R-SD: THE COMPREHENSIVE DEVELOPMENT AND UTILIZATION OF WATER RESOURCES OF RIVERS

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ABSTRACT

R-SD is a dynamic system model used to study the comprehensive development and utilization of water resources of rivers. This problem covers a wide range of aspects, such as hydraulic power generation, water transportation, flood cotrol, water consumption of industry and households, irrigation in agriculture, reservoir fishery, around-reservoir tourism and recreation facilities. R-SD also relates to the thermal power generation and land transportation. It is a system with multivariables, nonlinear and complex feedback structure. Usually, it is called as economic system of a river-valley.

This paper emphasises on the structure of R-SD model. First, it gives the interrelationship figures between the subsystems, then the main cause-and-effect chains and flowchart of the system. Finally, a part of the results of a case study is given. It turns out that during the comprehensive development and utilization of water resources of rivers, the emphasises should be placed on the development of hydraulic power generaion in association with water transportation and other aspects. Meanwhile, thermal power generation and land transportation should be jointly developed to promote the economic prosperity in the river-valley. In R-SD, we have also posed three degrees of satisfaction, which are guided to decide the development velocities and investment proportions of power generation, transportation, and water-supply.

1. PROBLEM

China is rich in water resources in its many rivers. Once developed, the water resources may benefit the people and serve the construction of the four modernizations. Water resources are regenerable and inexhaustible as soon as they are developed. one remarkable example is the Dujiangyan Irrigation Works which was constructed in 250 B.C. Up to now, it has been benefitting for more than 2200 years. On the contrary, the water resources will slip by in vain if they are not exploited. A river may be beneficial, they may do evil as well. Some rivers' flood and waterlogging calamities often cause tremendous losses of people's lives and properties, due to lack of appropriate harnessing and development. In Chinese history, the Yellow River and the Huaihe River were wellknown for inundation which caused disasters. Before the Dujiangyan Irrigation Works, the Minjiang River was also destructive.

Today, we have comprehensive contents in our discussion of the development of water resources. The following issues are included:

hydraulic electrogenerating, water trasportation, water-supply-and-consumption of industry and households, irrigation in agriculture, flood-control and waterlogged fields' draining, reservoir fishery, around-reservoir tourism and recreation facilities; meanwhile, thermal electrogenerating and land transportation should also be taken into consideration.

At present, most researchers at home and abroad adopt the optimization method of mathematical program in the study of water resources' development, laying particular emphasis on one aspect, such as hydraulic electrogenerating or problem of hydropower station sequence, many of which achieved practical effects (Li Mi-an, 1986). This paper studies the comprehensive development and utilization of water resources of rivers, by means of the method of System Dynamics (Forrester, 1968. Wang Qifan, 1986). Its model is called: R-SD (River-SD).

2. OBJECTIVES AND BOUNDARY OF THE SYSTEM

2.1 Objectives of the System

Our system is a river-valley economic system. R-SD deals with the following issues:

(1) The quantitative relationship between the total output value of industry and agriculture within the river-valley (TOIA) and the total investment in the comprehensive development and utilization of water resources (TIV).

(2) The proportion of investment in power, transportation, water-supply and flood-control (in terms of the total investment).

(3) The proportional relationship between the investments in hydropower and thermal power.

(4) The proportional relationship between the investments in water and land transportation.

(5) The rates of development of hydraulic electrogenerating, thermal electrogenerating, water transportation, land transportation, agro-irrigation, water-supply, etc.

(6) The amount of each investment and its sum within a historical period.

2.2 Subsystems

R-SD is composed of four blocks (subsystems): industry, agriculture, transportation and water-supply-consumption. The general relationship between them is shown in Figure 1. The total output value of industry (TOI) and that agriculture (TOA) decide the demand for transportation, while the capacity of transportation affects TOI remarkablly. TOI, agro-irrigation and the water-consumption of households decide the total consumption of water, while, water-supply affects TOA remarkablly. Other influences are relatively less, so they do not appear in Figure 1.

