Water Resources Systems—Water Availability and Global Change (Proceedings of symposium HS02a held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 280, 2003.

Assessment of the vulnerability of water resource systems in China with the runoff sensitivity factor

LIHUA XIONG & SHENGLIAN GUO
Department of Hydrology and Water Resources, Wuhan University, Wuhan 430072, China
lhxiong@public.wh.hb.cn; slguo@peoplemail.com.cn

Abstract Based on the relationship of watershed long-term runoff change rate with both long-term precipitation and potential evaporation rates of change, the expressions for the sensitivity factor of watershed runoff to climate change were derived for the watersheds in China. By using information on average annual precipitation, potential evaporation, discharge and land surface properties of the watershed, the sensitivity factors of runoff to precipitation for the nine major hydrological regions and 82 hydrological sub-regions of China were calculated. It was found that the sensitivity factor of runoff to precipitation in the humid watersheds such as southwest China was much smaller than that in the arid regions such as the Yellow River region. Based on these sensitivity factors, the vulnerabilities of water resources systems of all regions in China were assessed and the results were very consistent with what people have recognized in reality.

Key words climate change; runoff; sensitivity factor; vulnerability; water resources system

INTRODUCTION

It is well known that climatic and environmental changes have very significant impacts on the water resources available to mankind, especially on the watershed surface runoff (Wigley & Jones, 1985; Cohen, 1986; Gleick, 1987b; Nash & Gleick, 1991; Risbey & Entekhabi, 1996; Vogel *et al.*, 1998). As the climatic and environmental changes continuously alter the precipitation pattern and the evaporation conditions on the Earth, the runoff generation in watersheds appears to be more irregular and unpredictable. This variation in runoff generation pattern has caused critical problems in many aspects of human life, such as in agricultural irrigation, hydroelectricity supply, flood control, etc. For scientists, one of the most important questions is how the runoff generation pattern will be affected by the changes of precipitation and potential evaporation as a result of climatic and environmental changes.

Sankarasubramanian *et al.* (2001) listed five approaches used for assessing the impacts of climatic and environmental changes on water resources. Among all these methods, conceptual water balance models, especially the monthly water balance models (Alley, 1984), have been found to be very useful and effective tools (Xu & Singh, 1998). Such applications of water balance models have appeared in many papers (Nemec & Schaake, 1982; Gleick, 1986, 1987a,b Schaake & Liu, 1989; Lettenmaier & Gan, 1990; Arnell, 1992; Panagoulia & Dimou, 1997a,b; Dooge *et al.*, 1999).

Apart from being used to deterministically simulate runoff generation in watersheds under the different scenarios, water balance models are also employed in the qualitative assessment of the vulnerability of the water resources system of a watershed to climate change by the so-called sensitivity factor of runoff to climate change. With precipitation and potential evaporation representing the hydroclimatological conditions, the sensitivity of watershed runoff to climate change was first defined by Schaake & Liu (1989) and called the "elasticity" factor, which was later called the sensitivity factor by Dooge *et al.* (1999). Using different water balance models, Schaake & Liu (1989), as well as Dooge *et al.* (1999), have derived the corresponding expressions for the sensitivity factors of runoff and concluded that the larger the value of the sensitivity factor, the more vulnerable the water resources system of a watershed to climate change is. Dooge *et al.* (1999) established a basic relationship of the watershed long-term runoff change rate with the long-term precipitation and potential evaporation change rates, which is very informative for people to understand the general impact of climate change on the whole water resources system in a watershed.

In this paper, an expression of the sensitivity factor is derived specifically for the watersheds in China. By using the information on the average annual precipitation, potential evaporation, discharge, and the land surface properties of a watershed, the sensitivity factors of the watershed runoff to precipitation for the nine major hydrological regions and 82 hydrological sub-regions of China have been calculated. With these values of the sensitivity factor, the vulnerability of water resource systems in major Chinese basins was then analysed and assessed.

SENSITIVITY FACTOR OF THE WATERSHED RUNOFF TO CLIMATE CHANGE

The long-term water balance model for a watershed can be written as:

$$\overline{Q} = \overline{P} - \overline{AE} \tag{1}$$

where $\overline{P}$, $\overline{AE}$ and $\overline{Q}$ are the long-term averages of precipitation, actual evaporation (or evapotranspiration) and runoff at the outlet of a watershed, respectively.

