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Human Impact on Yellow River Water Management

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Contents

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HUMAN IMPACT ON YELLOW RIVER WATER MANAGEMENT

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1. Water management issues in the Yellow River catchment

The Yellow River is the second largest river in China. It originates in the Northern foothills of the Tibetan Plateau, and empties into the Bay of Pohai. The river length is 5,460 km, and the catchment area is above 750,000 km^2 (Cheng Xeumin, 1980). Most of the basin's area is arid or semi-arid. The control and development of the Yellow River agricultural development in the area. Both land and water availability are severe constraints to expanding the agriculture productivity in the North China Plain. The control of floods and sedimentation seems to be the dominant problem in the lower reach of the Yellow River.

Water may become a barrier to sustainable development of a region under consideration due to several mutually dependent factors, such as:

- Water scarcity depending on the relation between water supply and demand,
- Pollution of rivers, lakes and groundwater aquifers,
- Technological and economic shortcomings,
- Institutional impediments and low public awareness.

All these problems are present in the Yellow River basin. The aim of this study was to analyze the possible impact of various aspects of human activities on water resources in the Yellow River basin. Most of them are directly related to the catchment itself, as e.g. significant increase of irrigation in recent decades, and construction of a number of storage reservoirs changing the temporal pattern of river flow. Some may be, however, a result of global geophysical processes.

Climate change impact assessment of the Yellow River water resources was undertaken in the framework of this study with the understanding that the main indicators of water economy, projected over the next decades, will be influenced not only by climate, but first of all by the population and economic growth, and technological progress. Some of these factors are quite removed from physical processes, and are subject to policy decisions which, if rationally applied, may also help to adapt water resources systems to non-stationarities of geophysical processes.

2. Climate and climate change in the Yellow River basin

Climatological and hydrological baseline data used in the Yellow River study are based on:

(a) global climatic data sets extracted from the FAOCLIM CD-ROM of the U.N. Food and Agriculture Organization,

(b) discharge data provided by the Global Runoff Data Centre in Koblenz (Germany),

(c) various published sources on water resources in Asia.

Methodological approaches of transferring climatic forcing to water balance characteristics vary widely. The key input variables to most of the hydrologic models are catchment precipitation P and potential evapotranspiration PET, the latter being calculated from other meteorological variables, e.g. the air temperature.

Because of a limited access to data, the Thornthwaite (Thornthwaite, 1948) method was used in this study, according to which PET was calculated based on air temperature only. Potential evapotranspiration [mm/month] for *i-th* months is:

$$PET_i = 0.198\left(10\frac{T_i}{IND}\right)^{\alpha} \arccos\left[\tan(\varphi)*\tan(\delta)\right], \tag{1}$$

where:

$$IND = \sum_{i=1}^{12}\left[\frac{T_i}{5}\right]^{1.514}, \tag{2}$$

$$\alpha = 0.492 + 0.0179 IND - 0.0000771 IND^2 + 0.000000675 IND^3, \tag{3}$$

$$\delta = \arccos\left[-\tan(\phi)*\tan(-19.7 - 7.75*i + 7.50*i^2 - 1.102*i^3 + 0.0441*i^4)\right]. \tag{4}$$

Φ means the station latitude expressed in degrees. Calculations were implemented for separate months, and then averaged for the whole period of observations.

Average yearly sums of observed rainfall and calculated potential evapotranspiration for a number of climatic stations located in the Yellow River catchment are given in Table 1. These data show considerable differences among stations distributed throughout the catchment. As could be expected the largest precipitation values are observed in the southern part of the Yellow River basin.

STATION	FAO symbol	LONGITUDE (East)	LATITUDE (North)	P mm/year	PET mm/year
HOHTOT	CN01HHHT	111.86	40.82	424	660
BAYAN-MOD	CN04BYNM	104.50	40.75	79	705
HALIUT	CN18HLT0	108.52	41.57	183	645
WANYUAN	CN28WNYN	108.02	32.04	1127	866
ZHUMADIAN	CN34ZHMD	114.01	33.00	923	930
ZHENGZHOU	CN43ZHNG	113.39	34.34	662	921
XI'AN	CN48XN00	108.56	34.18	610	862
TONGDE	CN50TNGD	100.39	35.16	422	444
YUNCHENG	CN51YNCH	111.01	35.02	553	901
PINGLIANG	CN56PNGL	106.40	35.33	580	664
LANZHOU	CN631NZH	103.53	36.03	340	705
DULAN	CN68DLN0	98.06	36.18	187	500
YAN AN	CN69YNN0	109.30	36.36	564	713
TAIYUAN	CN72TYN0	112.33	37.47	524	732
SHIJIAZHUANG	CN84SHJZ	114.25	38.02	599	889
YINCHUAN	CN86YNCH	106.13	38.29	192	717
YULIN	CN89YLN0	109.42	38.14	441	705
JIUQUAN	CN98JQN0	98.29	39.46	87	669

Table 1. Yearly precipitation and potential evapotranspiratiom for selected locations

Spatial distribution of *P* and *PET* are shown in Fig. 1 and Fig. 2, while the monthly distribution of these climatic characteristics is presented in Fig. 3 and Fig. 4. It can be seen that most of the rain appears during the monsoon period, mainly in July and August. As could be expected, also the maximum potential evapotranspiration is observed in summer months.

