GLOBAL ANALYSIS OF CHANGES IN WATER SUPPLY YIELDS AND COSTS UNDER CLIMATE CHANGE: A CASE STUDY IN CHINA

PAUL KIRSHEN[1], MARK McCLUSKEY[2], RICHARD VOGEL[3] and KENNETH STRZEPEK[4]

[1]*Department of Civil and Environmental Engineering and WaterSHED Center, Tufts University, Medford, Massachussetts 02155, U.S.A.*
E-mail: paul.kirshen@tufts.edu
[2]*CDM, Inc., Denver, Colorado, U.S.A.*
[3]*Department of Civil and Environmental Engineering and WaterSHED Center, Tufts University, Medford, Massachussetts 02155, U.S.A.*
E-mail: Richard.vogel@tufts.edu
[4]*Department of Civil, Environmental and Architectural Engineering, and Environment and Behavior Program, Institute for Behavioral Science, University of Colorado, Boulder, Colorado 80309, U.S.A.*

Abstract. Using China as a case study, a methodology is presented to estimate the changes in yields and costs of present and future water production systems under climate change scenarios. Yield is important to consider because it measures the actual supply available from a river basin. Costs are incurred in enhancing the natural yield of river basins by the construction and operation of reservoirs and ground water pumping systems. The interaction of ground and surface waters within a river basin and instream flow maintenance are also modeled. The water demands considered are domestic, irrigation, and instream flow needs. We found that under climate change the maximum yields of some basins in China may increase or decrease, depending upon location, and that in some basins it may cost significantly more or it may not be possible to meet the demands. While our results for China could be improved with more hydrologic and economic data, we believe that the cost curves developed have suitable accuracy for initial analysis of water supply costs in Integrated Assessment Models.

1. Introduction

Vorosmarty et al. (2000) and Nijssen et al. (2001) have made important recent contributions to understanding the possible biophysical and socioeconomic impacts of global-warming-induced climate change upon global water resources. Vorosmarty et al. (2000) used a distributed grid-cell water balance model applied to digitized river basins to estimate annual river basin runoff for the world's river basins under present and possible future climate change conditions. The runoffs were then compared to present and future possible water demands, using indicators relating various types of demands to the annual discharges. Nijssen et al. (2001) applied a water balance to nine large river basins in North America, South America, and Asia to determine changes in mean monthly discharges under climate change.

Here we go one step further and present how both yields and costs of present and future water production systems in global river basins may change, under possible scenarios of climate change, using a case study of China. The water production

Climatic Change (2005) 68: 303–330

component of a water supply system consists of the wells, river intakes, and storage reservoirs that actually provide the raw water to the system. From the production system, water enters the transmission system to bring the water to demand centers for distribution, with treatment if necessary, to individual users. Yield is the annual amount of supply that can be obtained from a river basin with a high level of reliability considering (1) the annual and seasonal variation in ground water, surface water and water demands and (2) the capacity of ground water wells and the storage provided by surface reservoir systems. Without surface reservoirs and wells, the annual yield of a river basin is usually significantly less than the mean annual discharge. The yield is thus important to consider because it measures the actual supply available from a river basin. Costs are incurred in enhancing the natural yield of river basins by the construction and operation of reservoirs and ground water pumping systems. In river basin yield analysis, it is also important to consider the interaction of ground and surface water within a river basin; here, we assume that ground water and surface water systems are hydraulically interconnected so that taking from the ground water directly decreases surface water flows.

Our goal is to eventually apply our methodology to the rest of the world. Thus our approach is based upon internationally available data sets. The research presented here concentrates upon water use for domestic and irrigation purposes subject to meeting environmental instream flow needs. Domestic water supply is essential for survival, and irrigation accounts for 70% of all water withdrawals (United Nations Educational, Scientific and Cultural Organization, 2003). In addition, irrigation demand is very sensitive to climate change. Another goal is to provide a realistic model of water supplies and costs for use in Integrated Assessment Models (IAM). IAMs are highly aggregated models that provide insights and guidance on the global and regional socioeconomic and environmental impacts of climate change and their interactions and feedbacks. They require large-scale aggregation of economic, climate and biophysical systems; thus some aggregate the world into a single region, while most divide the world into a number of regions. The challenge of integrated assessment modeling is to capture the most influential regional aspects of the key driving processes in reduced form relations. A review of IAMs indicated that water resources are not adequately considered in most models. China was chosen as the test case for the methodology, since this is a separate region in many IAMs.

