Theory of annual runoff evolution under natural-artificial dual mode and case study of Wuding River basin on the middle Yellow River

WANG Hao, WANG Chengming, WANG Jianhua, ZHOU Zuhao & CHEN Yiming

Department of Water Resources, China Institute of Water Resources and Hydropower Research, Beijing 100044, China

Correspondence should be addressed to Wang Jianhua (email: wjh@iwhr.com)

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Abstract Water cycling process in a river basin becomes more complicated because of the intensified impact by human activities. Study of the law of annual runoff evolution in a river basin is of great significance to quantitative analysis of the water resources condition in varied environment and prediction of the law of the water resources evolution in the future because year-based time span may best reflect the law of the water resources evolution driven by the nature and human activities in the river basin. This paper advances the theory of annual runoff evolution under natural-artificial dual mode based on the dual mode of the water resources evolution, and the theory is applied for the Wuding River Basin on the middle Yellow River as a case study. A thorough analysis of the precipitation-runoff relationship is made in the case of dynamic variation of ground surface conditions of the Wuding River basin, and the concept of water-soil conservation index area that indicates adoption of various measures for water and soil conservation to reflect ground surface conditions. Furthermore, precipitation-runoff empirical model is developed to reflect dynamic variation of the ground surface conditions of the river basin. The study may lay a solid foundation for the integrated theoretical platform of the law of the water resources evolution in the Yellow River basin and the dual model of the evolution.

Keywords: annual runoff, dual mode, water resources variation, evolution theory, Wuding River.

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Increasingly intensified human activities may produce a great impact on water cycling process, thus on the law of water resources evolution in a river basin. As an important link of water cycle and a basic representative factor of water resources, river runoff is considered as the most important basis of comprehensive development and utilization, scientific management and optimized allocation of water resources. Owing to gradual variation in water resources evolution driven by human activities, the law of runoff evolution process of year-based time span may best reflect the process and the result of water cycle variation driven by human activities in a river basin. Methodologies of statistics, runoff restoring and correction are currently applied for expression of impacts of human activities on water resources evolution, which may not satisfy the requirement of the dynamic water resources assessment and planning for varied environment by explicitly considering impacts of human activities. Formulation and study of the theory of the mode of annual runoff evolution of a river basin under the impacts of the "natural-artificial" dual driving forces may provide a theoretical basis for the practice of water resources of a river basin in an area influenced by intensified human activities.

1 Theory of annual runoff evolution under dual mode

1.1 Generalization of surface water cycling process

Surface water cycling process of precipitation and runoff in a river basin under the natural condition on year-based time span may be described as follows. Supposing precipitation $\boldsymbol{P}$ (the bold indicating precipitation distribution with time and space, usually generalized by areal average, P) in the river basin and annual runoff R at the outlet of the river basin, precipitation-runoff relationship of the water cycling process may be expressed by the following equation:

$$R = f(\boldsymbol{P}), \tag{1}$$

where function f is a precipitation-runoff function that integrally reflects characteristics of the ground surface, such as evaporation, runoff producing, runoff concentrating, infiltration and draining, in the river basin and characteristics of the water cycle. When precipitation is expressed in terms of areal average, the specific expression of the function f is usually simplified into linear or logarithmic linear function involving parameters of inner-annual distribution of precipitation for practical application. The law of annual runoff evolution is dependent totally upon the law of the natural variation of precipitation and that of ground surface conditions of the river basin. In case that ground surface conditions of the river basin remain relatively stable, the law of annual runoff evolution is dependent totally upon the law of the variation of precipitation.

1.2 Formation of dual mode

Human activities in developing progress considerably alter the water cycling process in a river basin under the natural condition in the contexts of the system, response and the structure. For the input of water cycle, a whole series of secondary effects exerted by human activities alters conditions of the input and the output of a water cycle system in a river basin. For example, climate change and atmospheric temperature change resulting from green-house effect exert influence on precipitation and evaporation in the water cycle in a river basin. Then water and soil conservation, water resources development and utilization, industrial and agricultural development, land uses and urbanization alter ground surface condition, micro-relief and distribution of vegetation to a large extent, thus resulting in changes in characteristics of surface runoff producing and concentrating and in those of groundwater recharge and discharge in the river basin, and finally change in corresponding relationship of runoff to precipitation. In addition, water resources development and utilization alter river/lake system, groundwater storage condition and way of transformation between surface water and groundwater, and then form an artificial water cycle of lateral branch constituted by five basic links of water withdrawal, delivery, use, drainage and return within the higher-level framework of the natural water cycle.