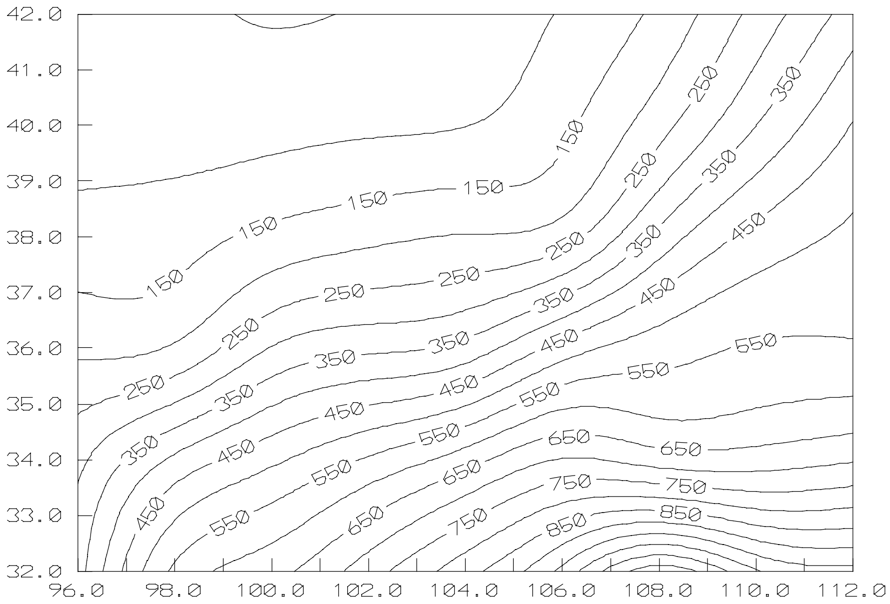

Fig. 1. Spatial distribution of rainfall [mm/year] over Yellow River catchment

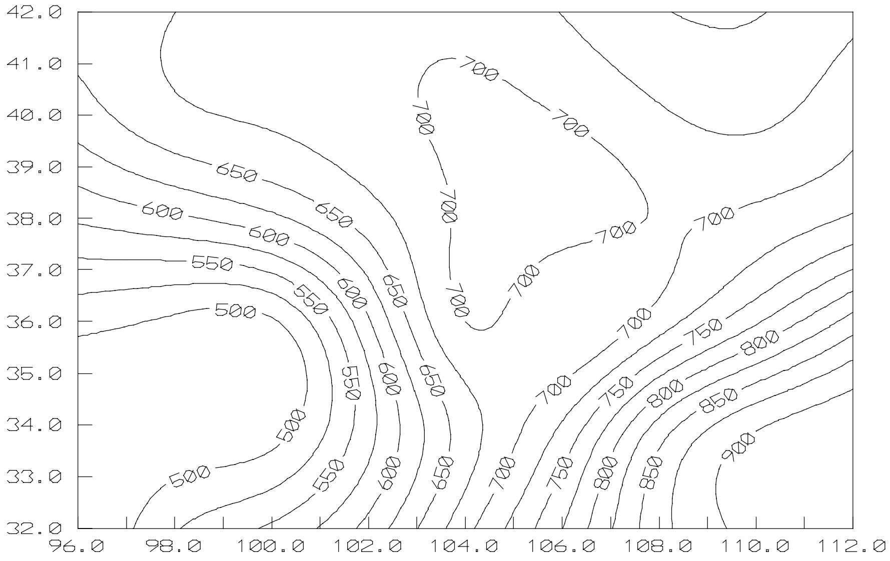

Fig. 2. Spatial distribution of *PET* [mm/year] over Yellow River catchment

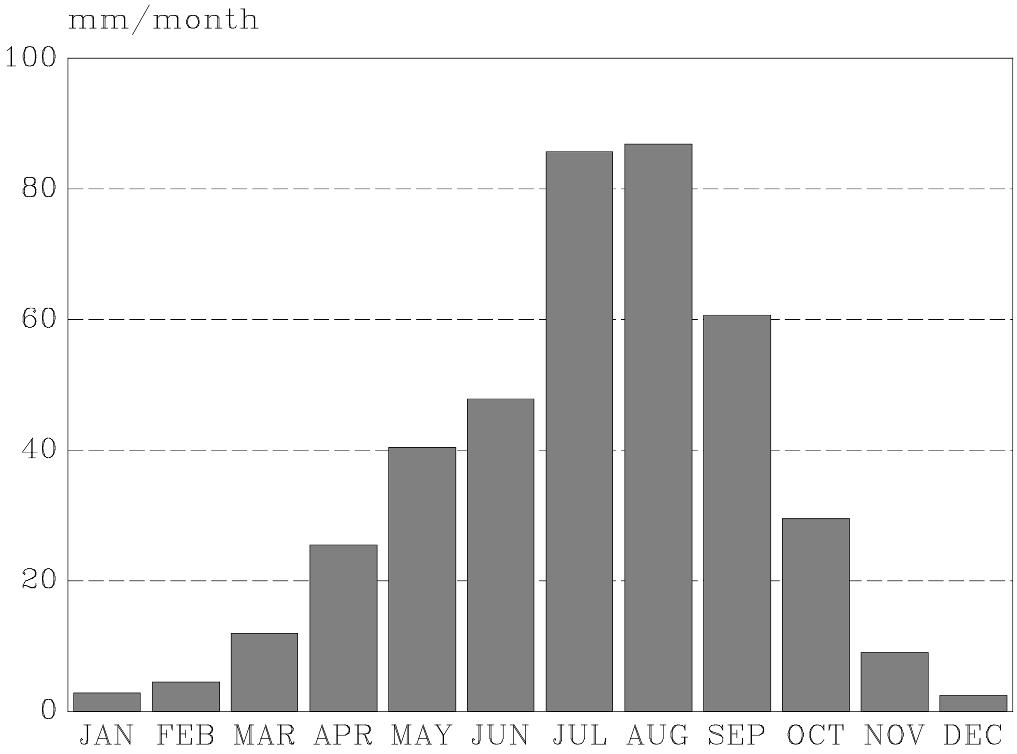

Fig. 3. Average monthly precipitation in the Yellow River basin

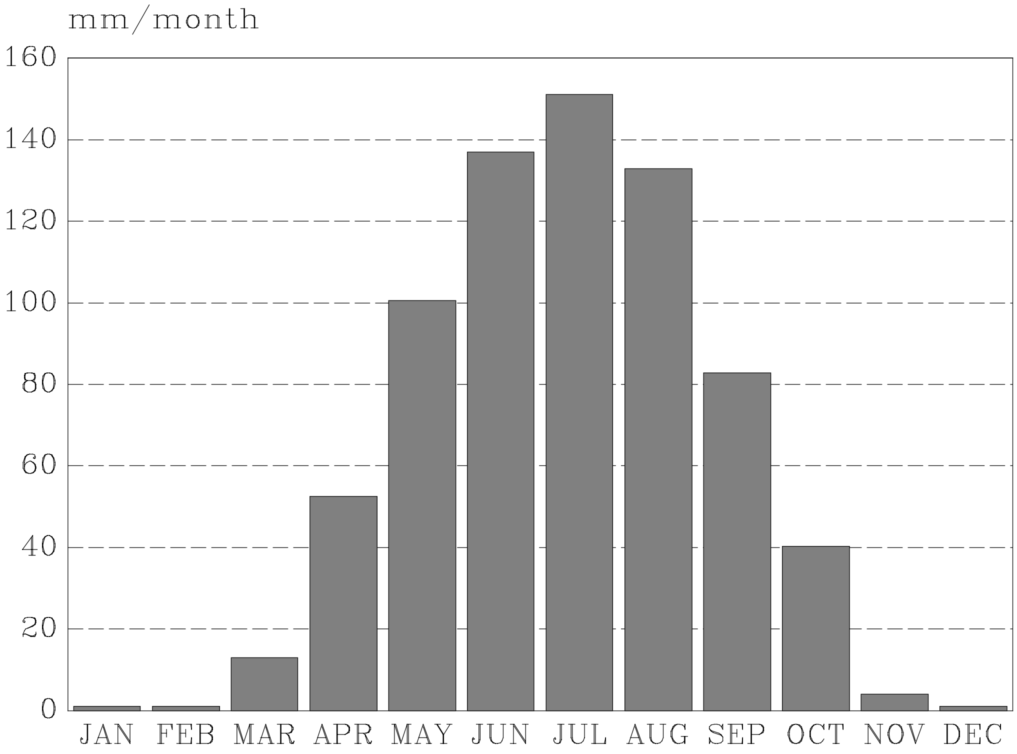

Fig. 4. Average monthly potential evapotranspiration in the Yellow River basin

Possible temperature and precipitation changes in the Yellow River catchment were assessed based on three transient Atmospheric Global Circulation Models (GCMs), developed by:

Geophysical Fluid Dynamic Laboratory, U.S.A. (Scenario GFTR),
Hadley Centre, U.K. (Scenario HCTR),
Max-Planck Institute for Meteorology, Germany. (Scenario MPTR).

Scenarios of temperature increments ΔT and precipitation changes (ratio values) r_P, as predicted by the above models for the middle of next century in the Yellow River basin, are shown in Fig. 5 and Fig. 6. Relatively large discrepancies among scenarios may be observed, particularly in case of precipitation.

There are difficulties in applying GCMs scenarios as inputs in hydrological impact studies. Firstly, the spatial scale of current global atmospheric models is much coarser than required for water resources analysis. Secondly, regional climate estimates, particularly in case of rainfall, are very uncertain. Therefore, for the water resources impact study several - all feasible - climate scenarios should be used, in order to assess the possible range of water supply and demand implications. The usual procedure is to assess "disturbed" climatic condition by adding expected differences ΔT to "historical" temperature data. Similarly, current precipitation data are multiplied by the ratios rP of GCMs precipitation for future and control climates.

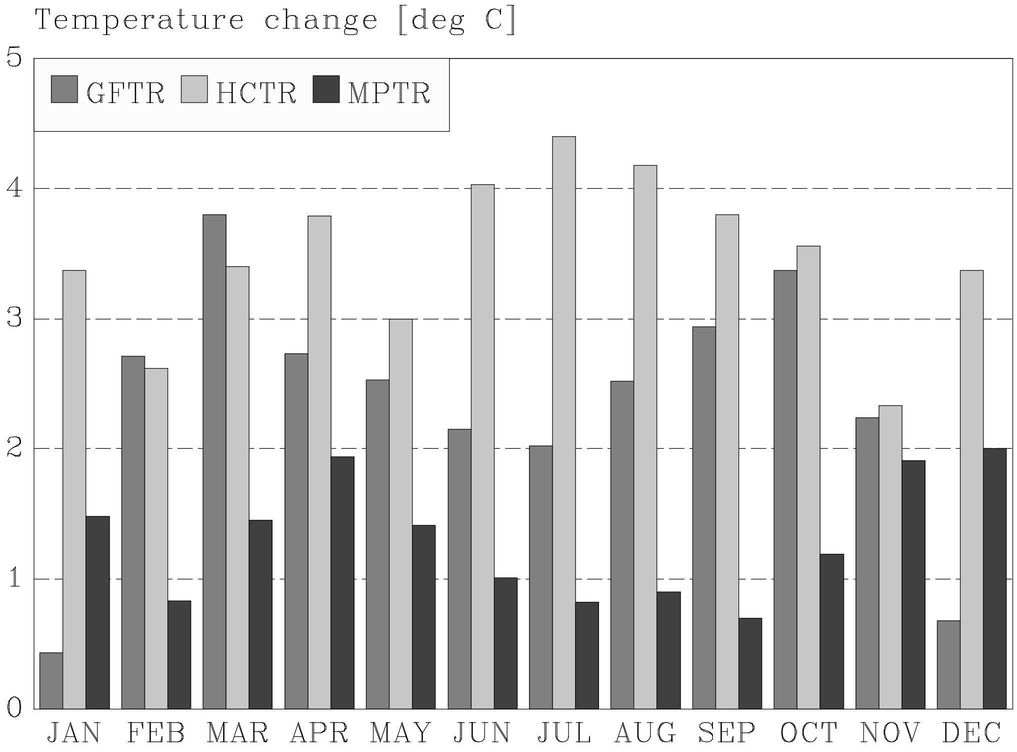

Fig. 5. Temperature change scenarios for the Yellow River catchment

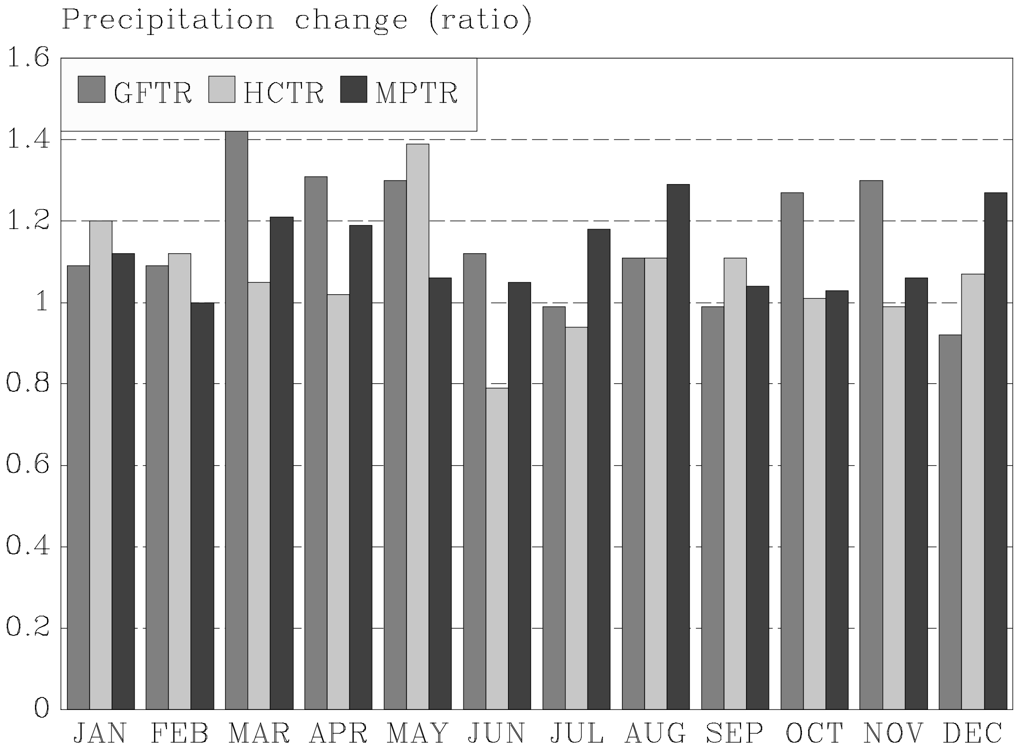

Fig. 6. Precipitation change scenarios for the Yellow River catchment

3. Water supply in the Yellow River system

The Yellow River water resources are scarce and unevenly distributed in time and space. The average runoff is about 60 mm/year, i.e. much less then flowing from river catchments in Southern China. The upper part of the basin (above gauging station Lanzhou) "produces" runoff of more than 140 mm/year, much more than the densely populated middle and lower parts of basin with the runoff equal only to 30 mm/year. Systematic hydrological records on the Yellow River are available from year 1919, but to evaluate observed data the impact of human activities, predominantly the diversion of water for irrigation, must be taken into account. According to some sources (Cheng Xeumin, 1980) the diversion of water has increased markedly in the last 30 years, reaching $16.5*10^9$ m^3 water used in agriculture. Fig. 7 shows average annual discharges of Yellow River at Sanmenxia (catchment area of 688,400 km^2) in years 1921-1988. Analyzing data presented in Fig. 7, a decreasing trend in mean annual discharges may be noticed starting from the year 1960. In order to clarify a possible ground for such tendency, runoff coefficients *R/P* were calculated for the last 45 years. Results shown in Fig. 8 confirm the decreasing trend, what means that for the same amount of annual precipitation less water reaches the river. This phenomenon is probably caused by various forms of human activities in the catchment.