The next section of the paper describes the relevant features of China for this research. This is followed by the application of a monthly water balance model to all the river basins in China to determine the total water availability in each basin as a function of basin precipitation, temperature, and potential evapotranspiration. Here, total basin water availability is defined as the total amount of water available from the surface and ground waters of a basin and is assumed to equal the streamflow (which consists of both ground water contributions and surface runoff) at the mouth of a basin. The model was calibrated for 14 sub-basins of China using monthly time series of streamflow data selected from the Global Runoff Data Centre (GRDC) in Koblenz, Germany and 0.5 degree by 0.5 degree monthly climate time series data sets from the LINK Project (Viner, 2000). The water balance model was then extended to all the river basins in China using regional hydrologic techniques. Ninety-five-year monthly streamflow sequences were then generated under present and possible future climates using the LINK dataset and possible changes in climate from Generalized Circulation Models (GCMs). Storage reservoir yield and ground water yield models were then used with the time series of monthly water availability to determine required storage and ground water pumping capacities to meet varying consumptive domestic and irrigation demands with high levels of reliability given instream environmental needs. Thus a relationship was developed for each basin of required reservoir storage and wells, to reliably meet different levels of demands or yields. Finally the capital and operating costs of the surface reservoirs and wells (in year 2,000 dollars) associated with each yield were calculated to determine a relationship between river basin yield and cost.

2. China Case Study

China is the largest country in Asia with a total area of 9,562,904 km^2. Moving from west to east, China's topography consists of high mountains, plateaus and low coastal plains. In the northwest (the Tibetan plateau) the climate is desert and steppe. This is in contrast to the monsoon climate in the south and a cool, humid temperate climate in the north (Yoshino and Jilan, 1998). Because of the vast area, spanning from 75 to 135° longitude and 20 to 50° latitude and the varying topography, the regional distribution of precipitation in China varies from less than 50 mm in the northwest to over 1,600 mm in the southeast (Ministry of Water Resources, 1992). Most of the precipitation occurs during April through July.

China has over 1,500 rivers that have drainage areas greater than 1,000 km^2 (United Nations (UN), 1997). The 14 major river basins used in this study are illustrated in Figure 1 and summarized in Table I. Most of these rivers follow the general tendency of the topography and flow west to east emptying into the Pacific Ocean. Ground water conditions vary greatly within China with the distribution dependent upon local precipitation, hydrogeology, and vegetation. Reported in Table I are average well depths in each river basin, which is defined as "depth at which local wells operate" (Republic of China, 1979). The depths have been averaged for the larger river basin areas used in the study; specific ground water conditions may be quite different.

China began constructing waterworks projects about 4,000 years ago in the North China plain (UN, 1997). One example of these structures is the Dujiang Yan irrigation system in the Min Jiang basin built around 250 BC to control sedimentation and floods, and facilitate irrigation. Another example is the Grand Canal, which is the longest artificial waterway in the world and was built in the Sui Dynasty (AD 581–618) to divert water from the Chang Jiang river to drought prone cities and irrigation districts in the north (Vorosmarty, 1998).

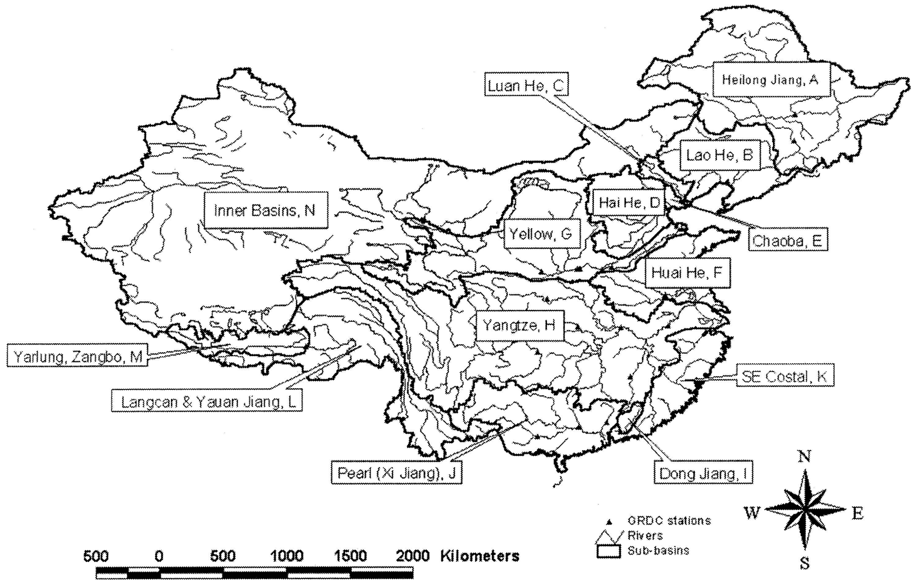

Figure 1. Fourteen river basins of China and calibration sites.