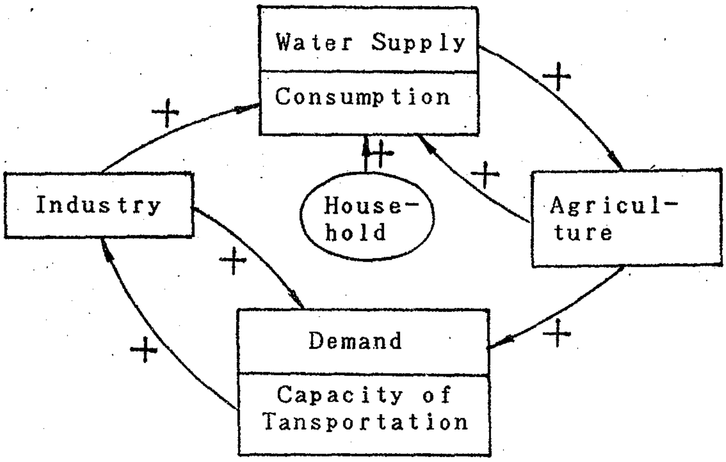

Figure 1. The General Relationships Between Subsystems

There are altogether ten level variables in the model of R-SD, their distribution is:four in industry block, two in agriculture, two in transportation, and other two are in water-supply-consumption block.

2.2.1 Industry Subsystem

Industry subsystem focuses on electricity generations, of which, hydraulic electrogeneration is a certain aspect to considered. Today world is faced with energy crisis. It is specially true to develop hydraulic electrogeneration in a river-valley, in which there is shortage in coal, oil and natural gas but is rich in water-power resource. Water resources can be developed stepwise: after generating electricity at upper reache, the water can be used for generating electricity for the second or more times at lower reaches of the river. The water devoted to electricity generation can still be used for irrigation or supplied to industry or households. Thermal power plants, however, burn coal or oil to generate electricity, the waste residue and gas left over in the process cause pollutions. Water resources are regeneratable, while, coal and oil are not, once burnt in generation, the nature's accumulations for millions upon millions of years will never return.

But, it is unwise only concentrate on hydraulic electrogenerating ignoring thermal. Both have their own weak and strong points. For instance, the construction period of thermal power plants is generally shorter than that of hydropower stations. (The construction period of a hydropower station can also be shortened provided constructs efficiently. For example, the Xin'anjiang Hydropower Station in Zhejiang Province of China was completed basically within three years in 1950s.) Thermal generators may run continuously for a year, with usual annual generating hours of more than 5000; hydraulic generators,however,have less,due to the influence of natural precipitation (large-and-medium-scale hydropower stations have annual generating hours of more than 4000, but small stations only have less than 2000). But hydropower generation can be realized instantaneously: electricity can be transmitted out a few minutes after opening the sluice; however, thermal electro-generating process takes as long as several hours from strengthening combustion to increasing power output. Therefore, hydropower stations should be appropriately matched by thermal power plants, making up each other's deficiencies, even though it is in a river-valley being rich in water-power resources.

There must be equal techno-economic conditions upon which the research of matching of hydropower and thermal power is done. A hydropower station possesses two major functions: store water and generate electricity.Storing water is to realize the exploitation and storage of the primary energy (water energy), electro-generaing is to transform the primary energy into secondary energy (electro-energy). While, a thermal power plant only realize the transformation of the primary energy (chemical energy in coal or oil) into secondary energy.The exploitation and storage and transmit of coal or oil are not involved in a thermal power plant's function. When comparing the two method of power generation, of course, rational conclusion can only be obtained when both the development of the primary energy and the transformation of the secondary energy are involved, that is to say, the exploitation and transportation cost of coal or oil (including the investments in expanding the capacities of coal or oil production and transportation, which are essential to a thermal power plant) should be added to the construction cost of a thermal power plant. Under such comparison, the per unit kilowatt investment ingenerator capacity is hardly any difference between the two.

In R-SD, we choose recoverable water energy reserves (WER), hydropower generator capacity (HPG) and thermal power generator capacity (TPG) as level variables.

Total power amount (TTPA), consisted of hydropower (HPA), thermal power and net power input from outside the system (NIA), is supplied to industry in a certain proportion. The product of industrial consumption of power (ICP) and output value per kilowatt-hour is designated as TOI1. The TOI1 will be the actual total output value of industry (TOI) if the system is supplied with insufficient power. The output value per kilowatt-hour is given as an increasing table function, for it will increase in pace with the improvment of product structure, the progress of productive techniques and the raising of managerial level. If there is a glut of power supply, it will be exaggerative to regard TOI1 as TOI. Therefore,R-SD takes it another way:designate the product of fixed assets of industry and its rate of output value as TOI2, and

A TOI3.K=MIN(TOI1.K,TOI2.K) (1)

A TOI.K=TOI3.K*MTRS.K (2)

in which, MTRS.K $\in$ (0,1), is a multiplier decided by the degree of transportation satisfaction (DTRS).

Fixed assets of industry (FAI) is chosen as a level variable too.