For calculating the long-term average of actual evaporation, the Budyko hypothesis (Dooge *et al.*, 1999; Xiong & Guo, 1999) suggested a general formula form for $\overline{AE}$, which is expressed by:

$$\overline{AE} = \overline{PE}\,\Phi\left(\overline{P}/\overline{PE}\right) \tag{2}$$

where $\overline{PE}$ is the long-term average of potential evaporation rate and $\Phi()$ is an empirical function. Substituting equation (2) into equation (1) yields:

$$\overline{Q} = \overline{P} - \overline{PE}\,\Phi\left(\overline{P}/\overline{PE}\right) \tag{3}$$

Based on equation (3), Dooge *et al.* (1999) derived a basic relationship of the watershed long-term runoff change rate $\mathrm{d}\overline{Q}/\overline{Q}$ with the long-term precipitation change rate $\mathrm{d}\overline{P}/\overline{P}$ and the long-term potential evaporation change rate $\mathrm{d}\overline{PE}/\overline{PE}$, which is expressed by:

$$\frac{\mathrm{d}\overline{Q}}{\overline{Q}} = \psi_{\overline{P}} \frac{\mathrm{d}\overline{P}}{\overline{P}} + \psi_{\overline{PE}} \frac{\mathrm{d}\overline{PE}}{\overline{PE}} \tag{4}$$

$$\psi_{\overline{P}} = \left(\frac{\overline{P}}{\overline{PE}}\right)\left[1 - \Phi'\left(\frac{\overline{P}}{\overline{PE}}\right)\right] \Big/ \left[\frac{\overline{P}}{\overline{PE}} - \Phi\left(\frac{\overline{P}}{\overline{PE}}\right)\right] \tag{5}$$

$$\psi_{\overline{\mathrm{PE}}} = \left[\frac{\overline{P}}{\overline{PE}}\Phi'\left(\frac{\overline{P}}{\overline{PE}}\right) - \Phi\left(\frac{\overline{P}}{\overline{PE}}\right)\right] \Big/ \left[\frac{\overline{P}}{\overline{PE}} - \Phi\left(\frac{\overline{P}}{\overline{PE}}\right)\right] \tag{6}$$

where $\psi_{\overline{P}}$ is called the sensitivity factor of runoff to precipitation and $\psi_{\overline{PE}}$ the sensitivity factor of runoff to potential evaporation (Dooge *et al.*, 1999). Besides the expression for $\psi_{\overline{P}}$ in equation (5), Sankarasubramanian *et al.* (2001) also defined and tested many different expressions for $\psi_{\overline{P}}$ in order to find an unbiased estimator of $\psi_{\overline{P}}$. It should be noted that there is a complementary relationship between two runoff sensitivity factors $\psi_{\overline{P}}$ and $\psi_{\overline{PE}}$, i.e.:

$$\psi_{P} + \psi_{PE} = 1 \tag{7}$$

In the calculation of the sensitivity factors $\psi_{\overline{P}}$ and $\psi_{\overline{PE}}$, the expressions of the function $\Phi(\overline{P}/\overline{PE})$ and its derivative $\Phi'(\overline{P}/\overline{PE})$ are yet to be determined. Schaake & Liu (1989) as well as Dooge *et al.* (1999) employed some simple water balance models to deduce the approximate expression of the actual evaporation rate $\overline{AE}$ as a function of the humidity ratio $\overline{P}/\overline{PE}$.

SENSITIVITY OF RUNOFF TO CLIMATE CHANGE IN CHINA

For different regions with different hydro-climatological conditions and watershed characteristics, the different formulae for calculating $\overline{AE}$ have been proposed. In China, an empirical formula has been developed and widely used to estimate $\overline{AE}$, which is expressed by (Yin, 2000):

$$\overline{AE} = \overline{PE} \times \left\{1 + \frac{\overline{P}}{\overline{PE}} - \left[1 + \left(\frac{\overline{P}}{\overline{PE}}\right)^{m}\right]^{1/m}\right\} \tag{8}$$

where *m* is a constant reflecting the effect of the land surface properties of watersheds on evapotranspiration. The larger the value of *m* is, the larger the ratio of $\overline{AE}$ to $\overline{PE}$. Comparing equation (8) to equation (2) yields:

$$\Phi\left(\frac{\overline{P}}{\overline{PE}}\right) = 1 + \frac{\overline{P}}{\overline{PE}} - \left[1 + \left(\frac{\overline{P}}{\overline{PE}}\right)^{m}\right]^{1/m} \tag{9}$$

and its corresponding derivative is:

$$\Phi'\left(\frac{\overline{P}}{\overline{PE}}\right)=1-\left(\frac{\overline{P}}{\overline{PE}}\right)^{m-1}\left[1+\left(\frac{\overline{P}}{\overline{PE}}\right)^{m}\right]^{1/m-1} \tag{10}$$

