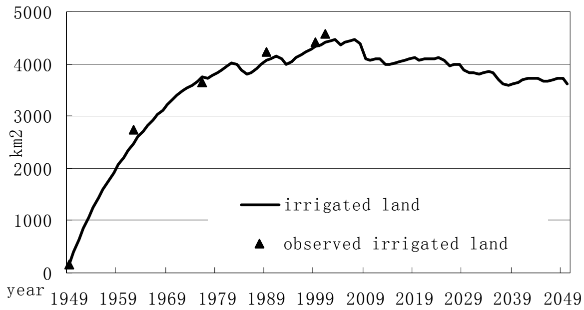


Fig 10 Comparison of observed and simulated irrigated land

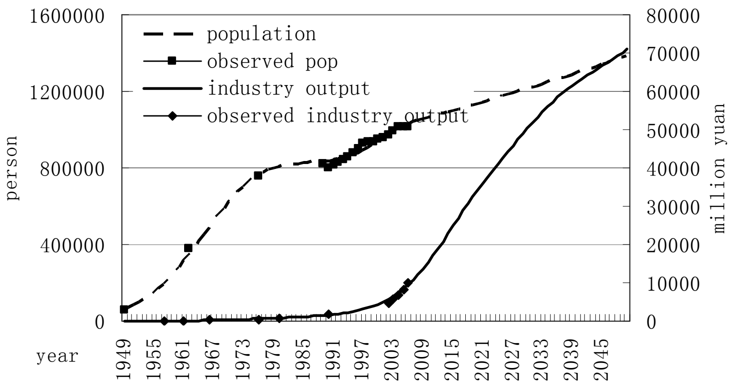


Fig 11 Comparison of observed and simulated population and industry output

2.5 Policy implications

For the public and political leaders, a useful model should explain causes of important problems and provide a basis for designing policies that can improve behavior in the future. A variety of water conservation alternatives were modeled as part of the planning process. The policy implications of a model are also tests for confidence building. The purpose was to provide a quantitative basis for comparatively evaluating the alternatives in terms of the resulting water savings and cost to implement and maintain.

Policies to resolve water resource scarcity mainly are: (a) to increase water resource supply by technology improving, such as water conservancy. (b) to decrease water resource demand, such as water saving project. Many policies based on the supply reason have been demonstrated being inefficient. take the inefficient for further increase in demand and continuation of the water deficit.

A total of 24 alternatives were modeled, and are grouped according to 6 broad classes: reservoir evaporation and leakage, urban water recycle rate, irrigation water demand per area, the available surface water, industrial water demand per capita, and industry output scale.

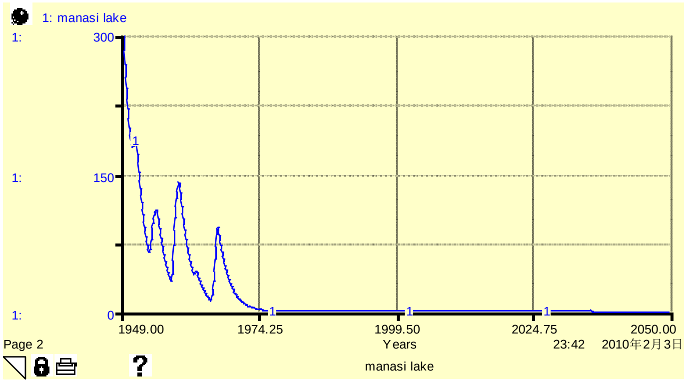
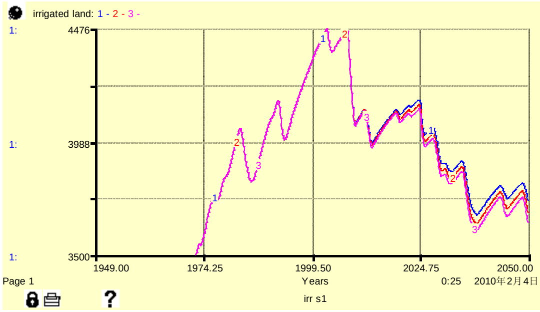


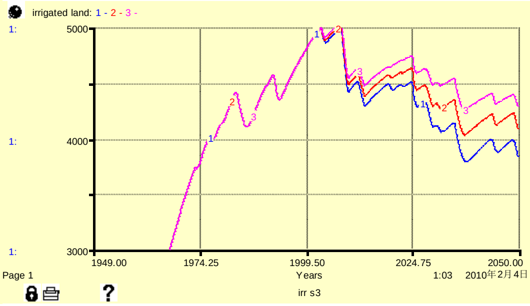
Fig 12 the drying out process of Manas river