In 1949, water resources engineering projects started to be constructed at an accelerated rate particularly for flood management and water diversions for irrigation. For example, according to International Commission on Large Dams (ICOLD, 1988, 1984), 17,400 dams greater than 15 m in height were built in China from 1950 to 1986.

Table II shows water use in China in 1993 for the nine subareas used by a UN, study (1997); agricultural withdrawals are the major use. According to the UN (1997), the increase in the volume of water withdrawn for agriculture use over the period from 1993 to 2010 is expected to be 13%. Over the same period, urban and industry use is expected to increase by 250%.

Table III from UN (1997) indicates that surface water is the major source of water for all regions except the Hai He and Luan He basins in the north where ground water supply dominates. As shown in Table IV, there are also many major storage reservoirs.

3. Calibration of "abcd" Water Balance Model

The major challenges in modeling all of the river basins of China with internationally available data are that only short time series are available that might represent natural flow variations and that not all basins have streamflow records. To overcome these challenges, we used all of the streamflow data to calibrate the models for rivers where there are sufficient data and used other types of data to verify the models. We also determined relationships between the water balance model parameters and reported geophysical characteristics in the basins with adequate data. We then

TABLE I
Major river basins in China

ID	Basin	Area (km^2)	Well depth (m)
A	Heilong Jiang	915,112	20
B	Lao He	334,462	20
C	Luan He	42,097	20
D	Hai He	262,524	100
E	Chaoba	16,322	50
F	Huai He	326,990	120
G	Huang He (Yellow)	799,462	50
H	Chang Jiang (Yangtze)	1,769,162	12
I	Dong Jiang	25,161	20
J	Xi Jiang (Pearl)	487,397	15
K	SE Coastal	267,495	10
L	Langcan Jiang, Yauan Jiang	646,878	20
M	Yarlung, Zangbo	152,240	20
N	Inner basins	3,377,548	50

Note. Area is computed from ArcVIew coverage; depths from various sources in literature.

used these regional relationships to estimate parameter values in the basins without adequate streamflow records, given their geophysical characteristics. Therefore, we needed a hydrologic model with as few parameters as possible that converts precipitation, temperature and potential evapotranspiration to runoff on a watershed scale and is robust and sensitive to climate change. Following other researchers such as Fernandez et al. (2000), Vorosmarty (2000), Yates (1996), Alley (1984) and many others, we used a hydrologic model known as a water balance model. Our particular model, the "abcd" model originally developed by Thomas (1981) and Thomas et al. (1983) and recently fully described in Fernandez et al. (2000), has only four parameter values required for each watershed, accepts monthly precipitation, temperature and potential evapotranspiration (PET) as input and produces monthly watershed streamflow as output. In addition, a simple two-parameter snow accumulation/melt model is employed. Internally, the model represents soil moisture storage, snow accumulation and snow melt, ground water storage, direct runoff, ground water outflow to the stream channel and actual evapotranspiration. Others such as Xiong and Guo (1999), Guowei and Yifeng (1991), Vorosmarty (2000) and Nijssen et al. (2001) have applied water balance models to either all or parts of China, but we elected to apply a model with which we were familiar.

The first step to apply the abcd model to all Chinese river basins was to calibrate the model to basins where there were historic streamflow time series prior to 1950; based upon China's history of water resource development it was judged that there were minimal anthropogenic influences on the data prior to 1950 in most river

TABLE II
Water withdrawals in China, 1993 (in billion m^3)

Region	Basin	Industry	Urban water supply	Agriculture: Irrigation	Agriculture: Forestry, pasture, fishery	Agriculture: Rural water supply	Agriculture: Subtotal	Total
Northeastern	Heilong Jiang, Lao He	9.69	2.77	34.90	2.86	1.71	39.47	51.93
Hai He, Luan He basins	Hai He, Luan He, Chaoba	6.82	3.67	32.57	1.65	1.76	35.98	46.47
Huai He basin	Huai He	7.22	2.29	56.72	3.26	3.97	63.95	73.46
Huang He basin	Huang He (Yellow)	5.45	1.83	35.16	0.99	1.52	37.67	44.95
Chang Jiang basin	Chang Jiang (Yangtze)	34.44	7.42	139.82	6.44	8.41	154.67	196.53
Southern	Xi Jiang (Pearl)	13.85	3.87	51.71	3.26	4.50	59.47	77.19
Southeastern	SE Coastal	4.61	1.41	23.50	0.83	1.74	26.07	32.09
Southwestern	Langcan Jiang, Yauan Jiang	0.35	0.08	6.77	0.81	0.36	7.94	8.37
Interior basins	Inner basins	1.40	0.76	43.14	16.37	0.45	59.96	62.12
National total		83.83	24.1	424.29	36.47	24.42	485.18	593.11