The degree of power consumption satisfaction (DPCS) is defined as follows:

A DPCS.K=MIN(1,TOI1.K/TOI2.K) (3)

in which, DPCS.K $\in$ (0,1), which decides the multiplier of the rate of power development. The less the value, the greater the rate of power development, by means of increasing power development.

2.2.2 Agriculture Subsystem

In agriculture subsystem, the irrigated area (IRA) and non-irrigated area (NIRA) are chosen as level variables. The grain yields per unit area of the two sorts of cultivated land are different. The sum of the two sorts of land's grain yields is the total grain yields (TGY). Then we obtain the value of TGY, which accounts for a certain proportion in the total output value of agriculture (TOA), thus obtaining TOA1. TOA is liable to the influence of degree of water supply satisfaction (DWSS), so

A TOA.K=TOA1.K*MWSS.K (4)

in which, MWSS.K $\in$ (0,1), is a multiplier decided by DWSS.

2.2.3 Transportation Subsystem

The "hydro-railway" river channels are the cheapest way of transportation. The unit cost of inland river transportation is one fifth that of railway and one twenty-fifth that of highway. Therefore, the development of water transportation is an important part of the comprehensive and utilization development of rivers.

Water transportation must develop with land transportation coordinatively. In China, railroad are programed, constructed and run by the central government department (in R-SD, we reguard it as an external variable.) The strong points of water transportation are: large freight volume, low cost; land transportation, however, has its strong points of high speed, flexibility and door-to-door service. Obviously, they are mutually complementary.

In transportation subsystem, land transportation capacity (LTRC) and water transportation capacity (1) (WTRC1) (formed under investment in water transportation) are chosen as level variables. Under rational program, hydropower development may bring about a great advance to water transportation. For example, after stepwise development of the Ganjiang River in Jianxi Province, the river opens to navigation to ships with tonnages each over 1000, as compared with before development, navigable tonnage is merely 50--100 in ordinary months, and a little better tonnage of 100-300 in flood season at the lower reaches from Ganzhou city in the province (Dai xichou, 1986). As for the Yangtze River, ships with tonnages each over 10,000 may be expected to reach the Chaotianmen Port, Chongqing, Sichuan Province, as soon as the Sanxia (Three Gorges) Engineering is developed. Therefore, WTRC1 should be multiplied by a multiplier decided by hydropower development (MHP), obtaining an actual water transportation capacity (WTRC):

A WTRC.K=WTRC1.K*MHP.K (5)

The total capacity of transportation (TTRC) consists of water, land and railroad transportation capacities, excluding air and pipeline transportation for the time being. The degree of transportation satisfaction (DTRS) is defined as:

A DTRS.K=MIN(1, TTRC.K/TRD.K) (6)

DTRS.K $\in$ (0, 1], in which, TRD.K is transportation demand. If DTRS.K is less one, TOI will be affected remarkablly, then R-SD will speed up the development of transportation capacity. In case the total capacity of transportation exceeds transportation demand, R-SD will restrict the development of transportation.

2.2.4 Water-Supply-and-Consumption Subsystem

In water-supply-and-consumption subsystem, we choose potential groundwater reserves (PGW) and its exploitation(EGW) as level variables. Totalwater-supply(TWS) is composed of three parts: water intakes from rivers, lakes and ponds(WRLP), from reservoirs (WRS) and from groundwater drawing(WGD) which is to replenish the forementioned two parts. Total water-consumption(TWC) is also composed of three parts: water for agro-irrigation(WAC), for industry(WIC) and for households (WHC). The degree of water-supply satisfaction (DWSS) is defined as follows:

A DWSS.K=MIN(1, TWS.K/TWC.K) (7)

DWSS.K $\in$ (0, 1], which will affect TOA if it is less than one. Then, R-SD will increase the investment in exploitation of watersources. In case TWS exceeds TWC, R-SD will restrict the investment.

3. COUPLING BETWEEN SUBSYSTEMS, AND THE SYSTEM FLOWCHART

In R-SD, subsystems are coupled closely, and hydropower development plays the role of the core. System Dynamics fits right for studying such a nonlinear system with multivariables and a complicated structure of cause-and-effect chains, especially for the research of long term development program in overall amounts (Wu Jianzhong, 1986).

3.1 The Constitution and Allocation of the Total Investment

The constitution of total investment (TIV) demanded by the development of water resources of a river is shown in Figure 2. In which, the flood-control cost (FCC) is the sum of urban flood-cotrol cost and agro-flood-control cost. The development of hydropower may increase the ability of flood-control, thus cutting down on FCC. The investment in each part is decided by the rate of its development.