In view of intensified impacts of human activities on water cycling process in a river basin, the authors, in the light of specific conditions of a river basin, advance the theory of dually driven water resources evolution mode of the river basin by explicit consideration of impacts of human activities. It is recognized the “natural-artificial” dual driving forces jointly lead to the present conditions of the water cycle and the water resources evolution in a river basin, and the dual driving forces may be systematically separated. As a result, a new quantification process that differs from the traditional unary static mode of “observation-restoration-modeling-regulation” is developed. The basic process of the mode of the expanded dual dynamic water resources evolution may be outlined as “observation-separation-coupling-modeling-regulation”. The separation indicates identification of respective contributions of the natural factors and impacts of human activities to the observed hydrological process, and coupling indicates maintenance of the dynamic relations among separated parameters [1,2]. Moreover, the quantification process of the secondary effects of water cycle in a river basin under the impact of the dual driving forces is developed[3].

1.3 Theory of annual runoff evolution based on dual mode

The above-mentioned precipitation-runoff functional relation under the natural condition is untenable in case of the dual mode. The observed annual runoff in a river basin is much less than the calculated annual runoff by formula (1) because of evaporation and seepage in the process of artificial water cycle of lateral branch and effect of decrease in runoff yield resulting from variations of ground surface condition. Therefore, in study of law of annual runoff evolution, a new approach should be explored for considering such differences in order to quantify the changes of water resources in the varied environment.

The current studies on the impacts of human activities on variation of runoff mainly focus on the impacts of water resources development and water and soil conservation on the annual runoff, such as the study on variations of water and sediment of the Yellow River[4]. In the purpose of these studies is quantification of the effect of decrease in runoff yield resulting from human activities. The conventional methodologies are approach of hydrology, approach of water and soil conservation, approach of environment factor [5], approach of comparison and analysis [6] and so on, and among them, approach of hydrology and approach of water and soil conservation are mostly commonly used. The approach of hydrology extendedly applies precipitation-runoff relationship without impact of human activities (formula (1)) to that with impacts of human activities to derive the decrease in runoff yield by comparison of the calculated annual runoff with the observed annual runoff. The approach of water and soil conservation calculates decrease in runoff yield of each tributary based on amount of water and soil conservation measures and water storages of the tributary and then summarizes to the entire river basin. From the point of view of the dual mode of water resources evolution, the approach of hydrology and the approach of water and soil conservation essentially belong among "observation-restoration" unary mode of water resources evolution because the former directly calculates the restored runoff under the natural condition and the latter adopts the concept of runoff yield decrease that is relative to the restored runoff under the natural condition.

In order to overcome the inherent shortcomings of the unary mode in describing the law of annual runoff evolution influenced by human activities in a river basin, the theory of annual runoff evolution on the basis of the dual mode is advanced by applying the dual mode of water resources evolution to annual runoff evolution to study water resources conditions in varied environment.

Comparing with formula (1), the primary water cycle driven by the nature and men on year-based time span can be expressed as follows:

$$R + W_c + \Delta V = f'(\boldsymbol{P}) \tag{2}$$

where W_c is the annual artificial water consumption in the river basin, R is the annual runoff at the outlet of the river basin, ΔV is summation of variations of all the reservoir storages in the river basin, f' expresses precipitation-runoff functional relationship under the ground surface condition influenced by human activities, and $R + W_c + \Delta V$ reflects the actual runoff and water resources conditions of the river basin. Inter-basin water transfer and change in groundwater storage are not considered in formulae (1) and (2). In case that inter-basin water transfer and change in groundwater storage exist, the relevant terms should be added to or subtracted from the formulae.

By introducing two variables in the artificial water cycle of lateral branch, W_d and W_r representing annual water diversion and returned water to the rivers in the river basin respectively, process of artificial water cycle of lateral branch on year-based time span can be expressed as follows:

$$W_d = W_c + W_r. \tag{3}$$

Formulae (2) and (3) summarize the law of annual runoff evolution driven by the dual elements of the nature and men. Determination of the precipitation-runoff function, $f'(\boldsymbol{P})$, under the dynamically changed ground surface conditions influenced by human activities is crucial for application of the above theory of the dual annual runoff evolution. By the conventional methodologies, the restored natural annual runoff, $f(P)$, may be derived by the approach of hydrology and reduction of the restored natural annual runoff, $f(P)$-R, may be derived by the approach of water and soil conservation. The study on water resources, such as assessment and prediction, under varied conditions, may not be carried out because annual runoff at the outlet of the river basin, R, may not be determined by one approach independently. This is the fundamental shortcomings of the conventional methodologies as the annual runoff at the outlet of the river basin, R, in the future is of great importance to determination of water resources conditions and ecological water demand in the river basin. In principle, the annual runoff in a river basin, R, in the future may be predicted by applying approach of hydrology with approach of water and soil conservation simultaneously[7]. The approach of water and soil conservation includes consumptive water use in the reduction of runoff, and R may be derived by simultaneous application of the approach of hydrology and approach of water and soil conservation thus the function $f'(\boldsymbol{P})$ indirectly determined. However, two outstanding issues do exist in the simultaneous application of two approaches. Firstly, verification of observed annual runoff data indicates a considerable difference between the results of two approaches, and the simultaneous application of two approaches may produce a significant random error that cannot be estimated in derivation of annual runoff, R. Secondly, two approaches, established on the basis of the concept of restoring the natural annual runoff, implicitly consider the impacts of human activities, and, as time goes on, the impacts of human activities on a river basin become increasingly considerable. The restored natural runoff may not reflect the effect driven directly by human activities because response of runoff to the impacts of human activities is very complicated. The dual evolution mode is established to meet the needs in practice.

Just as mentioned above, because of shortcomings of approach of hydrology and approach of water and soil conservation, a new methodology has to be sought to derive the precipitation-runoff function, $f'(\boldsymbol{P})$, under the dynamically changed ground surface conditions influenced by human activities. At the macro level, the empirical-statistical method is firstly considered to be applied. By the method, the main factors influencing runoff yield, such as precipitation and ground surface conditions influenced by human activities like check dam for silting-up, terraced fields and afforestation, are found and empirical relation between the factors and the actual runoff, $R + W_c$, is established to provide guidance in the practice of water resources development. At the micro level, such approaches as distributed hydrological model may be applied to simulating the precipitation-runoff function, $f'(\boldsymbol{P})$, in the area with impacts of human activities.

2 Case study: law of annual runoff evolution in Wuding River basin

Wuding River basin is a tributary river basin with the most serious soil and water losses on the middle Yellow River between Hekouzhen and Longmen. Extensive water and soil conservation projects launched in 1970 s marked the beginning of a new period of impacts of intensive human activities in Wuding River basin. The conditions of Wuding River basin were presented in detail[7]. From the previous studies on variation of annual runoff of Wuding River basin, it is concluded that, as compared with decrease in runoff caused by decrease in precipitation, water usages and water and soil conservation are recognized as main reasons of decrease in runoff in the river basin. By the dual evolution mode, the law of water resources evolution in the river basin under the varied conditions is studied based on the law of annual runoff evolution. Through the case study of the model river basin, the theory may be extended to the entire Yellow River basin to bring to light the law of water resources evolution in Yellow River basin quantitatively.

Differing from the conventional methodologies in data series applied, the new approach applies a 24-a data series from 1973, when the impacts of human activities became significant as the extensive water and soil conservation projects were launched, to 1996, when the observed data was relatively complete. The precipitation data cover those of seventy-eight rain gauges and the runoff data cover those at Baijiachuan, the outlet of the river basin and water diversions and water consumptions in the river basin over the years. The data of water and soil conservation projects, such as check dams for silting-up, terraced fields, afforestation and grass planting, in Wuding River basin are quoted[7].

2.1 Annual precipitation-runoff relationship reflecting dynamic variation of ground surface conditions of the river basin

As preliminary application of the dual annual runoff evolution theory, the empirical annual precipitation-runoff relationship reflecting dynamic variation of ground surface conditions of the river basin is studied at macro level. Thiessen polygon method is applied for derivation of the mean annual areal precipitation, expressed by P, in the river basin. However, it is difficult to generalize the dynamic variation of ground surface conditions of a river basin. In Wuding River basin, ground surface conditions reflecting the impacts of human activities may be represented by such factors as areas of check dam for silting-up, terraced fields, afforestation and grass planting, and the empirical precipitation-runoff relation may not be established if all the factors appear in the formula. For this reason, water-soil conservation index area, FI, is introduced. Experiments and investigation data showed retention storage capacities of different water and soil conservation projects as 700.5 m^3/hm^2 for terraced fields, 4500 m^3/hm^2 for check dams, 199.5 m^3/hm^2 for forest lands and 150.0 m^3/hm^2 for grass lands[8]. All the areas of water and soil conservation projects are added together according to the respective coefficients of the different retention storage capacities. The coefficient of the area of the project of check dam for silting-up is equal to 1, and the coefficients of the areas of the other projects of water and soil conservation are determined according to the ratio of their retention storage capacities given above to the retention storage capacity of the check dam for silting-up (for example, the coefficient of terraced fields is 700.5/4500 = 0.1557). The water-soil conservation index areas, FIs, of Wuding River basin over the years are calculated based on the above method and shown in table 2.