Source: United Nations (1997).

TABLE III
Water withdrawal in China, 1980

Region	Surface water (billion m^3)	Ground water (billion m^3)	GW/SW	Total
Northeastern	26.89	8.49	0.316	35.38
Hai He, Luan He Basins	18.14	20.24	1.116	38.38
Huai He Basin	40.23	12.89	0.320	53.12
Huang He Basin	27.4	8.44	0.308	35.84
Chang Jiang Basin	128.62	6.7	0.052	135.32
Southern	65.45	0.61	0.009	66.06
Southeastern	18.8	0.51	0.027	19.31
Southwestern	4.32	0.07	0.016	4.39
Interior Basins	51.92	3.95	0.076	55.87
National total	381.77	61.9	0.162	443.67

Source: United Nations (1997).

TABLE IV
Reservoirs in China

Basin	Number of reservoirs	Total storage	Average reservoir size (m^3)	Average reservoir area (m^2)
Heilong Jiang	8	15,152,600,000	1,894,075,000	119,264,104
Lao He	27	36,368,150,000	1,346,968,519	87,825,273
Luan He	3	3,269,000,000	1,089,666,667	72,606,747
Hai He	33	17,522,850,000	530,995,455	38,082,291
Chaoba	3	1,243,520,000	414,506,667	30,490,935
Huai He	57	11,822,970,000	207,420,526	16,377,994
Huang He	207	41,508,261,000	200,523,000	15,888,255
Chang Jiang	460	165,510,416,000	359,805,252	26,853,233
Dong Jaing	15	20,048,136,000	1,336,542,400	87,214,793
Xi Jiang	180	43,959,674,000	244,220,411	18,964,105
SE coastal	214	39,822,185,000	186,084,977	14,857,452
Langcan Jiang, Yauan Jiang	30	16,859,704,000	561,990,133	40,071,875
Yarlung, Zangbo	0		–	0
Inner basins	19	46,486,900,000	2,446,678,947	150,076,294

Source: ICOLD (1984, 1988).

basins. Twelve stations with such records were available for China from the GRDC in Koblenz, Germany. These stations are shown in Figure 1. As can be seen, there are not calibration stations available for all river basins or the entire western section of the country.

A unique regional calibration approach introduced by Fernandez et al. (2000) was employed to estimate the water balance model parameters at all 12 river basins, while simultaneously relating those parameters to river basin geophysical characteristics. We found that the geophysical variable "soil water holding capacity" resulted in the best regional relationships for describing the regional variations in the abcd model parameters across China. The Food and Agriculture Organization (FAO) has global maps of soil water holding capacity in 0.5 by 0.5° gridded formats. The selection of water balance model parameter values and the fitting of regressions relating those model parameters to the geophysical characteristics of basins were achieved using a generalized nonlinear programming algorithm available as an extension to Excel® (Premium Solver Plus Version 3.5, 1999). The objective was to simultaneously maximize the goodness-of-fit of the abcd model for all 12 river basins while simultaneously maximizing the goodness-of-fit of the regional regression models which relate water balance model parameters to soil water holding capacity. The calibration was performed for the 12 basins using streamflow time series varying in length from 24 to 600 months. The regional calibration approach is explained in more detail in Fernandez et al. (2000) and McCluskey (2000).

As stated earlier, we lacked sufficient runoff data at most stations to perform split sample calibration and verification. Therefore, we used all of the limited historical data for model calibration. Model verification is subsequently described.

The regional relationships between water balance model parameter values and basin geophysical characteristics were then used to determine abcd model parameters for the 24 basins that covered all of China. The resulting streamflows for the 24 basins were then aggregated to the 14 major river basins shown in Figure 1, for development of water supply yield and cost curves.