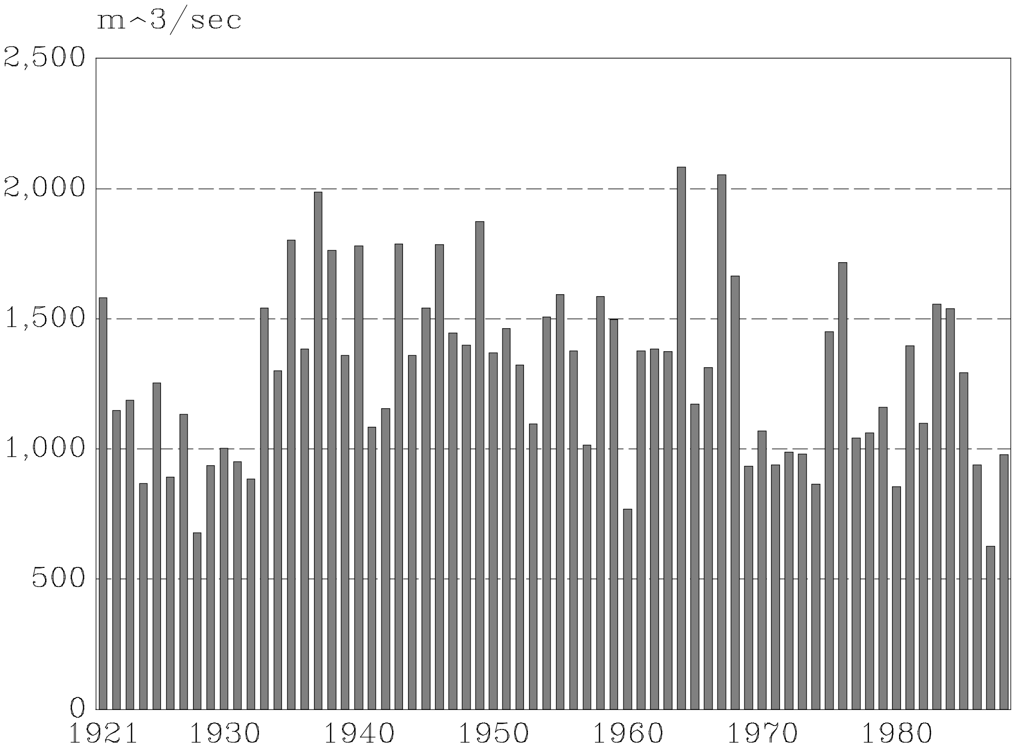

Fig. 7. Annual discharges of the Yellow River at Sanmenxia

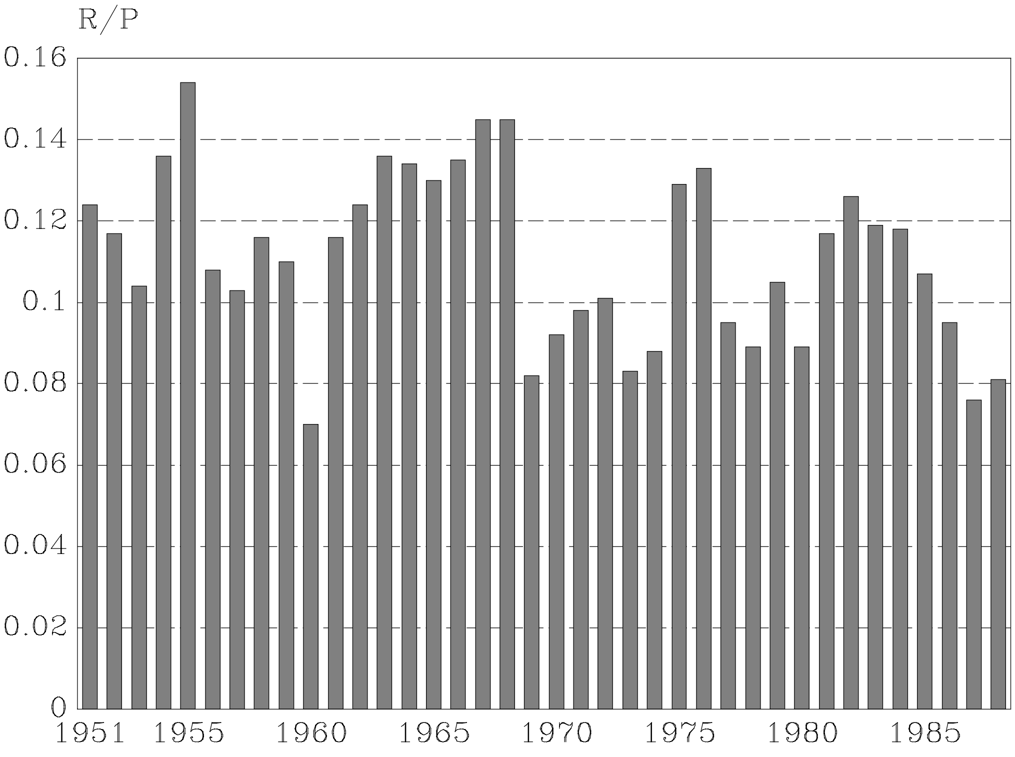

Fig. 8. Runoff coefficients of the Yellow River at Sanmenxia

Fig. 9 shows monthly discharges for two sub-periods of observations, clearly exhibiting differences in flow patterns, what can be explained by water diversions and as a result of operation of storage reservoirs. It should be noticed that the total storage capacity of more than 130 reservoirs in the basin above Sanmenxia gauging station is about $13.1*10^9$ m^3, i.e. 31 per cent of the average yearly runoff of the river.

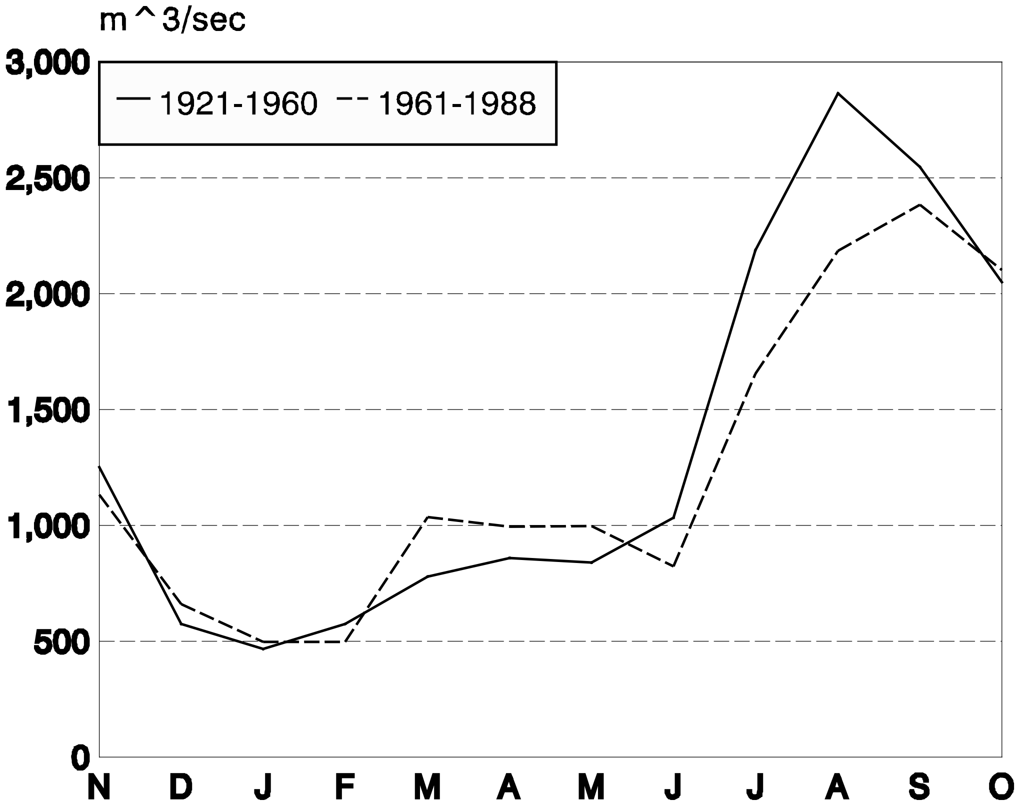

Fig. 9. Mean monthly discharges of the Yellow River at Sanmenxia

To assess the impact of climate on water resources, models linking the climatic and hydrological processes must be applied. There is a possibility of implementing a range of analytical approaches, from simple empirical relationships to complex conceptual models based on simplified representation of the processes involved in the hydrological cycle. Hydrological models usually include certain number of parameters which need to be identified by means of a calibration procedure, or estimated from empirical relationships with measurable catchment properties.

Authors of most of the climate change impact assessment studies applied conceptual hydrologic models, for which the important assumption is that the calibration done for current climatic conditions remains appropriate for the changed climate. Although such approach has been strongly criticized by some scientists, the effect of this assumption can be, at least partly, evaluated by examining the performance of the models during periods of extreme meteorological phenomena. It may be possible to evaluate how a particular model parameters might change (e.g. those reflecting vegetation cover), but very few studies have so far attempted this. The physical background of some conceptual models (e.g.the mass conservation law) is an argument for concluding that their implied sensitivity to climate change is not as much dependent on current climatic conditions for which the models are calibrated, as in case of purely empirical (black box) methods.