On the left-hand side of the formula (2), R is given by the observed data from hydrological stations, W_c derived from water draft/uses and consumptive water uses, and

ΔV given by the observed data. The correlation coefficients of the observed 24-a data of $R+W_c+\Delta V$ with mean annual areal precipitation, P, and water-soil conservation index area, FI, are 0.660 and −0.535 respectively, from which the impact of water-soil conservation index area on the runoff can be seen. Three types of empirical formulae, linearity, non-linearity Ⅰ (precipitation linearity and negative exponential correction of precipitation linearity as impact of ground surface condition) and non-linearity Ⅱ (logarithmic linearity), are shown in table 1. The precipitation, P, and the water-soil conservation index area, FI, are considered as the equal influencing factors in the formulae of linearity and nonlinearity Ⅱ. The first 18-a data series in the 24-a data series are used as a sample set for model formulating, with the regression coefficients and calibration factors presented in table 1, and the last 6-a data series as a sample set for model verification. The results of calibration and prediction by three types of the models are summarized in table 2.

Table 1 Empirical formulae of annual precipitation-runoff relationship reflecting dynamic variation of ground surface conditions of Wuding River basin

Type	Formula	A	B	C
Linearity	$R+W_c+\Delta V = A\times P - B\times FI+C$	162.96	87.46	104618
Non-linearity Ⅰ	$R+W_c+\Delta V = (A\times P+C) \times e^{-B\times FI}$	203.71	0.0006577	93305
Non-linearity Ⅱ	$R+W_c+\Delta V = C\times P^{A}\times FI^{-B}$	0.4166	0.2548	50472

2.2 Comparative analysis of different formulae

Comparing the prediction results of the 6-a sample set for model verification by three formulae, as presented in table 2, the average relative errors of the formulae of linearity, non-linearity Ⅰ and non-linearity Ⅱ are 6.91%, −5.13% and −2.75% respectively. If only considering the aspect of prediction, the formula of non-linearity Ⅱ (logarithmic linearity) shows the highest accuracy in prediction, indicating more significant trend of non-linearity relationship between precipitation and runoff in the water cycle of the river basin under the condition of impacts of intensive human activities. The above conclusion is reached on the basis of accurate observed data, while the data of consumptive water use and water and soil conservation in a river basin may not be reliable. Therefore, the results obtained in Wuding River basin should be further verified in other river basins. With the increasingly enhanced water resources development, measurements and observations of artificial water uses and water and soil conservation projects inevitably become more and more accurate, thus further heightening the practical value of the above methodologies. In the future, the accurate expression of the functional relation, $f'(\boldsymbol{P})$, may be improved and other micro simulation methodologies, such as distributed hydrological model, may be applied as the understanding is continuously deepened. It can be seen that the restored natural runoff is no longer regarded as the criterion in the study of the theory of the dual mode of annual runoff evolution. In this case study, the formula of logarithmic linearity is recommended because the predictions by the formula are more accurate than those by the other two formulae. The rather low observed