The monthly meteorological data were taken from the LINK dataset of Viner (2000), a globally gridded 0.5 by 0.5° time series for the years 1901–1995. The Priestly Taylor method (Shuttleworth, 1993) was used to calculate the monthly PET from the Viner (2000) data.

The best results from the regional calibration procedure were obtained when the parameter a was fixed at 0.98 and c was set to 0.0. Setting c to 0.0 means that d becomes unnecessary in the model. The corresponding values of b are in Table V. Parameter a is typically between 0.8 and 1.0 and so fixing it removed an additional source of variability in the model. Parameter b is related to the upper limit on the sum of actual evapotranspiration and soil moisture storage in a given month and thus is likely to be effected by the soil water holding capacity. Parameters c and d are related to ground water influences and thus are unlikely to be related to the soil water holding capacity. These calibration results are not surprising as Vandewiele et al. (1992) compared monthly water balance models in Belgium, China and Burma and found that parameters c and d were not statistically significant for many catchments. Similar results were found by Alley (1984) whose research found that soil moisture and evapotranspiration are the dominant state variables in the monthly water balance.

TABLE V
Mean monthly runoff in mm/month

Major basin	Station	Region in China	*b* parameter	Mean Qobs	Mean Qest	Bias
Songhua Jiang	Jilin	Northeast	178.5	30.8	30.8	0.00
Luan He	Luanxian	Central (northeast)	106.9	7.3	7.3	0.00
Huai He	Bengbu	Central (east)	448	11.3	14.3	−0.26
Huang He	Huayuankou	Central	202.6	6.6	6.9	−0.05
Huang He	Sanmenxia	Central	202.2	5.1	4.6	0.10
Chang Jiang	Datong	Central	171.9	49.7	40.4	0.19
Chang Jiang	Hankou	Central	143.3	41.3	35.0	0.15
Chang Jiang	Ankang	Central	100	34.6	29.3	0.15
Chang Jiang	Yichang	Central	100	37.8	31.7	0.16
Chang Jiang	Gongtan	Central	268.9	53.9	45.7	0.15
Xi Jiang	Wuzhou 3	South	359.1	53.8	58.8	−0.09
Xi Jiang	Nanning	South	258.6	58.0	60.0	−0.04

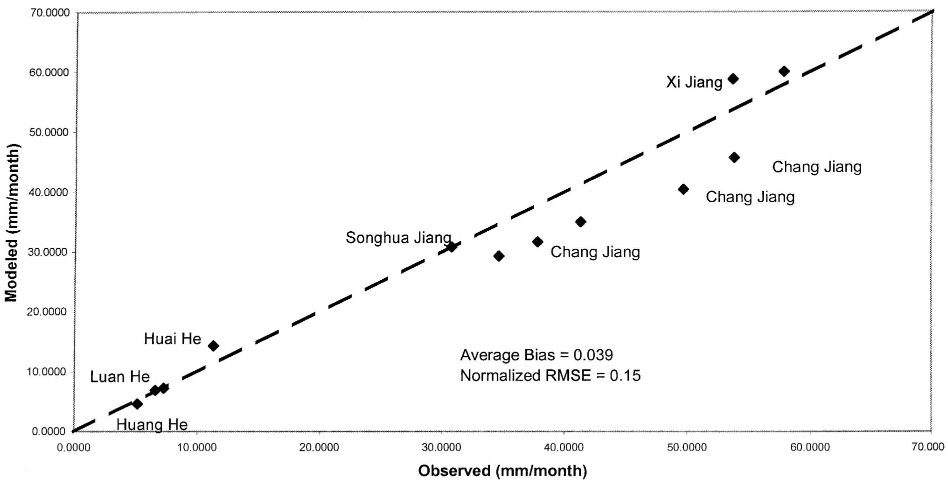

Figure 2. Modeled versus observed runoff for calibration sites.

Figure 2 compares the observed and modeled mean annual flows for the periods of record of each of the 12 basins. The bias (observed minus modeled normalized by observed) ranged from −26.5 to 18.7% with an average bias of 3.9% The root mean square error (RMSE, computed as the square root of the average squared modeled residual) normalized by the average observed runoff is 15%. Figures 3–5 compare the observed and estimated time series of monthly streamflows for three calibrated stations that are representative of the quality of calibration: Huai He at Bengbu, Wujinag at Gangtan in the Chang Jiang basin and Yu Jiang at Nanning in the Xi Jiang basin. Most of the plots are more like Figure 4 than Figures 3 or 5.