Time series of monthly values of catchment water storage, river runoff and actual evapotranspiration were simulated in the Yellow River basin and for the current climatic conditions and for assumed climate scenarios, by means of a conceptual hydrological model CLIRUN-3 (Kaczmarek, 1994). The model was extensively tested for a number of rivers in Poland as well as in other countries, and was recommended as an climate impact assessment tool by the U.S. Country Studies Programme. It is based on monthly-step water balance equation:

$$S_{\max}\frac{dz}{dt} = P - R_s - R_g - R_b - E \qquad (5)$$

where $z = S/S_{max}$, S_{max} is the total catchment capacity, $R_s(z,P)$ - immediate (surface and subsurface) runoff, $R_g(z)$ - delayed runoff, R_b - base flow, and $E(z,PET)$ - evapotranspiration. Substituting the above functional relationships into equation (2), one obtains after integration:

$$\int_{z_o}^{z_t} \frac{dz}{\Phi(z,P,PET,R_b)} = \frac{t}{S_{\max}} \qquad (6)$$

In case of CLIRUN_3.1 version of the model, water balance components are conceptualized as follows:

$$\begin{gathered} R_s = \varphi_1(z,P) = \frac{\varepsilon P}{1+\varepsilon-z}; \quad R_g = \varphi_2(z) = \alpha z^2; \quad E = \varphi_3(z,PET) = \frac{PET}{3}(5z-2z^2); \\ \Phi(z,P,PET,R_b) = \frac{(1-z^{\mu})P}{1+\varepsilon-z^{\mu}} - z^2\left[\alpha - \frac{2}{3}PET\right] - \frac{5}{3}zPET - R_b \end{gathered} \qquad (7)$$

Solving equation (6) for given z_o, precipitation P, potential evapotranspiration PET, and the base flow one gets:

$$z_t = \phi(z_o,P,PET,R_b,S_{\max},t) \qquad (8)$$

(for next time interval z_t becomes z_o). Average values of water balance variables for the time interval <0, t> may be then calculated by means of a formula:

$$\overline{\varphi_i}(..) = \frac{1}{t}\int_0^t \varphi_i(..)\,dt \tag{9}$$

or after replacing *dt* by *dz*:

$$dt = S_{\max}\frac{dz}{\Phi(z,P,PET,R_b)} \tag{10}$$

one finally gets:

$$\overline{\varphi_i}(..) = \frac{S_{\max}}{t}\int_{z_o}^{z_t}\frac{\varphi_i(..)}{\Phi(z,P,PET,R_b)}dz \tag{11}$$

For example:

$$\overline{R_s} = \frac{S_{\max}}{t}\int_{z_o}^{z_t}\frac{\varphi_1(z,P)}{\Phi(z,P,PET,R_b)}dz \tag{12}$$

In order to implement the CLIRUN model, input data should contain time series of monthly values of precipitation and potential evapotranspiration for the baseline period, as well as time series calculated for changed climatic conditions, as e.g. predicted by the three models described above. Identification of CLIRUN parameters for the Yellow River was based on data from the period 1961-1970. Mean monthly values of *PET* were estimated by the Thornthwaite method. To assess an impact of snow accumulation and snow melting on catchment precipitation, *P* values for winter were transformed based on the mean monthly air temperature. Mean monthly runoff of the Yellow River at Sanmenxia gauging station was used in a calibration procedure.

The calibrated hydrologic model was applied with an input vector based on the observed data, and later on input data calculated for "disturbed" climatic conditions predicted by the three scenarios. Output files include time series of monthly catchment storage, runoff, and actual evapotranspiration. Multi-year statistics of the water balance variables were calculated. Figure 10 shows a comparison of observed and simulated quarterly discharges of the Yellow River at Sanmenxia for the current climate, while Figure 11 presents an impact of climate change on the hydrological regime of the river. Only the HCTR scenario leads to some decrease of Yellow River discharges both for the winter and summer seasons. It should be noticed that the MPTR climate may cause significant increase of the summer flow. One can conclude, that according to the results obtained for the current generation of transient climate scenarios, the water supply conditions in the Yellow River basin may improve due to climate change.

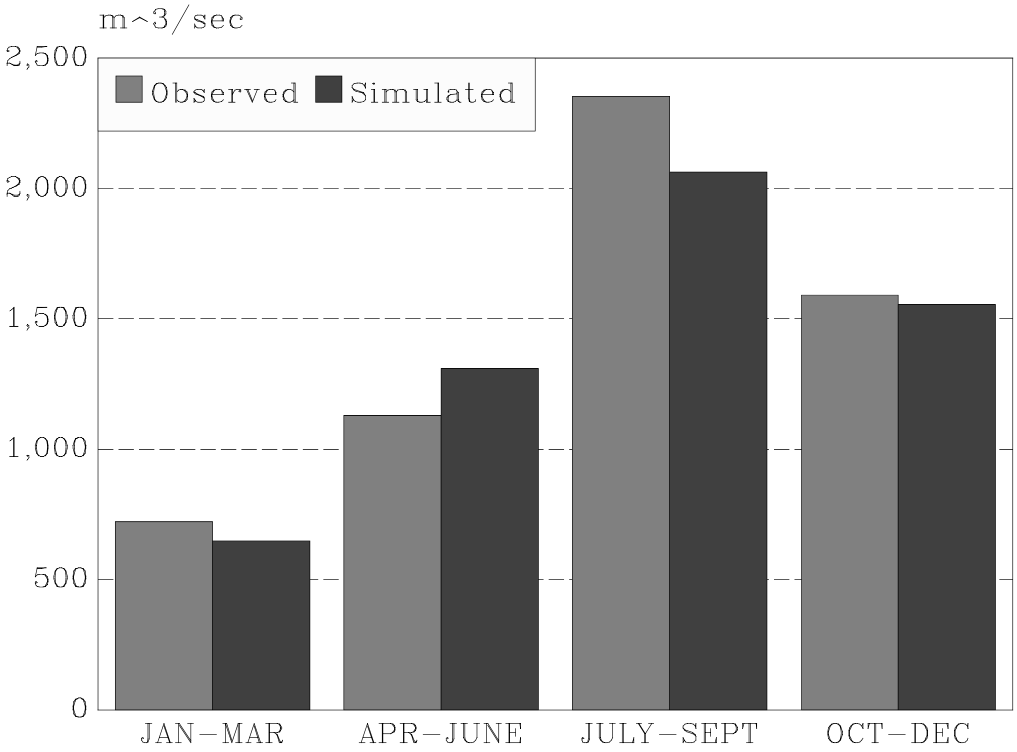

Fig. 10. Observed and simulated monthly discharges at Sanmenxia

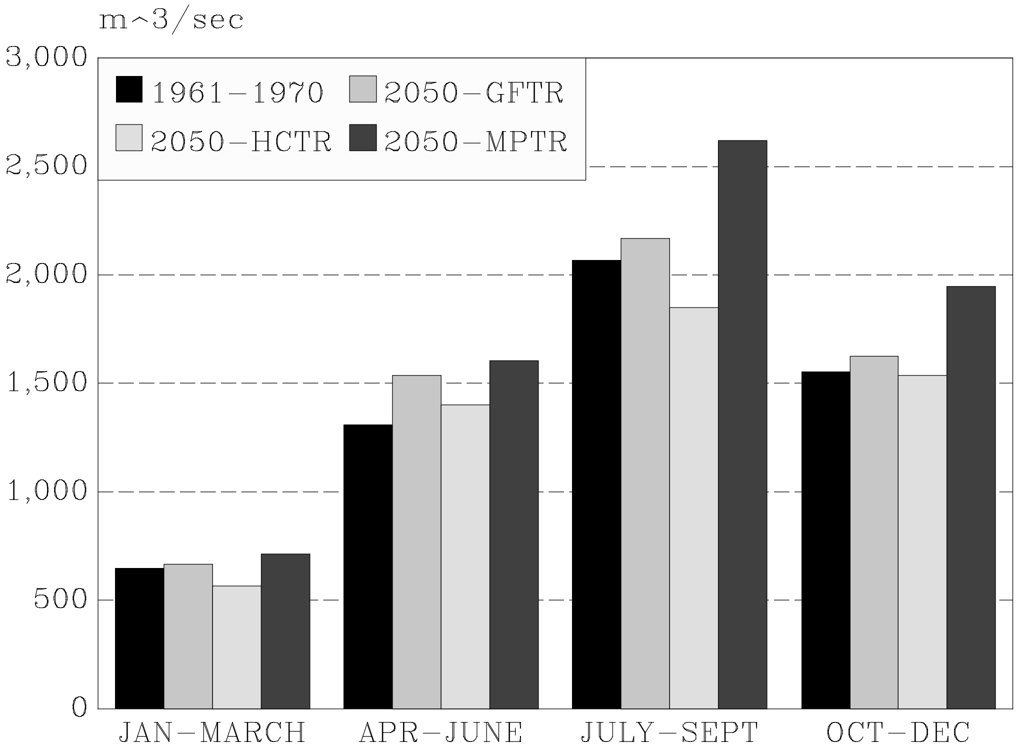

Fig. 11. Mean monthly discharges of the Yellow River at Sanmenxia: three scenarios

4. Impact of reservoirs on flow distribution

As mentioned in section 3, more than 130 reservoirs are operating in the Yellow River basin, with the overall storage capacity of $13.1*10^9$ m^3. Most of the reservoirs in the system are relatively small, while two of them (Liujlaxia and Sanmenxia) belong to the largest artificial lakes in Asia. Table 2 shows the categorization of existing reservoirs, depending on the ratio of storage capacity V to the mean annual inflow R to the reservoir.

Category	V/R	amount [%]
Inter-annual control	> .75	81.9
Intra-annual control	0.25 - 0.75	12.1
Short-term control	< 0.25	6.0

Table 2. Grouping of Yellow River reservoirs according to control potentiality

The operation of any water reservoir system is largely determined by the physical characteristics of the catchment, the hydrological regime of the basin, and the primary purposes the system is design to serve. In China most of reservoirs were built in order to improve reliability of irrigation water supply and to cope with negative consequences of floods and sedimentation. It means that a typical objective function of an operation plan is based on the requirement to equalize the downstream releases throughout the year. Because most of reservoirs located in tributaries of the Yellow River basin have objective functions that are either identical in their composition, or they follow similar operational patterns, the concept of an "equivalent catchment reservoir" seems a plausible approach in order to reduce the dimensionality in comparison with the reservoir-number and storage-state multi-dimensional approach (Yevjevich, 1982). An equivalent reservoir is defined as a reservoir of combined storage capacity that may produce similar results in water released, and flood control, as would be obtained from a number of reservoirs. This concept will be employed in a case study on the impact of storage capacity on water supply in the Jinghe river basin, taking also into account a possibility for changed climatic characteristics in the area.