Substituting equations (9) and (10) into equation (5), we obtain the expression of $\Psi_{\overline{P}}$ for the Chinese watersheds, which is expressed by:

$$\Psi_{\overline{P}}=\left(\frac{\overline{P}}{\overline{PE}}\right)^{m}\left[1+\left(\frac{\overline{P}}{\overline{PE}}\right)^{m}\right]^{1/m-1}\Bigg/\left\{\left[1+\left(\frac{\overline{P}}{\overline{PE}}\right)^{m}\right]^{1/m}-1\right\} \tag{11}$$

As there is a complementary relationship between $\psi_{\overline{P}}$ and $\psi_{\overline{PE}}$, the discussion will be mainly focused on $\psi_{\overline{P}}$ in the following section. From the response surface of $\Psi_{\overline{P}}$ against the humidity ratio $\overline{P}/\overline{PE}$ and the watershed land properties constant *m*, it is found that: when the value of $\overline{P}/\overline{PE}$ is fixed, the larger the value of *m*, the larger the value of $\Psi_{\overline{P}}$; when the value of *m* is fixed, the larger the value of $\overline{P}/\overline{PE}$, the smaller the value of $\Psi_{\overline{P}}$, which is very consistent with the conclusions made by Schaake & Liu (1989) and Dooge *et al.* (1999).

The whole of China has been divided into nine major hydrological regions and 82 hydrological sub-regions (see Fig. 1). These nine hydrological regions are listed as

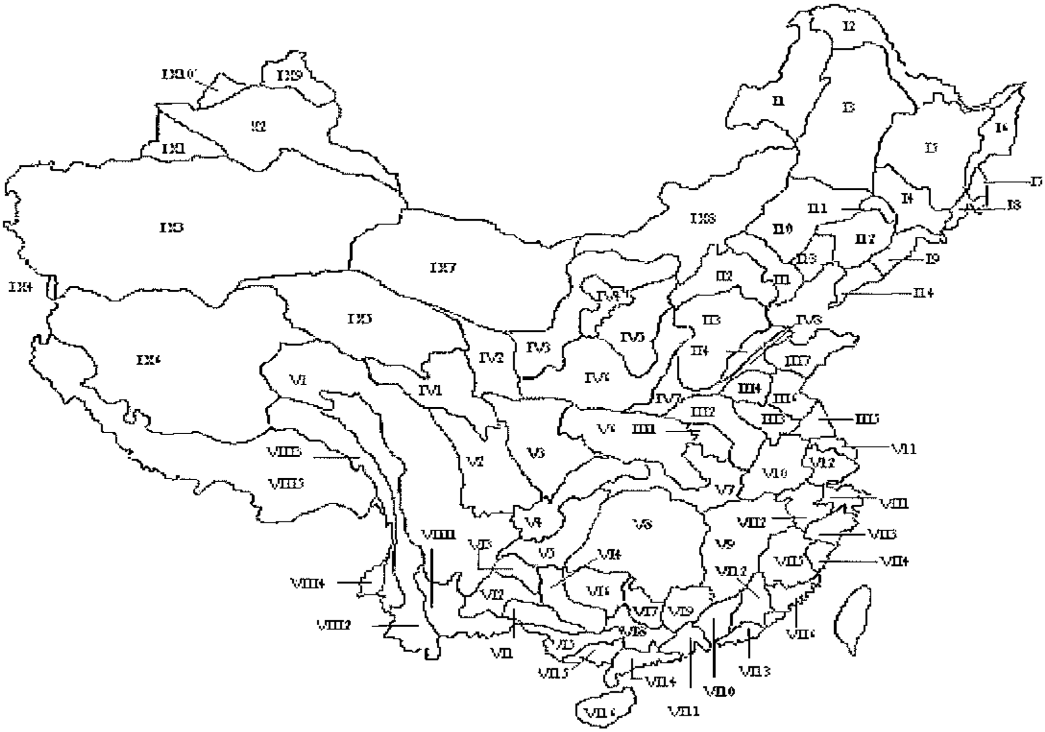

Fig. 1 The distribution of 82 hydrological sub-regions in China.