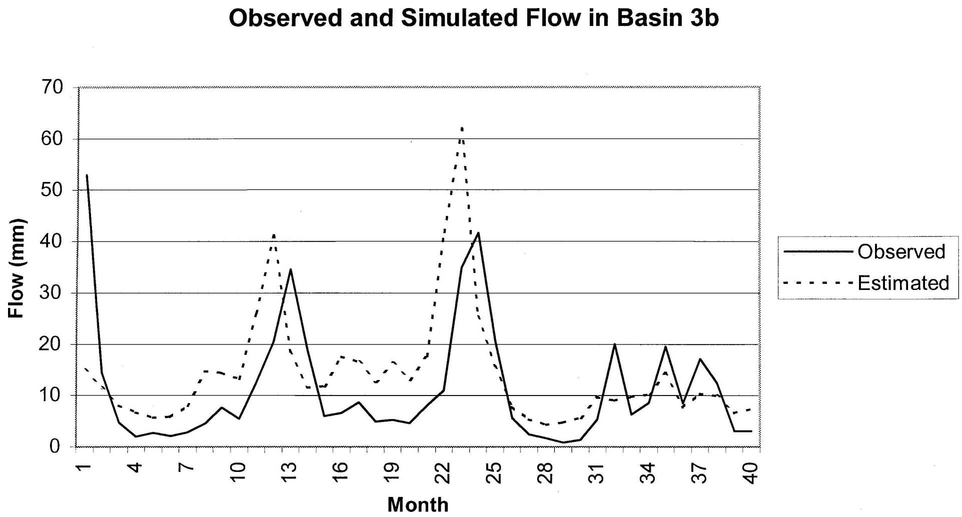

Figure 3. Observed and estimated flow basin 3b (Huai He at Bengbu).

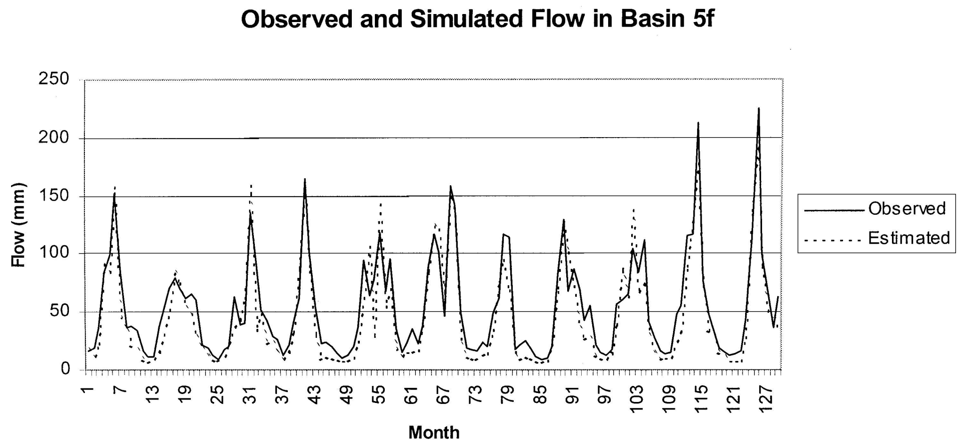

Figure 4. Observed and estimated flow for basin 5f (Wujiang river at Gongtan in Chang Jiang basin).

Overall, considering our objective of applying a lumped parameter water balance model to individual basins in order to provide a more complete country-level hydrologic picture than one would obtain by simply modeling the entire country as a whole we judged these calibrations to be acceptable. If we had just concentrated on calibrating the water balance model to individual basins, the calibrations would have been improved at the expense of the regional relationships between watershed model parameters and basin geophysical characteristics.

The calibration of our model to the Chang Jiang (Yangtze) river, the largest river in China, was among the poorest with an underestimate of reported annual flow of 15%. Generally, we underestimated the low flows that occur during the year. This is probably because this river was developed prior to 1950 and regulation resulted in