The decisions to be made in standard operations of an "equivalent" reservoir can be characterized by the quantity of water to be released in various time intervals, e.g. months. Required releases are then used as guides which the reservoir operator should follow unless there are good reasons for deviating. An algorithm for simulating reservoir operation has been discussed in (Kaczmarek, 1979), where the following reservoir operation rule was used:

$$Q_{ot} = D\left(1 - \frac{\alpha}{z_t}\right) + Q\left(\frac{\beta}{1 - z_t}\right), \tag{13}$$

where D and Q are the required release and inflow in the time t, $z_t = S_t/V_t$ is the relative storage, i.e. the ratio of actual storage to reservoir capacity. For this operation rule the storage equation in j time interval is:

$$\int_{z_k}^{z_{k+1}} \frac{z(1-z)\,dz}{\frac{V_{j+1}-V_j}{T_j} z^3 + \left[D_j - Q_k - \frac{V_{j+1}-V_j}{T_j}\right] z^2 + [Q_k(1-\beta) - D_j(1+\alpha)]\,z + \alpha D_j} = \Phi \tag{14}$$

where:

$$\Phi = \frac{T_j}{V_{j+1}-V_j} \ln \frac{V_{j+1}}{V_j}, \qquad when \quad V_{j+1} \neq V_j \tag{15}$$

or:

$$\Phi = \frac{T_j}{V_j}, \qquad when \quad V_{j+1} = V_j \tag{16}$$

Index $k = (i-1)M + j$. Integrating (14) for given initial storage, known parameters α, β, V_j, V_{j+1} and D_j, and for given inflow Q_k, one should solve the resulting equation in order to get the final storage level z_{k+1}. Finally, the reservoir release should be calculated by means of a formula:

$$Q_{ok} = Q_k - \frac{z_{k+1} * V_{j+1} - z_k * V_j}{T_j}. \tag{17}$$

The model is flexible in a sense that the operational storage capacity and the target releases may vary in time. Parameters α and β may be optimized by applying one of the standard optimization procedures.

A computer software is available which allows to calculate time series of reservoir releases either based on a time series of observed inflows, or on simulated input generated by means of Monte Carlo method, when only inflow statistics - mean values, standard deviations and correlation coefficients - have to be known. The latter procedure was applied below for the Jinghe river case study.

5. Jinghe river case study

The main objective of the Jinghe river case study was to analyze a joint impact of storage capacity and climate scenarios on the reliable water supply. A concept of one "equivalent" reservoir was applied as the basic storage model. The Jinghe river is a tributary of the Weihe river, which in turn joins the Yellow River shortly upstream the Sanmenxia reservoir. Catchment area at Zhangjishan (close to the river outlet) is 43,200 km^2, and the principal water balance characteristics are:

* average catchment precipitation: 560 mm/year,
* average potential evapotranspiration: 770 mm/year,
* mean annual runoff: 62 mm/year.

Several reservoirs were built in the basin with the overall capacity of 500 million m^3, i.e. about 20 percent of the average annual runoff. To characterize the hydrologic regime of the Jinghe river, a time series of mean annual discharges at Zhangjishan is shown in Fig. 12. It can be observed that the runoff process is approximately stationary with no significant trend. The intraannual distribution of water resources is shown in Fig. 13 in a form of monthly discharges with given exceedance probabilities. Similarly to the whole Yellow River catchment the maximum discharges reflect the monsoon type of hydrologic regime.

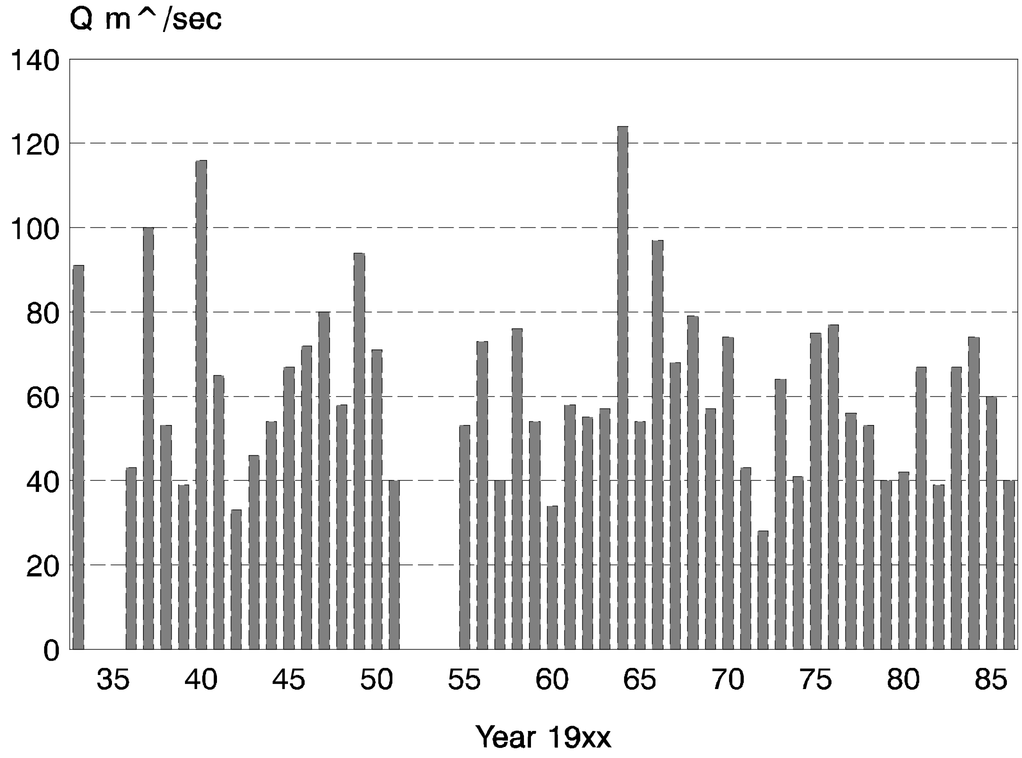

Fig. 12. Annual discharges of Jinghe river at Zhangjishan

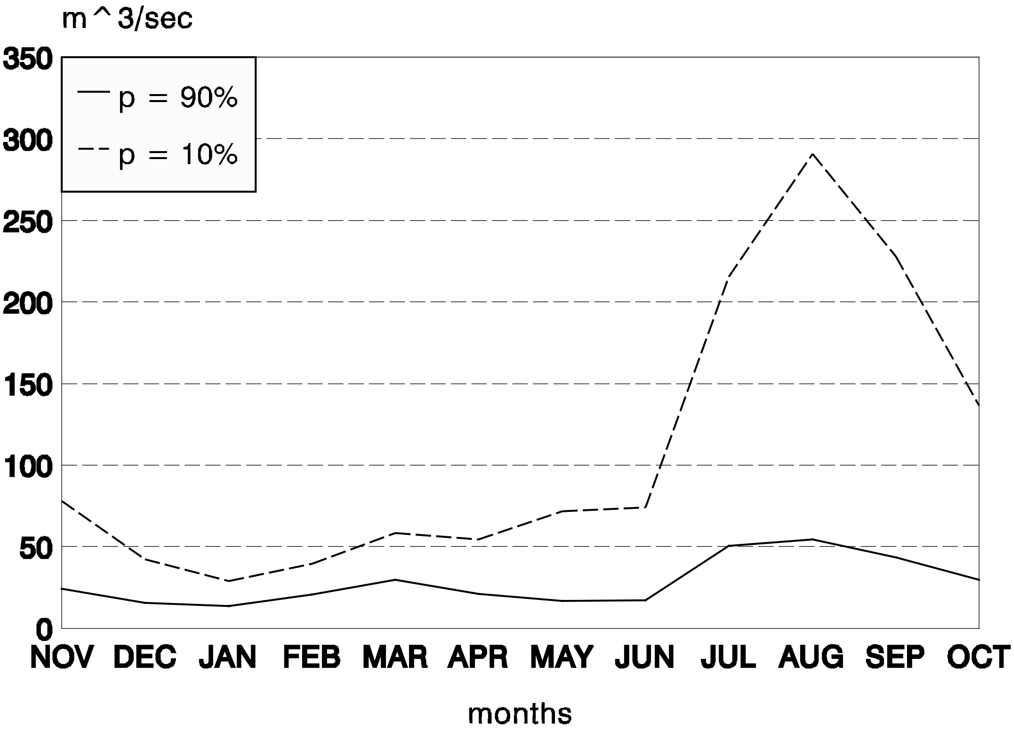

Fig. 13. Monthly discharges of Jinghe river for given exceedance probabilities

The CLIRUN model was used to simulate runoff and other water balance characteristics. Time series of monthly rainfall, potential evapotranspiration, and runoff, based on observations in years 1961-1970 at climatic stations:

HSI-NING-SINING (109.48 E; 36.36 N)
PINGLIANG (106.40 E; 35.33 N)
SHIJIAZHUANG (114.25 E; 38.02 N)
XI'AN (108.56 E; 34.18 N)
YAN AN (109.30 E; 36.36 N)
YULIN (109.42 E; 38.14 N)

form an input vector needed for model calibration. A comparison of observed and simulated average monthly runoff is shown in Fig. 14.

The CLIRUN model, calibrated for the above data, was applied to assess water balance components for the observed data, and for changed climatic conditions, as predicted by the three scenarios described in section 2, for the decade around year 2050 of transient runs of GFTR, HCTR, and MPTR global circulation models. The increments of basic climatic elements ΔT and r_P were taken the same as for the whole Yellow River catchment, as shown in Fig. 3 and Fig. 4. The possible impact of climate change on the Jinghe river runoff is shown in Fig. 15, which shows significant differences in the summer runoff for various scenarios.