follows: (I) the region of rivers in northeast China; (II) the region of Hai–Luan rivers: (III) the region of Huai River; (IV) the region of Yellow River; (V) the region of Changjiang River; (VI) the region of Pearl River and coastal area in south China; (VII) the region of rivers and coastal area in southeast China; (VIII) the region of rivers in southwest China; and (IX) the region of inland China. Each hydrological region has a certain number of sub-regions, whose average annual precipitation $\overline{P}$, average annual potential evaporation $\overline{PE}$, average annual discharge $\overline{Q}$, and the watershed land properties constant m are listed in Table 1. Using the above information for these 82 hydrological sub-regions, the sensitivity factors of the long-term runoff to precipitation $\Psi_{\overline{P}}$ are calculated and listed in Table 1.

Table 1 Hydro-climatological information and the sensitivity factor of runoff to precipitation in the 82 hydrological sub-regions of China.

No.	Serial no.	Sub-region name	$\overline{P}$ (mm)	$\overline{Q}$ (mm)	$\overline{PE}$ (mm)	m	$\Psi_{\overline{P}}$
1	I1	Ergun River	351.6	86.3	600	2.10	1.96
2	I2	Helongjiang (Amur) River, mainstream	510.0	173.5	550	2.25	1.92
3	I4	Nenjiang River	443.7	111.9	750	2.10	1.95
4	I4	No. 2 Songhuajiang River	682.9	242.9	700	2.30	1.93
5	I5	Songhuajiang River, mainstream	583.0	196.4	700	2.10	1.85
6	I6	Wusulijiang River	539.6	160.4	700	2.20	1.96
7	I7	Suifen River	536.3	160.8	700	2.15	1.92
8	I8	Tuman River	592.0	265.6	700	1.75	1.57
9	I9	Yalujiang River	925.5	500.0	700	1.80	1.49
10	I10	Xiliao River	382.5	52.7	1100	2.15	2.09
11	I11	Dongliao River	602.1	129.1	900	2.40	2.19
12	I12	Liao River, downstream	641.9	201.6	950	2.00	1.83
13	I13	Rivers in east Liaoning province	786.8	349.7	850	1.80	1.58
14	I14	Rivers in west Liaoning province	525.2	124.3	1000	2.20	2.08
15	II1	Luan River & coastal areas in east Hebei province	553.9	124.3	950	2.20	2.05
16	II2	North of Hai River	499.0	118.6	1100	1.95	1.86
17	II3	South of Hai River	566.1	143.1	1250	1.90	1.81
18	II4	Rivers of TuHaiMajia	567.4	131.6	1200	2.00	1.90
19	III1	Upstream of Wajianba Dam	1016.8	390.2	950	2.20	1.82
20	III2	Region of Wang-Bang	858.2	297.6	1100	2.00	1.79
21	III3	Region of Bang-Hong	882.5	286.6	1050	2.20	1.93
22	III4	Huai River, downstream	1013.8	309.5	950	2.80	2.22