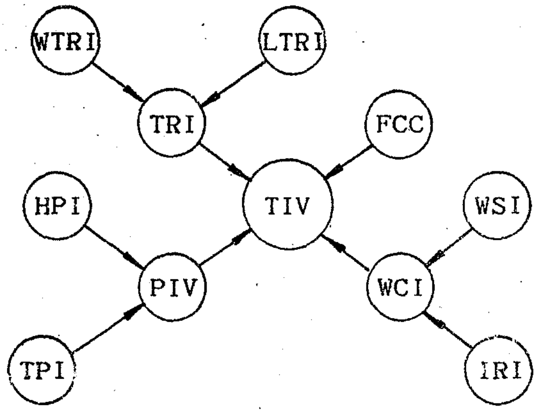

Figure 2. The Total Investment

All arrows drawn in Figure 2 can be simultaneously reversed, then it shows how TIV on hand is allocated.

The sources of TIV includes:self-raised funds by local government (SRF) (depending upon the development of industrial and agricultural production in the regions), central government investment (CGI), external investments (EXI) (from abroad or other provinces), other funds (OTF) (such as raised funds in society)

3.2 Multi-benefits Brought about by Hydropower Development

The development of hydropower may bring about multiple economic and ecological benefits, as is shown in Figure 3.

After the stepwise development of a river and constructing large reservoirs at upper and middle reaches, the distribution of runoff inner-year or even inter-years may be adjusted effectively, thus enabling water-supply balanced, and ensuring water-supply in dry season.

The flood-control and waterlogging-draining capacity may increase at middle and lower reaches as large reservoirs retain huge amounts of floods.

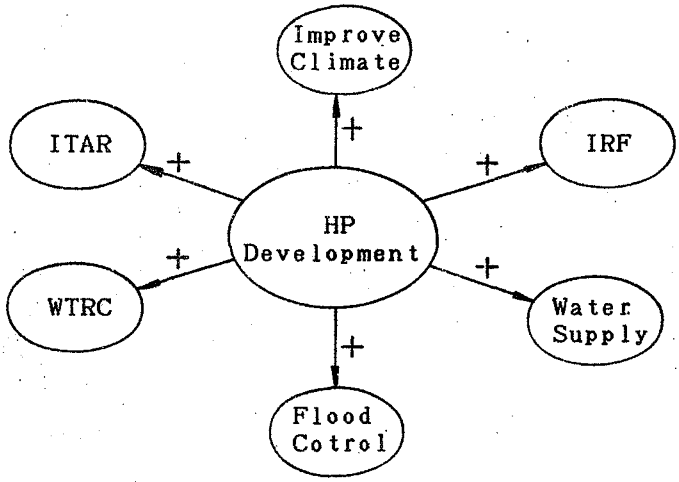

Figure 3. The Multiple Economic and Ecological Benefits by Development of Hydropower

Following hydropower development, reservoir fishery may be develop for improving people's life. Large reservoirs may improve partial and local microclimates, thus being advantageous for planting and the growth of forests and fruits. Moreover, it booms around-reservoir tourism and recreation. For instance, the Xin'anjiang Reservoir has become wellknown as Qiandaohu (a lake with a thousand islands) scenic spot, which received four hundred thousand person-time of tourists in 1983, and tourists keep coming to make tourism income of the reservoir to be second only to electricity sales income (Su Yunhua, 1986). In addition, a good economic circle may be expected: sufficient hydropower supply -- much benefits -- more sufficient hytropower supply -- more and more benefits ... , provided we carry out the policies of " benefit the investors " and " hydropower stations support themselves ". For instance, we may invest the incomes from reservoir fishery (IRF) and around-reservoir tourism and recreation (ITR) into hydropower development. We may also draw partial investment of the water-transportation and water-supply and put them into hydropower development.

R-SD studies in details the relationships between electrogenerating and transportation and that between electrogenerating and water-supply.

3.2.1 The Relationship Between Electrogenerating and Transportion

If we concentrate only on developing hydropower while neglecting water transportion, then dam will hinder or cut out navigation. So we should build ship locks and open logways when developing hydropower to promote water transportation. Since channels are deepened in stepwise development, the annual rate of navigation may be increased.

As is mentioned above, thermal power plants should also be constructed. Because of the heavy demand for fuel transportation, thermal power development will increase the pressure on present transportation networks and reduce the degree of transportation satisfaction. Then we have to increase the investment in transportation to expand its capacity if it saturates.