Table 1 Policy implications

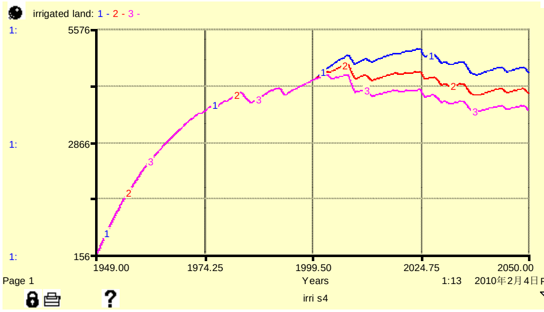
	Policy
Scenario 1	reduction of reservoir evaporation and leakage: 50% ,10%,Basic run
Scenario 2	improvement of urban water recycle rate :Basic run, 2 times, 3 times
Scenario 3	reduction of irrigation water demand per area : 20%, 10%, basic run
Scenario 4	Change of the available surface water: 20% reduction, no change, 20% improvement
Scenario 5	Change of industrial water demand per capita: 50% reduction, no change, 50% increase
Scenario 6	Change of the industry output scale: 0 times, 2.5 times, 5 times, 7.5 times, 10 times as the basic run.

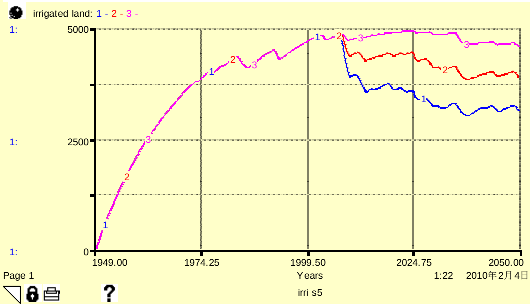
Available water resource is the most important limitation factor for regional development. The first 4 scenarios are all implemented to explore the impact of different available water resources on the development process. And the irrigated land is selected as a measuring index. The last two scenarios are discretionary industry construction adjustment policies. Carrying capacity varies according to the level of exploitation which is dependent on the development process. All water saving technologies surely increases the irrigated land area, and the implement to reduce the irrigation water demand per area is the most efficient method. The available surface water is a determinant factor, higher available surface water would enhance the economic development significantly, but it is also an exterior and unpredictable variable in this model. The industry construction adjustment policies are of emphatic consequences on the regional scale. If the industry expands too fast, all of this basin will turn to a metropolis with few countryside lands.





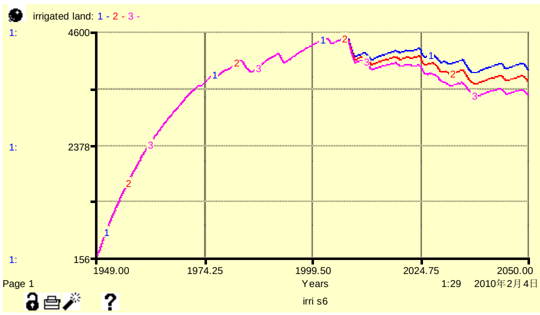
a) Scenario 1 b) Scenario 2

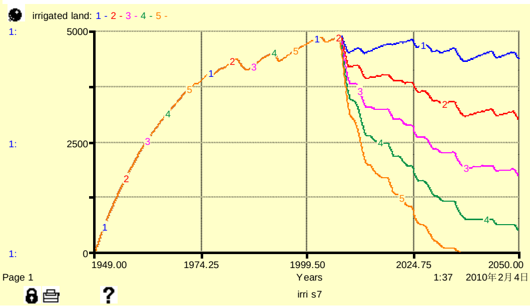




c) Scenario 3 d) Scenario 4

Fig.13 the impact of policy implications of water saving on irrigated land





a) Scenario 5 b) Scenario 6

Fig. 14 the impact of industry construction adjustment policies on irrigated land

3 Conclusion

In this research, a system dynamic model is proposed to grasp the interrelationships between water-socio-economic activities concerning to the water demand and the water supply in Manas river basin. Some important aspects are concluded through the results of the basic run. Firstly, the available water resource is the key and restrictive factor of the model. The complicated social-economic system makes the supply of the water provision the only and feasible solution to address the water stress to cultivate lands through building the reservoirs, the canals and pumping. As being showed in the applied scenarios, the area of cultivated land would eventually reach a bottleneck and be level off with some fluctuation under the constriction of water resource when the technology can not be enhanced any more. Secondly, industry adjustment policies are important for regional development. If the industry expands too fast, all of this basin will turn to a metropolis with the losing of countryside lands. Finally, the negative feedbacks between available water and water pumping would induce serious sinking water table and lead to the water stress issue unsolvable with the sacrifice of the deep aquifer system.

Based on the model, the use of the modern technology makes it possible to increase the available water for human use, but also might bring some unpredictable indirect negative impacts in long term. Water resources sustainable strategic research should be conducted based on the comprehensive understanding of the total basin complex system.

Given limitations in time, resources and data, some important metrics were not simulated by the model. For example, how might outsider investment effect economic growth, how would a water diversion project influence the system, how might the service industry affect the regional development? Certainly these are important considerations that in many circumstances were recognized and need to get more attentions in future studies.

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