No.	Serial no.	Sub-region name	$\overline{P}$ (mm)	$\overline{Q}$ (mm)	$\overline{PE}$ (mm)	m	$\Psi_{\overline{P}}$
23	III5	Region of Nanshi Lake	711.9	233.1	1150	1.90	1.76
24	III6	Rivers of Qi-Shu	878.5	324.5	1100	1.95	1.74
25	III7	Peninsula of Shandong	691.5	221.5	1100	1.90	1.76
26	IV1	Region of Heyuan-Longyangxia	475.1	154.4	850	1.80	1.69
27	IV2	Region of Longyangxia-Lanzhou	492.0	151.0	900	1.85	1.74
28	IV3	Region of Lanzhou-Hekou	264.6	23.5	1470	2.00	1.98
29	IV4	Region of Hekou-Longmen	445.1	58.0	1200	2.20	2.14
30	IV5	Region of Longmen-Sanmenxia	554.6	89.0	1000	2.50	2.35
31	IV6	Region of Sanmenxia-Huayuankou	662.2	168.8	1060	2.10	1.94
32	IV7	Region of Huayuankou downwards	665.2	172.2	1200	2.00	1.87
33	IV8	Inland area of Yellow River	280.8	23.0	1470	2.10	2.08
34	V1	Rivers of Jinshajiang	704.1	313.9	1000	1.65	1.52
35	V2	Rivers of Ming-Tuo	1087.4	628.3	800	1.70	1.42
36	V3	Rivers of Jialingjiang	962.1	441.6	800	2.10	1.70
37	V4	Changjiang River, upstream	1208.9	668.6	800	1.90	1.50
38	V5	Rivers of Wujiang	1165.2	614.8	750	2.10	1.59
39	V6	Rivers of Hanjiang	906.6	381.4	850	2.10	1.75
40	V7	Changjiang River, middlestream	1248.2	603.1	800	2.50	1.76
41	V8	Rivers of Dongting Lake	1417.4	764.6	850	2.20	1.60
42	V9	Rivers of Poyang Lake	1609.9	839.8	900	2.60	1.70
43	V10	Changjiang River, downstream	1237.3	523.2	900	2.60	1.89
44	V11	Delta, Nantong	1033.9	329.7	850	3.20	2.32
45	V12	Delta, Taihu Lake	1166.9	453.2	1000	2.45	1.93
46	VI1	Nanpanjiang River	1122.5	437.2	1100	2.15	1.81
47	VI2	Beipenjiang River	1214.1	531.0	1200	2.00	1.70
48	VI3	Hongshui River	1395.0	678.0	1000	2.20	1.69
49	VI4	Liujiang River	1663.9	915.3	950	2.20	1.57
50	VI5	Youjiang River	1318.5	446.2	1100	3.00	2.23
51	VI6	Zuoyujiang River	1673.4	617.4	1200	3.30	2.19
52	VI7	Guihejiang River	1735.8	899.8	1100	2.20	1.63
53	VI8	Xijiang River, downstream	1550.6	760.3	1200	2.20	1.73
54	VI9	Beijiang River	1765.4	1131.7	1100	1.65	1.36
55	VI10	Dongjiang River	1735.1	975.6	1100	1.95	1.51
56	VI11	Pearl River Delta	1902.5	1213.9	1300	1.58	1.34

No.	Serial no.	Sub-region name	$\overline{P}$ (mm)	$\overline{Q}$ (mm)	$\overline{PE}$ (mm)	m	$\Psi_{\overline{P}}$
57	VI12	Hanjiang River	1611.6	875.2	1200	1.82	1.50
58	VI13	Rivers in east Guangdong province & coastal area	1903.4	1124.5	1300	1.74	1.43
59	VI14	Rivers in west Guangdong province & coastal area	1809.1	1066.5	1400	1.65	1.41
60	VI15	Rivers in south Guangxi province & coastal area	1968.1	970.7	1200	2.50	1.72
61	VI16	Island of Hainan	1758.0	932.8	1500	1.78	1.51
62	VII1	Qiantangjiang River	1637.6	889.3	900	2.20	1.56
63	VII2	Region of Pu-Cao-Yong	1475.6	773.9	950	2.20	1.63
64	VII3	Region of Jiao-Ou	1739.8	1025.8	1000	2.20	1.58
65	VII4	Rivers in east Fujian province	1743.0	1172.6	1100	1.56	1.32
66	VII5	Mingjiang River	1712.2	955.0	1000	2.20	1.59
67	VII6	Rivers in south Fujian province	1566.1	904.7	1250	1.60	1.38
68	VIII1	Hong River	1284.6	633.7	1200	1.80	1.55
69	VIII2	Lancangjiang River	1014.9	459.9	1100	1.80	1.58
70	VIII3	Nujiang (Salween) River	921.2	510.7	1100	1.50	1.37
71	VIII4	Yiluowadi River	1985.6	1498.1	1100	1.35	1.19
72	VIII5	Yaluzhangbu River	1220.4	807.3	1200	1.35	1.24
73	IX1	Inland rivers in middle Asia	460.9	186.6	950	1.56	1.49
74	IX2	Zhunge'er Basin	168.6	53.5	1200	1.40	1.39
75	IX3	Talimu Basin	111.4	35.7	2000	1.30	1.30
76	IX4	Qiangtang Plateau	117.0	5.0	1400	2.00	2.00
77	IX5	Caidamu Basin	174.5	7.8	1600	2.00	1.99
78	IX6	Inland rivers of Qinghai province	247.9	119.3	1000	1.32	1.30
79	IX7	Inland rivers west of YellowRiver	152.0	14.8	1800	1.75	1.75
80	IX8	Inner Mongolia Plateau	256.4	15.2	1600	2.20	2.19
81	IX9	Ertix River	232.3	150.0	1000	1.18	1.17
82	IX10	Qipuqiapu River	311.0	30.0	1400	2.10	2.08