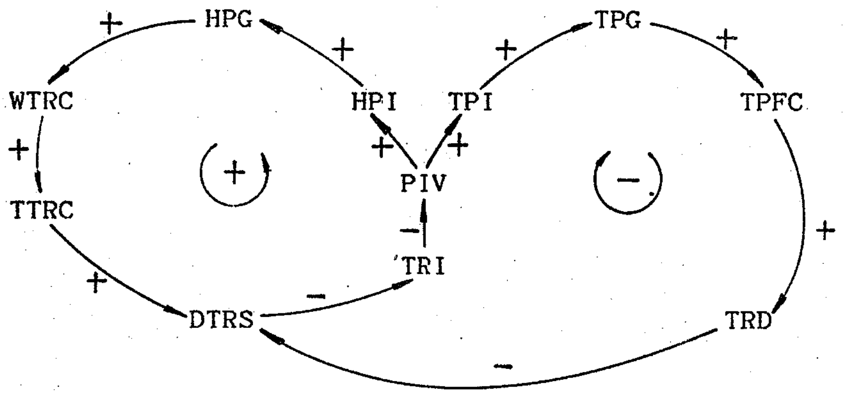

Figure 4. The Relationship Between Electro-generating and Transportation

Figure 4 shows us the relationships between hydraulic electrogenerating, thermal electrogenerating and transportation. The loop involved hydraulic electrogenerating is shown as a positive cause-and-effect chain in the left, while, the loop involved thermal electrogenerating is shown as a negtive chain in the right.

3.2.2 The Relationshp Between Power Generating and Water-Supply-Consumption

The relationship between power generating and water-supply-consumption is shown in Figure 5.

On the one hand, developing hydropower may increase the degree of water-supply satisfaction, so it is positive cause-and-effct chain, on the other hand, because developing hydropower and thermal power both will providemore electricity fir industry to increase TOI, thus increasing industrial consumption of water, so there emerges two negtive cause-and-effect chains.

3.3 System Flowchart

System flowchart is shown in Figure 6. The coefficients in the figure are mostly variables and are given as table functions in the process of simulation. They are simplified and are shown as small circles in the figure.

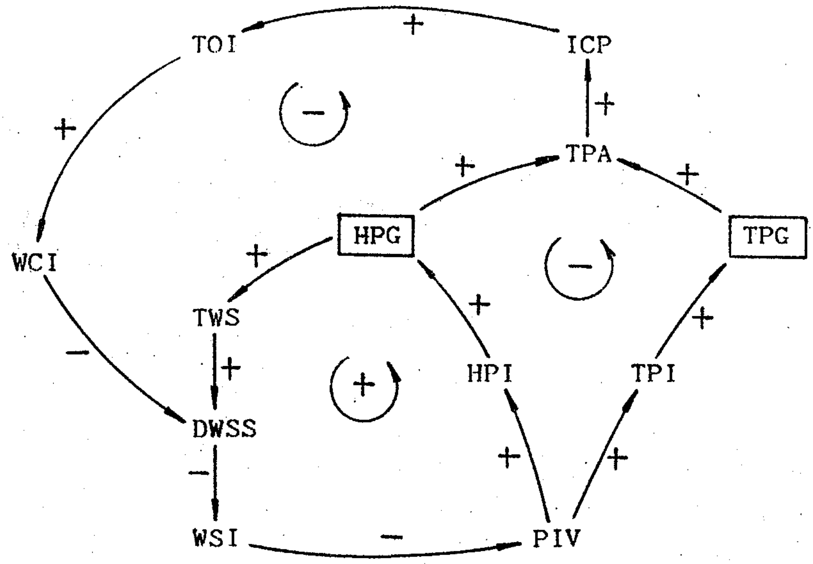

Figure 5. The Relationship Between Power Generating and Water-Supply-Consumption

The flowchart can be redraw another form having a few differents with the former, by reversing several arrows. The former determines easily the development velocities of electricity, transportation and water-supply by their investments, but the later determines easily the development investments by that development velocities respectively.

4. SYSTEM SIMULATION

In accordance with Figure 6, we compiled the programs in DYNAMO language, utilizing Micro-DYNAMO software, then may conduct system simulation in a IBM PC/XT. We call Figure 6 with its program R-SD (1), and the another version of Figure 6 with its program R-SD(2). Both R-SD(1) and (2) combine into the Model R-SD.

4.1 R-SD(1) and R-SD(2)

In R-SD(1), suppose the velocities of development are given, then we can work out a lot of alternatives for the development, and conduct system simulations to evaluate a series of investment proportions: the proportions of investment in power (PIP), transportation (PITR), irrigation and conservancy (PIIC) and in hydropower (PIHP), thermal power (PITP), water transportation (PIWTR), land transportation (PILTR), water-supply development (PIWS), etc. The supposed velocities of development are only bases which will be revised in the processes of simulation in accordance with the degrees of satisfaction of electro-consumption (DECS), transportation (DTRS) and water-supply (DWSS).