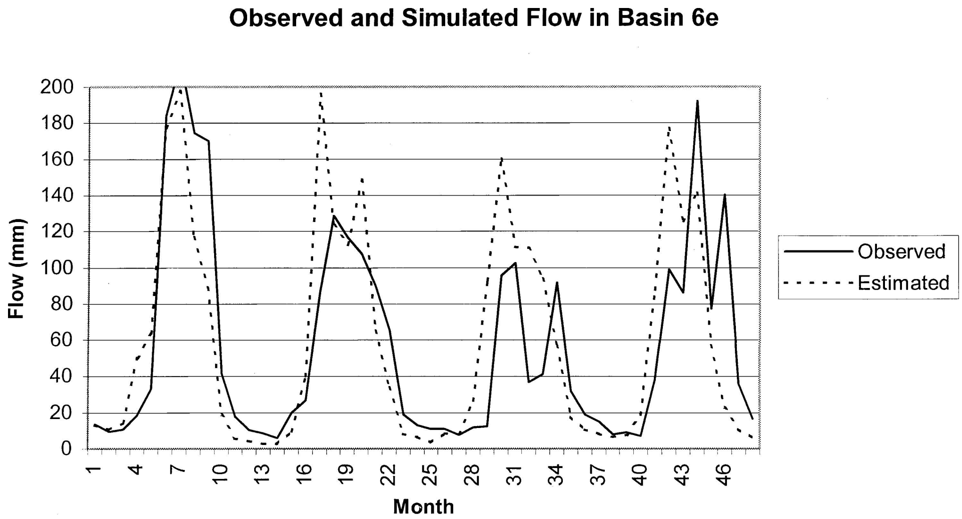

Figure 5. Observed and estimated flow basin 6e (Yu Jiang at Nanning in Xi Jiang basin).

higher low flows than naturally occur. This underestimation could result in higher reservoir storage than necessary to meet new demands just as over estimating peak flows would. As described subsequently, the underestimation in this case, however, does not significantly affect the estimates of the reservoir yields.

4. Application of abcd Model to All Chinese Basins

In order to model basins of similar scale to the 12 basins used above in the regional calibration of the abcd model, all of China was divided in 24 basins. The abcd model was then applied to each of the 24 basins using parameter values derived from the regional geophysical relationships and monthly precipitation, temperature and PET data for each basin for the period 1901–1995 from the LINK dataset. For verification of the calibration, the annual runoff at sites where there are reported values of mean annual flows were estimated by appropriate aggregation or dissaggregation of the annual flows of the 24 basins. These comparisons are provided in Figure 6. The bias ranged from −36 to 65% with an average bias of 0.10%. The RMSE normalized by the average observed runoff is 22.6%. The average annual flows compare well in Figure 6 except for the Tarim river, which is a relatively humid area in the generally low precipitation interior basins in the northwest. The poor fit is because there were no streamflow data in this region to calibrate the abcd model with, and because of the use of the low value of the spatially averaged precipitation of this generally dry climate for the precipitation estimate for the Tarim basin. Spatial averaging of climate data and lack of calibration data are also probably the causes of the flow differences in the Yarlung Zangbo basin.

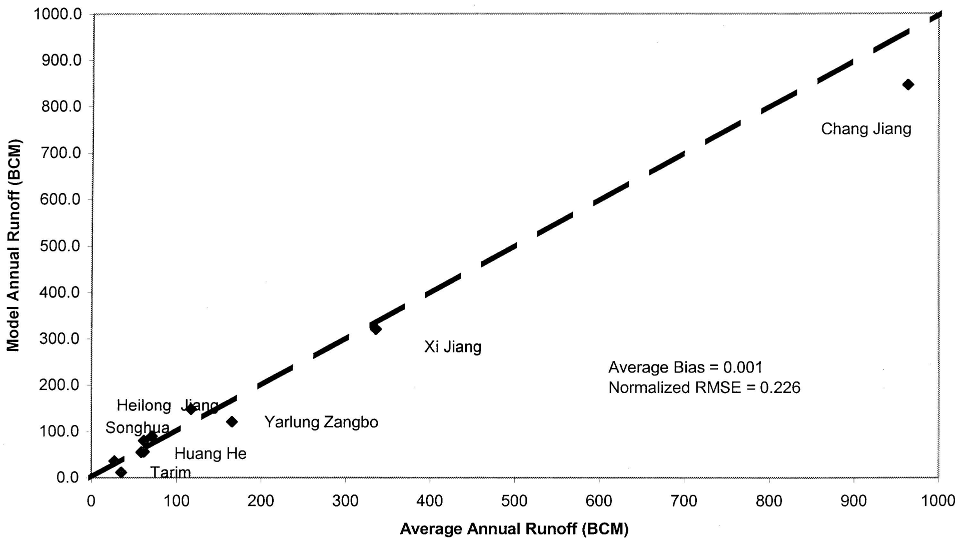

Figure 6. Modeled versus observed in aggregated basins.