VULNERABILITY OF THE WATER RESOURCES SYSTEM IN CHINA

Since the sensitivity factor of runoff to precipitation $\Psi_{\overline{P}}$ reflects the impact of climate change on the runoff generation in a watershed, it can be used as an index to assess the vulnerability of the water resources system to climate change: the larger the value of the sensitivity factor, the more vulnerable is the water resources system of watershed to climate change. It is suggested that the spectrum of $\Psi_{\bar{p}}$ can be roughly divided into five bands and the water resources system of the watershed can be classified according to the corresponding value of $\Psi_{\bar{p}}$: very stable, for $\Psi_{\bar{p}} < 1.3$; stable, for $1.3 \le \Psi_{\bar{p}} < 1.6$; fairly stable, for $1.6 \le \Psi_{\bar{p}} < 1.9$; fairly vulnerable, for $1.9 \le \Psi_{\bar{p}} < 2.2$; vulnerable, for $\Psi_{\bar{p}} \ge 2.2$.

For the nine major hydrological regions in China, the vulnerability of water resources system under the climate change is classified according to the average value of $\Psi_{\bar{p}}$: (I) the region of rivers in northeast China, $\overline{\Psi_{\bar{p}}} = 1.88$, fairly stable; (II) the region of Hai–Luan rivers, $\overline{\Psi_{\bar{p}}} = 1.91$, fairly vulnerable; (III) the region of Huai River, $\overline{\Psi_{\bar{p}}} = 1.86$, fairly stable; (IV) the region of Yellow River, $\overline{\Psi_{\bar{p}}} = 1.98$, fairly vulnerable; (V) the region of Changjiang River, $\overline{\Psi_{\bar{p}}} = 1.72$, fairly stable; (VI) the region of Pearl River and coastal area in south China, $\overline{\Psi_{\bar{p}}} = 1.64$, fairly stable; (VII) the region of rivers and coastal area in southeast China, $\overline{\Psi_{\bar{p}}} = 1.51$, stable; (VIII) the region of rivers in southwest China, $\overline{\Psi_{\bar{p}}} = 1.39$, stable; (IX) the region of inland China, $\overline{\Psi_{\bar{p}}} = 1.66$, fairly stable.

According to the value of $\overline{\Psi_{\bar{p}}}$, the ranking of the vulnerability of water resources system of these nine hydrological regions under climate change, from the most vulnerable to the most stable (least vulnerable), are: Yellow River; Hai–Luan Rivers; rivers in northeast China; Huai River; Changjiang River; inland China; Pearl River and coastal area in south China; rivers & coastal area in southeast China; and rivers in southwest China. This conclusion is consistent with what people have recognized in practice (MWR, 1995).

CONCLUSIONS AND DISCUSSIONS

This paper is focused on one important question, i.e. how sensitive is the watershed long-term runoff to climate change? It was found from the study in this paper that the sensitivity factor of long-term runoff to precipitation $\Psi_{\bar{p}}$ in the humid watersheds such as in southwest China is much smaller than that in the regions in need of water resources such as the Yellow River region. In terms of the average value of $\Psi_{\bar{p}}$, the ranking of the vulnerability of water resources system of the nine hydrological regions in China under climate change, from the most vulnerable to the most stable (least vulnerable), are: Yellow River; Hai–Luan Rivers; rivers in northeast China; Huai River; Changjiang River; inland China; Pearl River and coastal area in south China; rivers and coastal area in southeast China; and rivers in southwest China. This result is very consistent with what the people have recognized in reality, that is, the water resources system in the arid regions is indeed more fragile and vulnerable to climate change than those in the humid watersheds (MWR, 1995). It is hoped that this way of assessing the vulnerability of the water resources system will be useful in reasonably setting up the social and economic development plan in China.