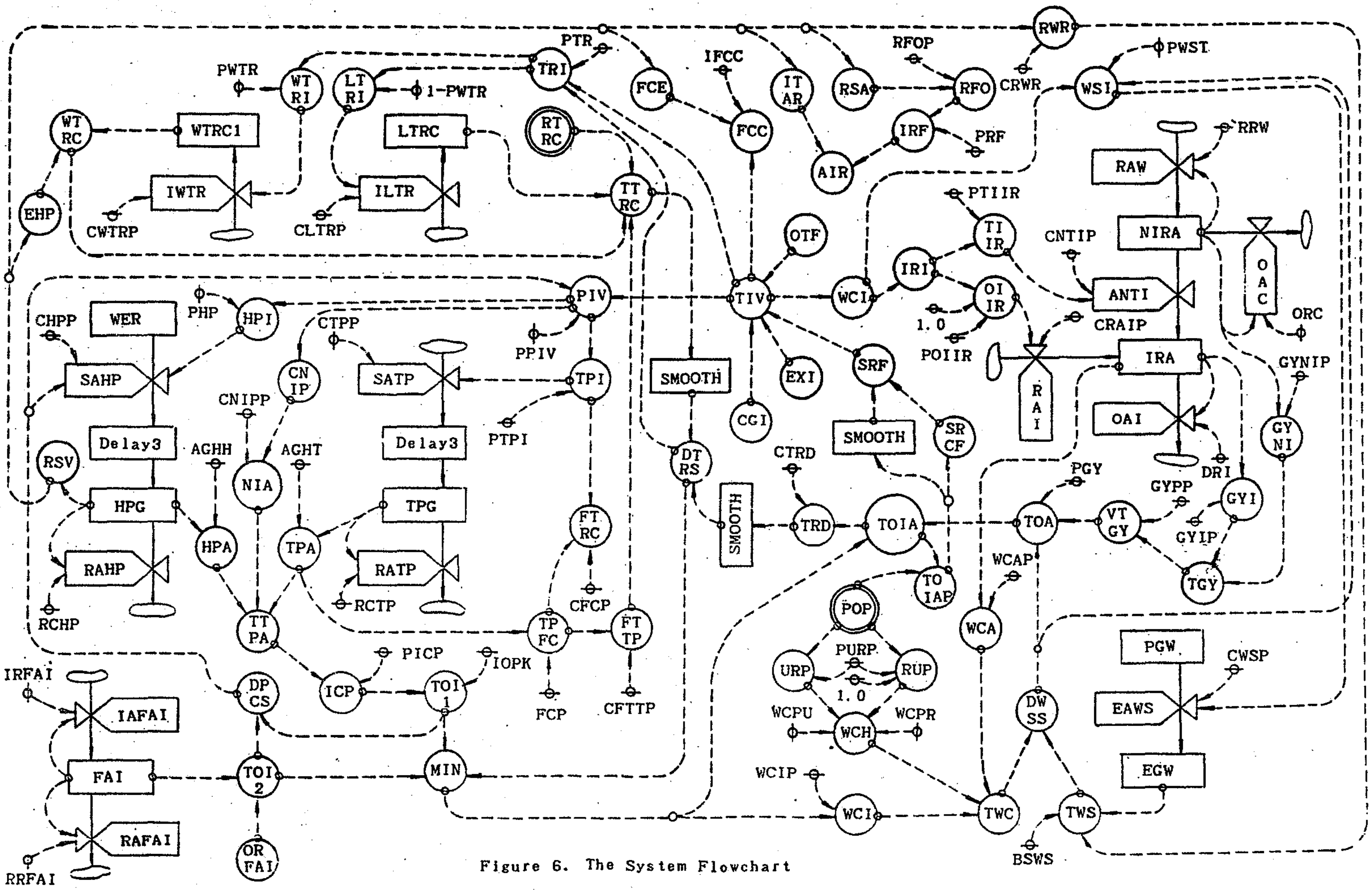

Figure 6. The System Flowchart

In R-SD(2), suppose the proportions of investment are given, we can work out a lot of alternatives for investment, and conduct system simulations to evaluate a series of velocities of development: the growth rates of hydropower (RHP), thermal power (RTP), water transportation (RWTR), land transportation (RLTR), water-supply (RWS), irrigated area (RIA), etc. The supposed proportions of investment are only bases too, which will be revised in the processes of simulation in accordance with DECS, DTRS, DWSS.