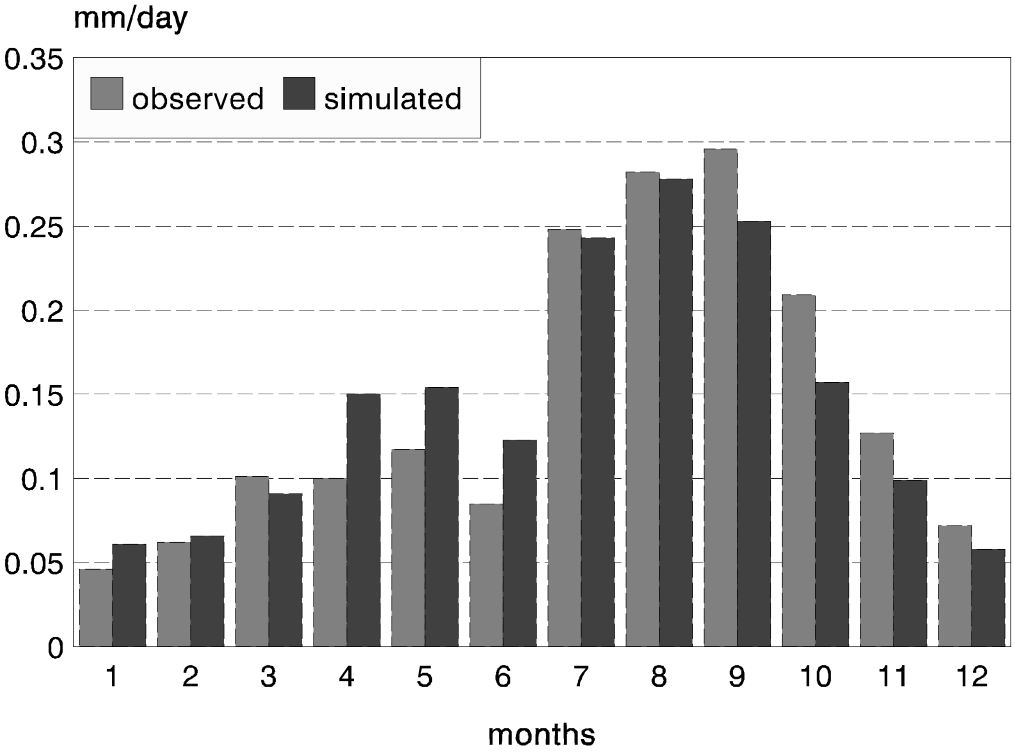

Fig. 14. Observed and simulated runoff of Jinghe river

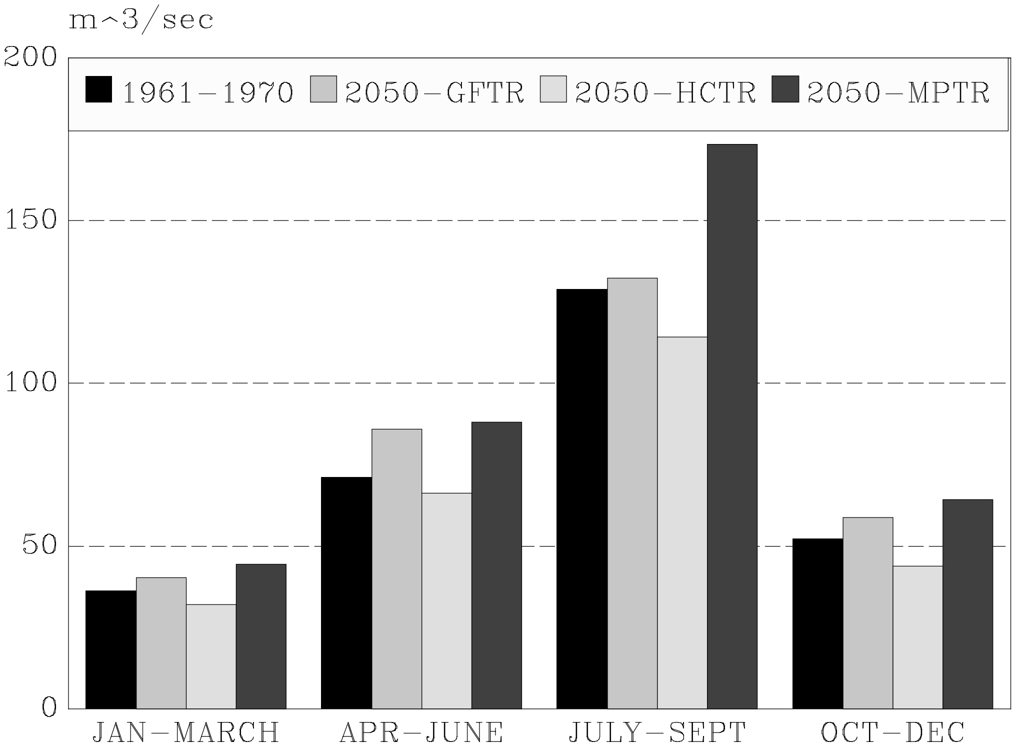

Fig. 15. Mean discharges of the Jinghe river: three scenarios

It should be noticed that only in case of the HCTR scenario the seasonal and annual of Jinghe river was obtained to be lower than in the observation period 1961-1970.

To assess a possible impact of increased storage in the Jinghe river basin, the simulated runoff statistics were utilised in order to generate 100-year long series of inflow data to a hypothetical "equivalent reservoir" of storage capacity equal to the average annual runoff of the river, i.e. $V = R$. Fig. 16 displays the reliability of reservoir outflows, defined here as a ratio of a number of months in which the outflow exceeds a given discharge value to the number of months in the simulated series. The reliability curve for $V = 0.2*R$ represents supply reliability for the current hydrologic regime in the basin.

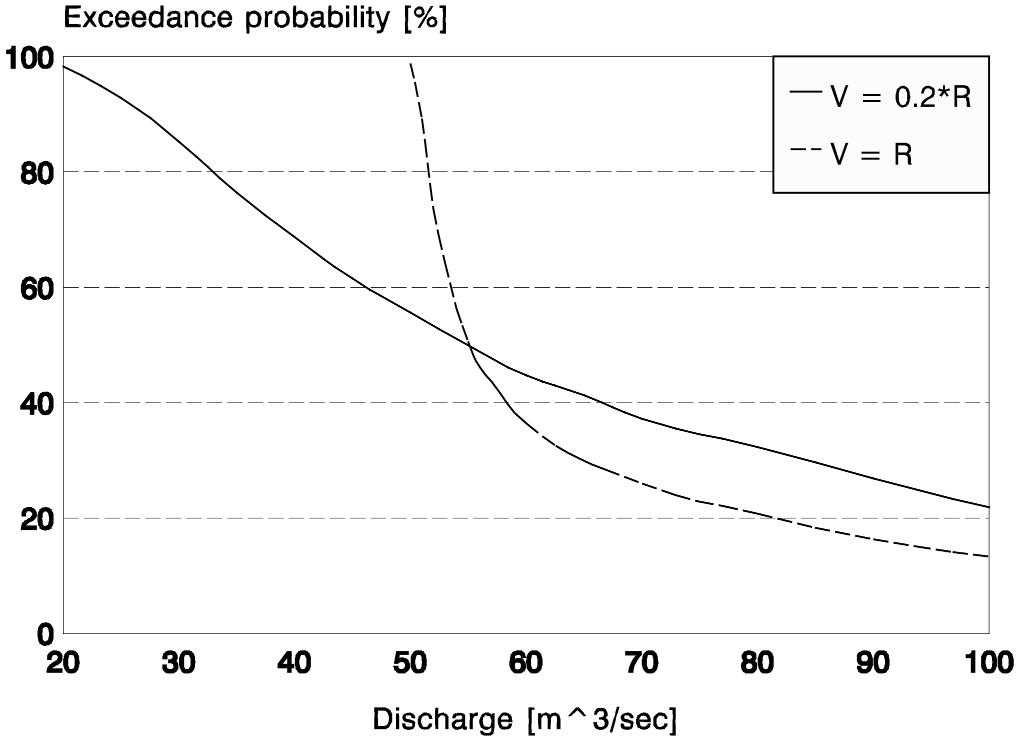

Fig. 16. Impact of storage capacity on reliable water supply: Jinghe river

Monthly time series of runoff data, as simulated for the three scenarios by the water balance model were then used to generate inflow data to the "equivalent" reservoir. The reservoir model was run for each scenario, for three levels of storage capacity of the "equivalent" reservoir, from 0.2 to 1.0 of the total annual runoff which is equal to 1,950 million m^3. Hundred year long time series of simulated reservoir releases were then analyzed in order to estimate release values of 80% exceedance probability. Results for three scenarios and assumed storage capacities are summarized in Fig. 17. It can be seen that for large reservoir capacity the impact of climate scenario on water supply reliability is negligible.

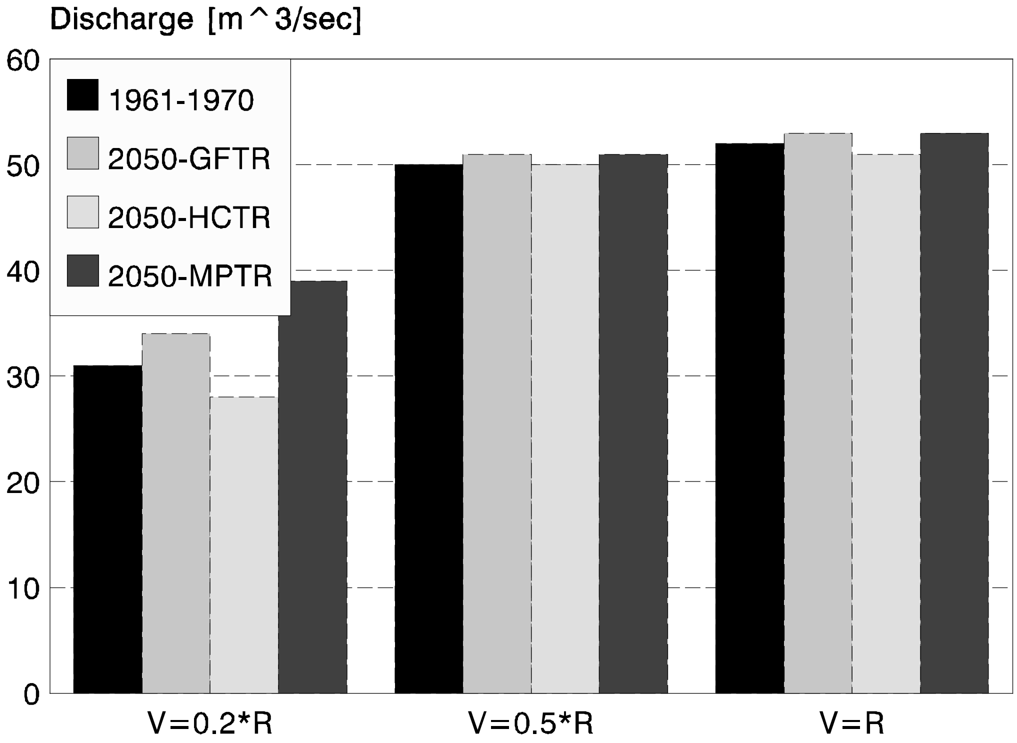

Fig. 17. Impact of storage capacity on reliability of water supply in the Jinghe region: three scenarios

6. Luanhe river case study

Similarly to the previous case, the objective of Luanhe study was to investigate an impact of climate scenarios on efficiency of hypothetical storage reservoirs of different available capacity. Again a concept of an "equivalent" reservoirs was employed. The Luanhe river is located east to Beijing and empties directly to the Gulf of Pohai of the Yellow Sea. Catchment area at Luanxian is 44,100 km^2, and the average water balance characteristics are:

* catchment precipitation: 569 mm/year

* average potential evapotranspiration: 837 mm/year

* mean annual runoff: 94 mm/year

Mean annual discharge time series at Luanxian gauge is shown in Fig. 18, and monthly discharges for exceedance probabilities p = 10% and p = 90% are shown in Fig. 19. Again a large runoff variability may be observed from data presented in both figures.