Although the above results are very informative and useful to help people to assess the vulnerability of the water resources system of a watershed to climate change, it is still not adequate enough to be the scientific basis for the integrated water resources management because the water resources system in a watershed is very complex and subject to many more influences than only climate change. Considering the simplifications and limitations of the hydrological models and the unpredictability of the future climate and human activities, what we can do at the moment in the assessment of the water resources vulnerability under the long-term climate change is more a qualitative than quantitative analysis. Much more hard work needs to be done in the future.

REFERENCES

Alley, W. M. (1984) On the treatment of evapotranspiration, soil moisture accounting and aquifer recharge in monthly water balance models. *Water Resour. Res.* **20**(8), 1137–1149.

Arnell, N. W. (1992) Factors controlling the effects of climate change on river flow regimes in a humid temperate environment. *J. Hydrol.* **132**, 321–342.

Cohen, S. J. (1986) Impacts of CO_2-induced climatic change on water resources in the Great Lakes basin. *Climatic Change* **8**, 135–153.

Dooge, J. C. I., Bruen, M. & Parmentier, B. (1999) A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. *Adv. Water Resour.* **23**, 153–163.

Gleick, P. H. (1986) Methods for evaluating the regional hydrologic impacts of global climatic changes. *J. Hydrol.* **88**, 97–116.

Gleick, P. H. (1987a) The development and testing of a water balance model for climate impact assessment: modelling the Sacramento basin. *Water Resour. Res.* **23**(6), 1049–1061.

Gleick, P. H. (1987b) Regional hydrologic consequences of increases in atmospheric CO_2 and other trace gases. *Climatic Change* **10**, 137–161.

Lettenmaier, D. P. & Gan, T. Y. (1990) Hydrologic sensitivities of the Sacramento-San Joaquin River basin, California, to global warming. *Water Resour. Res.* **26**, 69–86.

MWR (Ministry of Water Resources, China) (1995). *The Effects of Climate Change on Hydrological and Water Resources System in China and the Research for the Solutions* (unpublished reports, in Chinese), Beijing, China.

Nash, L. L. & Gleick, P. H. (1991) Sensitivity of streamflow in the Colorado basin to climatic changes. *J. Hydrol.* **125**, 221–241.

Nemec, J. & Schaake, J. (1982) Sensitivity of water resource systems to climate variation. *Hydrol. Sci. J.* **27**, 327–343.

Panagoulia, D. & Dimou, G. (1997a) Linking space-time scale in hydrological modeling with respect to global climate change, part 1: models, model properties and experimental design. *J. Hydrol.* **194**, 15–37.

Panagoulia, D. & Dimou, G. (1997b) Linking space-time scale in hydrological modeling with respect to global climate change, part 2: hydrological response for alternative climates. *J. Hydrol.* **194**, 38–63.

Risbey, J. S. & Entekhabi, D. (1996) Observed Sacramento basin streamflow response to precipitation and temperature changes and its relevance to climatic impact studies. *J. Hydrol.* **184**, 209–223.

Sankarasubramanian, A., Vogel, R. M. & Limbrunner, J. F. (2001) Climate elasticity of streamflow in the United States. *Water Resour. Res.* **37**(6), 1771–1781.

Schaake, J. & Liu, C. (1989) Development and application of simple water balance models to understand the relationship between climate and water resources. In: *New Directions for Surface Water Modeling* (ed. by M. L.Kavvas), 343–352. IAHS Publ. no. 181.

Vogel, R. M., Tsai, Y. & Limbrunner, J. F. (1998) The regional persistence and variability of annual streamflow in the United States. *Water Resour. Res.* **34**(12), 3445–3459.

Wigley, T. M. L. & Jones, P. D. (1985) Influences of precipitation changes and direct CO_2 effects on streamflow. *Nature*, **314**, 149–152.

Xiong, L. & Guo, S. (1999) A two-parameter monthly water balance model and its application. *J. Hydrol.* **216**, 111–123.

Xu, C.-Y., & Singh, V. P. (1998) A review on monthly water balance models for water resources investigations. *Water Resour. Manage.* **12**, 31–50.

Yin, A. (2000) The Effects of Climate Change on the Water Resources System in China. PhD Thesis, Wuhan Univ. of Hydraulic & Electrical Engineering, Wuhan, China.