The results from simulation in R-SD(1) and (2) may refer to and be adjusted by each other, thus obtaining some satisfactory plans to solve the problems raised in Section 2.1.

4.2 Case Study

A case study has been made on a river within the boundaries of a province, utilizing R-SD. The result shows that:

(1) Priority should be given to the development of hydropower, bringing along water transportation, irrigation, water-supply and flood-control. The results of the simulation about TOIA under three basic supposed rates of development for hydraulic and thermal power are shown in Figure 7. There are three alternatives: to develop thermal power with a equal rate to hydropower (its TOIA is noted by *); to develop hydropower prior to thermal power (its TOIA, i.e. TOIAH, is noted by H); and to develop thermal power prior to hydropower (its TOIA, i.e. TOIAT, is noted by T). Obviously, we may conclude that we have to give priority to the development of the hydraulic power generation. Figure 8 shows three curves of degree of satisfaction of Alternative H.

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         20.00B       42.50B        65.00B        87.50B       110.00B *HT
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1990.0 - - - - - - - - *H- - - - - - - - - - - - - - - - - - - - - *T
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Figure 7. The TOIA of Three Alternatives

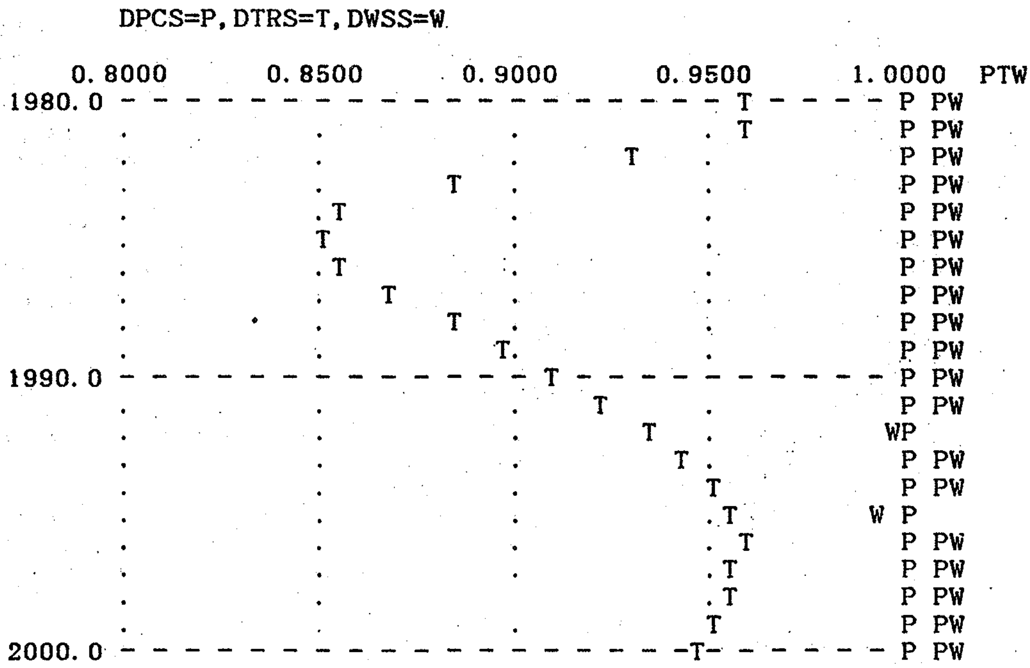

Figure 8. The Degrees of Satisfaction of Alternative H

(2) To develop thermal power properly and in cooperation with hydropower to solve the problem of insufficient power-supply in the river-valley.

(3) To develop land transportation properly and in cooperation with water transportation to solve the problem of heavy transportation in the river-valley.

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APPENDIX: NAMES OF VARIABLES AND COEFFICIENTS

HP	Hydraulic Power
TP	Thermal Power
WTR	Water Transportation
LTR	Land Transportation