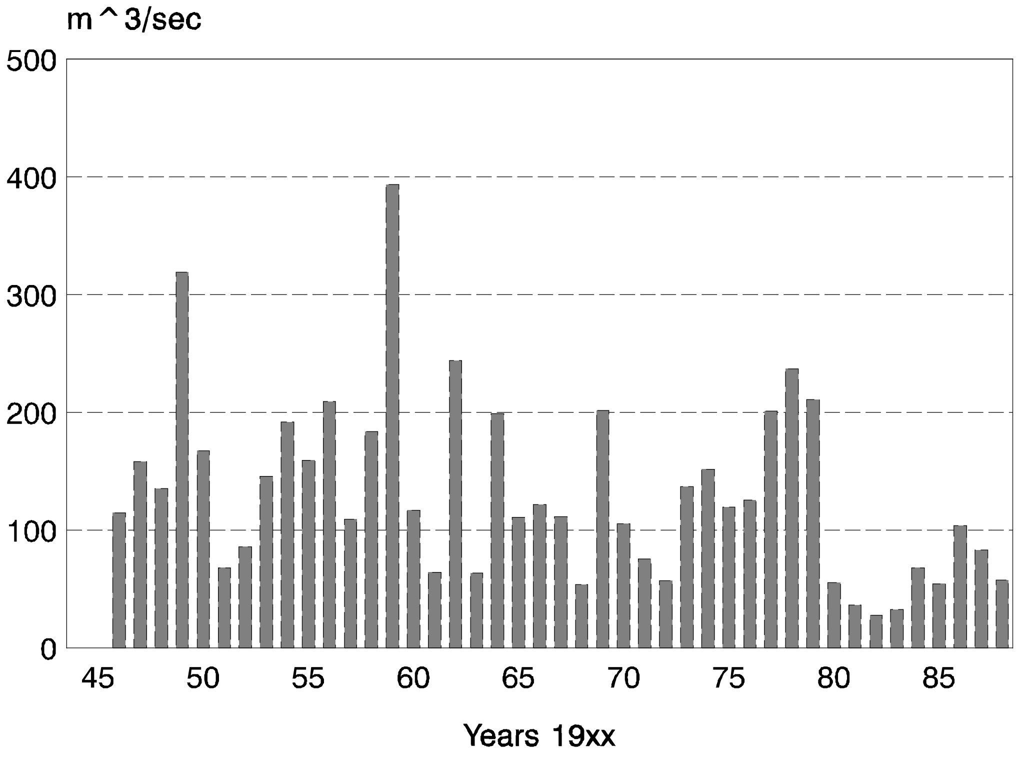

Fig. 18. Annual discharges of Luanhe river at Luanxian

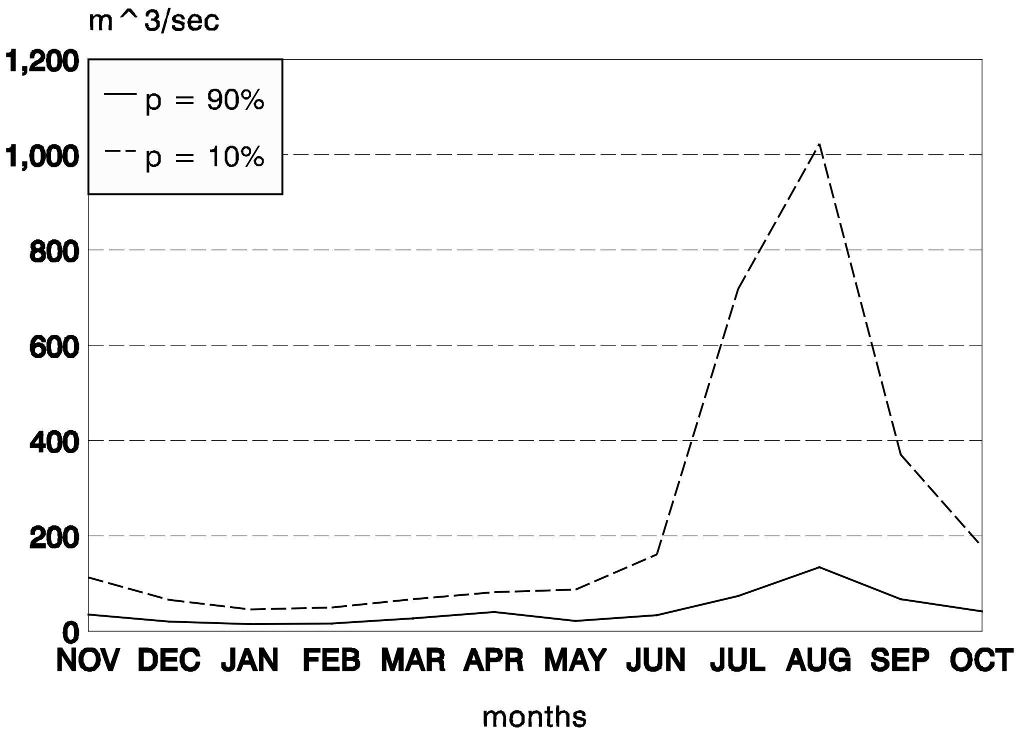

Fig. 19. Monthly discharges of Luanhe river for given exceedance probabilities

Parameters of the CLIRUN model were identified based on meteorological data in years 1961-1970 at three stations:

BEIJING (117.56 E; 40.58 N)
CHENGDE (116.17 E; 39.56 N)
TIANJIN (117.10 E; 39.06 N)

and on runoff data from the same period measured at Luanxian river gauge. Runoff characteristics, observed and simulated by the hydrologic model, were compared as shown in Fig. 20. The agreement between measured and calculated values seems to be quite satisfactory for all seasons. The CLIRUN model was then applied to assess water balance components (runoff, catchment storage, and actual evapotranspiration) for changed climatic conditions for the time period around the year 2050, as predicted by the GFTR, HCTR, and MPTR scenarios described the 2-nd section of the Report. Changes in temperature and precipitation patterns were assumed the same as for the whole Yellow River basin. The possible impact on the Luanhe seasonal runoff is shown in Fig. 21. Results are similar to those discussed for the Jinghe case (compare Fig. 15), and show serious differences among scenarios, particularly in case of the summer period from July to September.