Table 2 Calibration of and prediction by empirical models of annual runoff

Year	Observed data			Actual runoff calculated by different methods					
	P /mm	FI /km^2	$R+W_c+\Delta V$ /M m^3	linearity		non-linearity Ⅰ		non-linearity Ⅱ	
				value/M m^3	error (%)	value/M m^3	error (%)	value/M m^3	error (%)
1973	463.12	236.71	1417.90	1593.84	12.41	1605.91	13.26	1616.10	13.98
1974	262.43	264.94	1296.39	1242.11	−4.19	1232.93	−4.90	1239.50	−4.39
1975	349.20	283.92	1228.93	1366.91	11.23	1364.28	11.01	1371.73	11.62
1976	415.22	292.16	1406.24	1467.29	4.34	1467.88	4.38	1463.61	4.08
1977	443.18	297.26	1758.57	1508.39	−14.23	1509.81	−14.15	1497.27	−14.86
1978	511.15	298.80	1738.11	1617.80	−6.92	1622.04	−6.68	1586.88	−8.70
1979	340.48	300.99	1431.31	1337.77	−6.54	1334.47	−6.77	1337.30	−6.57
1980	279.06	318.91	1234.65	1222.02	−1.02	1217.40	−1.40	1212.95	−1.76
1981	391.08	353.71	1348.38	1374.12	1.91	1370.68	1.65	1359.68	0.84
1982	339.23	364.84	1276.88	1279.90	0.24	1277.59	0.06	1271.39	−0.43
1983	340.57	388.22	1200.47	1261.63	5.09	1260.21	4.98	1253.47	4.42
1984	396.09	415.71	1242.73	1328.06	6.87	1323.67	6.51	1311.79	5.56
1985	467.07	444.33	1344.03	1418.70	5.56	1406.93	4.68	1381.39	2.78
1986	307.49	469.38	1179.23	1136.74	−3.60	1145.21	−2.88	1144.52	−2.94
1987	323.17	495.10	1093.69	1139.81	4.22	1149.07	5.06	1152.70	5.40
1988	416.66	512.50	1409.62	1276.93	−9.41	1271.94	−9.77	1270.17	−9.89
1989	310.69	540.01	1121.39	1080.19	−3.67	1097.80	−2.10	1109.13	−1.09
1990	563.29	563.29	1174.01	1250.32	6.50	1245.52	6.09	1253.39	6.76
1991	583.21	583.21	1130.51	1072.28	−5.15	1092.49	−3.36	1113.88	−1.47
1992	600.01	600.01	1205.77	1171.68	−2.83	1176.60	−2.42	1198.39	−0.61
1993	613.24	613.24	878.83	970.97	10.48	1008.45	14.75	1032.77	17.52
1994	631.16	631.16	1369.72	1192.37	−12.95	1192.30	−12.95	1218.60	−11.03
1995	637.78	637.78	1220.41	1036.55	−15.07	1063.83	−12.83	1098.86	−9.96
1996	648.12	648.12	1254.00	1054.47	−15.91	1078.62	−13.99	1116.47	−10.97

runoff in the year 1993 results in comparatively high calculated runoff, and the observed runoff and consumptive water uses need to be checked.

2.3 Simplified predictions of actual runoff of and Yellow River inflow from the river basin

Through the frequency calculation of the average annual precipitation for 41 a period from 1956 to 1996, the annual precipitations of Wuding River basin in high flow year (75%), moderate flow year (50%) and low flow year (25%) are derived as 428.9, 371.5 and 317.0 mm respectively. According to water and soil conservation projects in the year 1996 and the plan of the watershed management, assuming 1000 km^2 of the water-soil conservation index area in a certain year and substituting predicted annual precipitation, P, and FI into the formula of non-linearity Ⅱ (logarithmic linearity), the volumes of actual water resources, $R+W_c+\Delta V$, in high flow year, moderate flow year and low flow year in the future are predicted as 1.085, 1.022 and 0.956 km^3 respectively. Moreover, according to the trend of changes in irrigated areas over the years and changes in irrigation norms in the river basin, assuming 0.2 km^3 of the consumptive water use (including industrial and domestic water uses) in the river basin in the predicted year and no change in the reservoir storages, the Yellow River inflows from Wuding River basin in high flow year, moderate flow year and low flow year in the future are predicted as 0.885, 0.822 and 0.756 km^3 respectively.

The above prediction is only a simplified example. The approach of applying long-series data combined with atmospheric circulation may be used for prediction of the annual precipitation. With the guidance of the methodologies, the outputs of different options can be predicted to select the options favourable to the sustainable development of the river basin as the basis of decision making.

3 Conclusions

The theory of dual mode of annual runoff evolution is advanced and applied to the study on the law of the annual runoff evolution and prediction of water resources evolution in Wuding River basin. Although established on the basis of year-based time span, the theory is applicable to other time spans as guidance. The theory and methodologies proposed in this paper lay a solid foundation for an integrated theory platform of law of water resources evolution and model of dual evolution in Yellow River basin. With the increasingly intensified impacts of the worldwide human activities on water cycle in a river basin, the mode and the theory of dual water cycle, established on the basis of artificial-natural driving force, will become even more valuable.

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