AGHH	Annual Generating Hours of HP
AGHT	Annual Generators of HT
AIR	Added Incomes of Reservoir
ANTI	Transformed Area from NIRA to IRA
BSWS	Base of Surface-Water-Supply
BUWS	Base of Underground-Water-Supply
CFCP	Coefficient of FCP
CFTTP	Coefficient of FTTP
CGI	Central Government Investment
CHPP	Cost of HP per Unit
CLTRP	Cost per Unit LTRC
CNIP	Cost of Net Input Power
CNIPP	Cost of Net Input Power per Unit
CNTIP	Cost per Unit ANTI
CRAIP	Cost per Unit RAI
CRAWP	Opened up Cost per Unit NIRA
CSRF	Coefficient of SRF
CTIIRP	Cost of TIIR per Unit
CTPP	Cost of TP per Unit
CTRD	Coefficient of TRD
DTRS	Degree of Transportation Satisfaction
CWSP	Cost Water-Supply per Unit
CWTRP	Cost per Unit WTRC
DPCS	Degree of Power Consumption Satisfaction
DWSS	Degree of Water-Supply Satisfaction
EAWS	Exploited Amount of Water-Supply
EGW	Exploited Groundwater Reserves
EXI	External Investment
FAI	Fixed Assets of Industry
FCC	Flood-Control Cost
FCE	Flood-Cotrol Effectiveness
FCP	Fuel Consumption per Unit Power
FTRC	Fuel Transportation Cost
FTTP	Fuel Transportation of TP
GYI	Grain Yield of Irridation
GYIP	Grain Yield per Unit IRA
GYNI	Grain Yield of Non-Irrigation
GYNIP	Grain Yield per Unit NIRA
GYPP	Grain Yield Price per Unit
HIV	HP Investment
HPA	HP Amount
HPG	HP Generators
IAFAI	Increased Amount of FAI
IFCC	Initial FCC
ILTR	Increased Amount of LTR
IOPK	Industrial Output Value per Kilowatt-Hour
IRA	Irrigation Area
IRF	Income from Reservoir Fishery

IRFAI	Increased Rate OF FAI
IRIV	Irrigation Investment
ITAR	Income from Around-Reservoir Tourism and Recreation
IWTR	Increased Amount of WTR
ICP	Industrial Consumption of Power
LTRC	LTR Capacity
LTRI	LTR Investment
NIA	Net Power from Outsite
NIRA	Non-Irrigation Area
OAC	Occupied Area of Cultivation
OAI	Occupied Area of Irrigation
OIIR	Opened Up Investment of Irrigation
ORC	Occupied Rate of Cultivation
ORFAI	Output Value Rate of FAI
ORI	Occupied Rate of Irrigation
OTF	Other Funds
PGY	Proportion of Grain Yield
PGW	Potential Groundwater Reserves
PHP	Proportion of HP
PICP	Proportion of ICP
PIV	Power Investment
POIIR	Proportion of OIIR
POP	Population
PPIV	Proportion of PIV
PRF	Price of Unit Fish Output
PTIIR	Proportion of TIIR
PTPI	Proportion of TPI
PTR	Proportion of TRI
PURP	Proportion of URP
PWSI	Proportion of WSI
PWTR	Proportuon of WTR
RAFAI	Retired Amount of FAI
RAHP	Retired Amount of HP
RAI	Reclaimed Area of Irrigation
RATP	Retired Amount of TP
RAW	Reclaimed Area of Wastaland
RCHP	Retired Coefficient of HP
RCTP	Retired Coefficient of TP
RFO	Reservoir Fish Output
RFOP	Fish Output per Unit RSA
RRFAI	Retired Rate of FAI
RRW	Reclaimed Rate of Wasteland
RSV	Reservoir Volume
RSA	Reservoir Area
RTRC	Railway Transportation Capacity
RUP	Rural POP
RWR	Retained Water of Reservoir
SAHP	Started Amount of HP
SATP	Started Amount of TP
SRF	Self-Raised Funds by Local Governments
TOI	Total Output Value of Industry
TPA	TP Amount
TPFC	Fuel Consumption of TP
TPG	TP Generators
TPI	TP Investment

TRI	TR Investment
TRD	Transportation Demand
TGY	Total Grain Yield
TOA	Total Output Value of Agriculture
TOIAP	TOIA per Person
TIIR	Transformed Investment of Non-Irrigation to Irrigation
TPIR	Transformed Proportion of Non-Irrigation to Irrigation
TTPA	Total Power Amount
TTRC	Total Capacity of Transportation
TWC	Total Water-Consumption
TWS	Total Water-Supply
URP	Urban POP
VTGY	Value of TGY
WCA	Water-Consumption of Agri-Irrigation
WCAP	Water-Consumptio per Unit IRA
WCH	Water-Consumption of Households
WCI	Water-Consumption of Industry
WCIP	Water-Consumption per Unit TOI
WCPR	Water-Consumption per RUP
WCPU	Water-Consumption per URP
WCIV	Water-Conservancy Investment
WER	Water Energy Reserves
WSI	Water-Supply Investment
WTRC	WTR Capacity
WTRI	WTR Investment