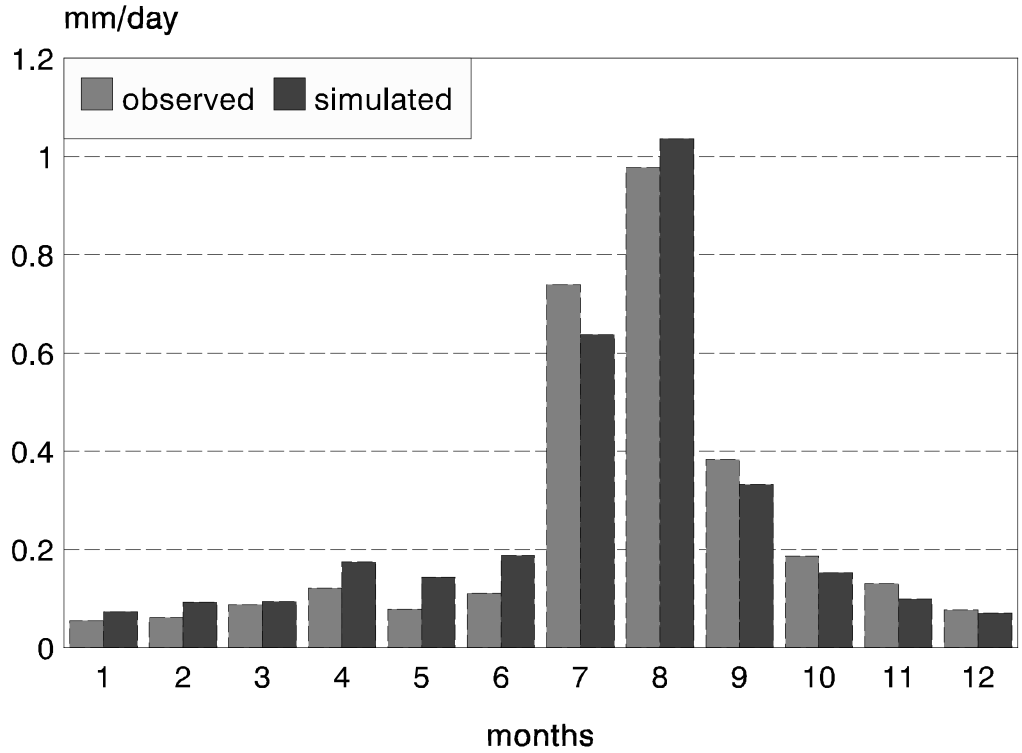

Fig. 20. Observed and simulated runoff of Luanhe river

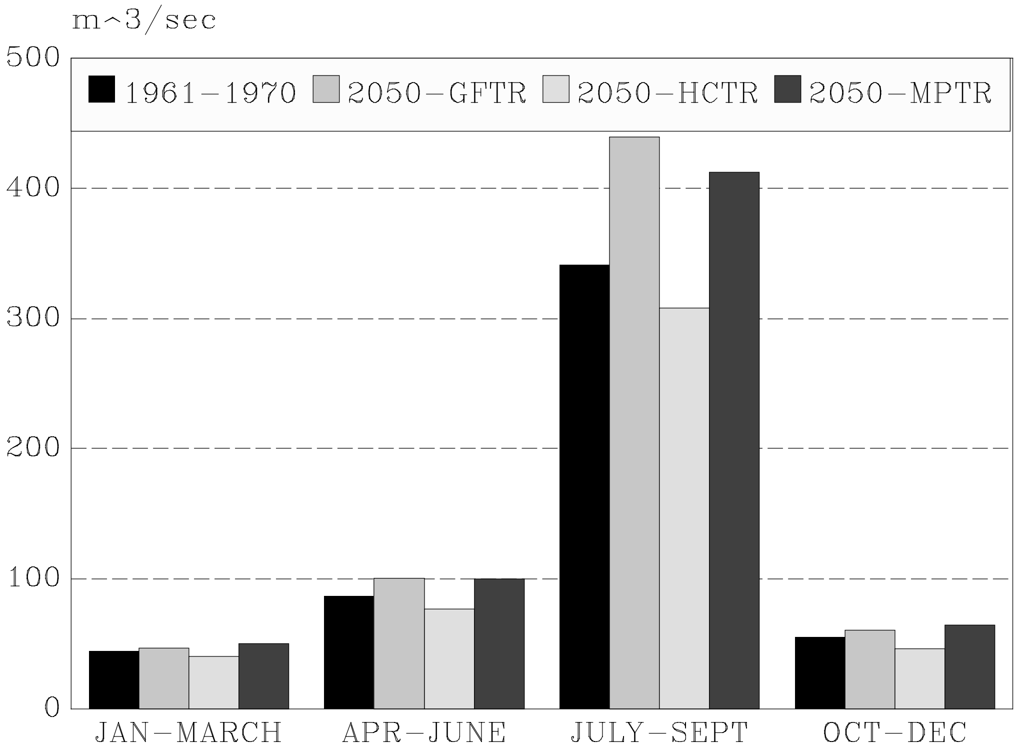

Fig. 21. Mean discharges of the Luahne river: three scenarios

The simulated runoff statistics (for "historical" climate, and for GFTR, HCTR and MPTR scenarios) were then used to generate 100-year long series of monthly inflow data to a hypothetical "equivalent" reservoir located in a lower stretch of the Luanhe river basin. Fig. 22 shows an impact of reservoir storage on water resources for the current climatic conditions: the measured (1961-1990) mean monthly discharges at Luanxian are compared with release values from a hypothetical reservoir with storage capacity equal to the annual runoff, i.e. about 4.15 billion m^3.

In turn, Fig. 23 presents discharge values of 80% exceedance probability below the reservoir, calculated on a basis of hundred-year long time series of release data obtained for observed inflow and inflows simulated by the CLIRUN model for three scenarios, assuming three levels of storage capacity. Similarly to the Jinghe case study it can be observed that for large reservoir capacity the possible impact of climate change on reliable water supply is negligible.

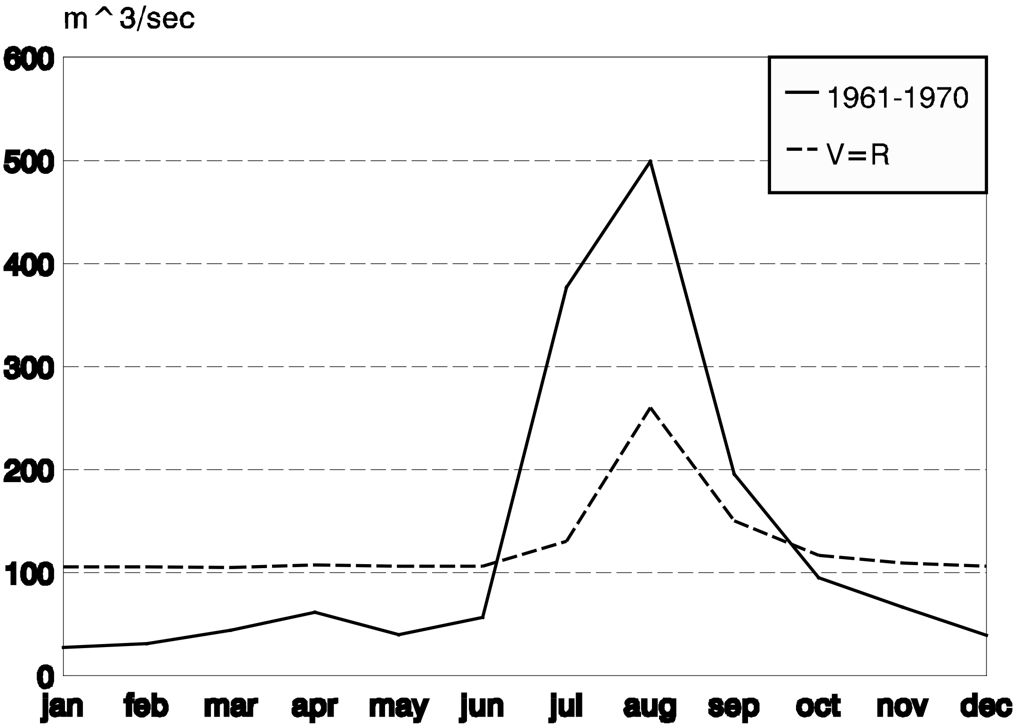

Fig. 22. Impact of reservoir operation on monthly discharges of Luanhe river

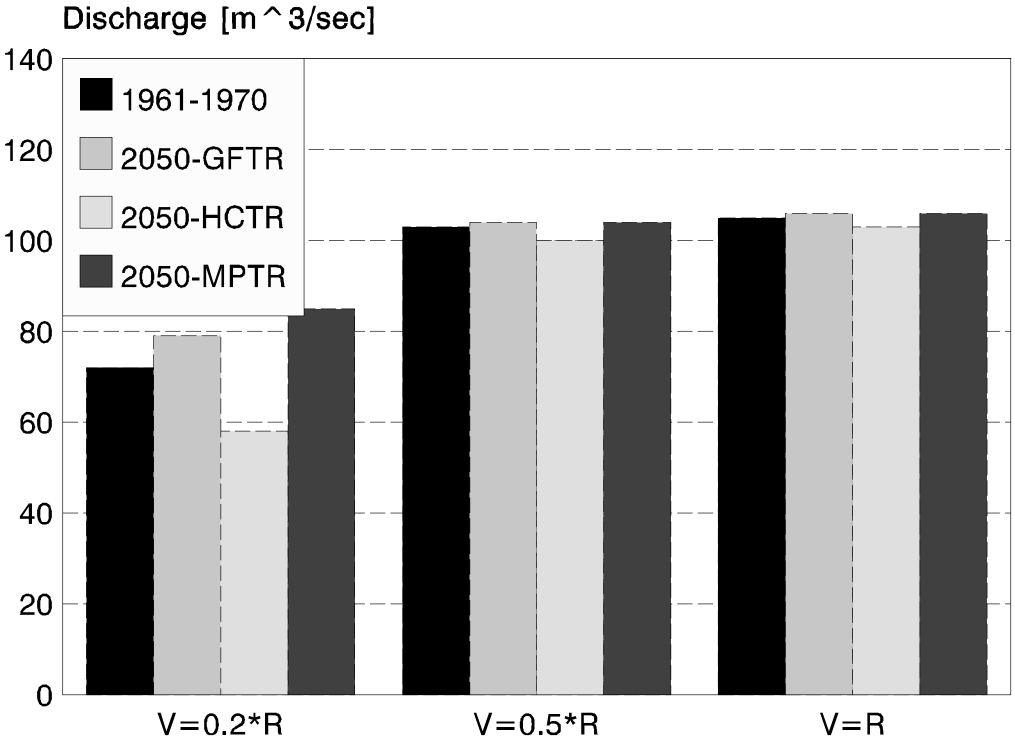

Fig. 23. Impact of storage capacity on reliability of water supplying the Luanhe region: three scenarios

7. Conclusions

The report presents an analysis of possible consequences of climate change and water systems development on the reliability of water supply in the Yellow River basin and its tributaries in Northern China. With only about 60 mm of an average annual runoff the region is scarce in water and therefore requires intense water management activities, particularly due to high water demands in the agriculture sector. Because of significant intra- and interannual runoff variability in the catchments under consideration, the role of storage reservoirs in assuring reliable water supply is vital. Based on two case studies for the Jinghe and Luanhe sub-basins it can be concluded that construction of additional reservoirs may seriously improve this reliability, independently on possible changes of regional climate.

The Intergovernmental Panel on Climate Change published in 1990 and 1992 two Assessment Reports, outlining extensive difficulties in conducting meaningful analyses of climate change impacts on hydrology and water resources (Shiklomanov *et al*, 1990; Stakhiv *et al*, 1992). Since then, several case studies have been implemented for different river basins - almost exclusively in developed countries. Their results were summarized in the 1995 IPCC Report (Kaczmarek *et al*, 1996). The main conclusion is that although uncertainties of climate change impact analysis at the catchment scale remain large, such impact highly depends on the characteristic of the water use system. In water scarce regions - as in the Yellow River basin - a small change may have a significant impact on regional water supply.

A long-term water resources strategy requires that a series of plausible development strategies be formulated based on different combinations of economic growth assumptions along with climatic scenarios (Carter, *et al.*, 1994). Taking into account the possibility of climate change, a long-term water management plan for the Yellow River basin should be formulated, based on different combinations of climate induced water resources assessments, development of hydraulic infrastructure, and policy instruments. In arid and semi-arid regions such plans should emphasize reliability of water supply. The selection of an "optimal" water policy path is a decision dependent on social preferences, and political and financial realities.

The following conclusions concerning future water resources problems in the region under consideration seem to be justified:

(a) Based on model simulation of water balance elements of the Yellow River it can be concluded that the sensitivities of hydrological processes in this basin to climate change are limited; higher sensitivity was found in some of the sub-basins, as for example in the Luanhe catchment;

(b) The current climate models do not offer, however, the required degree of regional-specific information on future climate; a continuous adaptation of development plans, operating rules and water allocation policies to new generations of climate scenarios is needed;

(c) Characteristic feature of water resources in the Yellow River catchment is dominating role of agriculture sector in water use, what may elevate the vulnerability of the region’s water management to climate change;

(d) Irrigation water requirements increase in a warmer climate; water resources strategies should not overlook technological solutions where there can improve a more rational use of water in agriculture;

(e) Rationalization of water use and development of storage capacity are primary components for increasing the robustness of the Yellow River water resources systems under increasing supply and demand uncertainty;

Research should continue in order to improve predictions and permit the evaluation of specific adaptive responses in important economic sub-regions in Northern China. Assessments of climate change impacts on various branches of water management: irrigation, hydropower, water supply for cities, and flood protection deserve attention. Three areas of research related to the climate\water resources interface may be of particular interest in Northern China:

(a) Continuous monitoring aimed on detecting changes in atmospheric and hydrological variables by means of selected indicators;

(b) Assessing the sensitivity of river runoff and other water balance elements to climate characteristics;

(d) Analyzing implications of climate change on regional water demand, and consequently on management of water resources systems.

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List of Figures