Given all the possible sources of error such as limited data, the heterogeneity of China's hydrology, and the possible anthropogenic influence on some of the streamflows, we judged that a match between the estimated and observed flows of within 25% was satisfactory verification. For example, applying the same methodology to river basins that are not anthropogenically influenced in the more hydrologically homogenous southeastern United States, the average bias as approximately 4% with a range of $-11 - +31\%$ Extreme accuracy is also less important here because of our purpose of providing a methodology and cost curves for a global analysis of water supply costs in integrated assessment models. Therefore, all basins were considered satisfactory except the northwestern or inner and southwestern basins. We still included them in the analysis, because these are basins with relatively low present water use compared to the total in China and even if water uses increase as much as 30–40% their relative demand will still be small. The calibration and verification could have been improved if there were more readily available streamflow and meteorological data.

The modeling calibration and verification shortcomings under the present climate are not expected to grow with a changed climate. Some of the calibration periods for the basins in Figure 2 had records as long as 6 to 20 years or more during which a wide range of precipitation and temperature conditions occurred. The ranges of these conditions are approximately equal to some of the possible permanent precipitation and temperature changes under climate change; therefore, the calibration period included climate data not only representative of the present climate, but also of future climates. Of course, if there are extreme fundamental changes in the climate, our modeling will not be appropriate.

The monthly runoff from the 24 sub-basins were then added together to calculate the runoffs for the 14 larger basins covering all of China (Figure 1). These runoff values were then used to estimate the river basin water supply yields in each of the 14 basins as functions of storage reservoir and ground water development.

5. Basin Yields

In the future it is expected that China will continue to rely upon a combination of surface water and ground water to meet demands. Here, basin yield was defined as water supply that is available with a high degree of reliability for consumption from the development of surface water (that is, reservoir storage) and ground water sources after the maintenance of sustainable environmental flows in rivers. The use of consumption instead of total basin withdrawal as the basin yield is the correct variable to model in our yield model (described subsequently) because water is re-used as it flows downstream. If yield is set as the withdrawal requirement, the storage will be overestimated to meet the actual consumptive needs of those withdrawals. The modeling assumption, however, has to be made that there is sufficient water in the channel or ground for the withdrawal. We meet that by setting instream flow targets in the rivers. A user of our yield and cost curves, thus, must consider water reuse and efficiency in estimating consumptive demand of water uses.

Few, if any, studies on the river basin scale attempt to separate water supplies into ground and surface water sources. Most are concerned with total water availability as measured by the outflow from the basin. We separate them because we are estimating the cost of supplying monthly demands throughout the year, and ground water and surface water supply have different costs. Given the broad river basin scale of our analysis and the lack of detailed ground water data, we cannot model ground water–surface water interactions in detail. Instead, the assumption was made that any pumping of ground water will lower surface water flows. This is certainly the case in most river basins in humid areas where ground water generally drains into surface waters. Thus removal of ground water will subtract from surface water flows. The assumption does not always hold in arid areas dominated by long dry seasons where sometimes in dry seasons the elevation of the ground water is below the bottom of the river channel. These areas, however, do not generally provide large amounts of water and thus any inaccuracies due to this assumption have little impacts on the economic results. The assumption is also not valid in basins where ground water is being used that is not being recharged. Since these basins are probably located in the drier regions of China where water use is presently low, any accuracies again have little impacts on the economic results.

Simulation was used to determine the amount of ground water development and surface storage to meet various amounts of basin yield targets. For each basin yield target, the breakdown between surface water and ground water use was based upon the present ratio of ground water and surface water use in the basin in 1980, given in Table III. These are the most recent data available by basin. Data from the World Resources Institute (2003) indicates that by the early 1990s the ratio of total ground water to surface water use in China decreased from 0.16 in 1980 to 0.10; total ground water withdrawals decreasing from 62 to 53 BCM and surface water withdrawals increased from 382 to 526 BCM. Without knowing exactly in which basins these changes occurred, it is difficult to determine how to update the results to reflect these changes in water use. Since, however, ground water consumption in either case is a relatively small amount of the total water use once instream needs are considered (see later), the impacts of this shift in water sources will not significantly change the economic results.

In the simulation process, monthly ground water consumption was subtracted from the basin discharge time series and then reservoir storage necessary to provide the surface water consumptive demand and low flows was calculated. Ground water consumed varied throughout the year and was set by a monthly demand coefficient. Since it was assumed that most ground water withdrawals would remain agricultural, the monthly demand coefficient was based upon the difference between potential evapotranspiration and precipitation in the basin for each month.

Once the ground water consumption was subtracted from the streamflow time series, the reservoir storage required for a specific surface water yield was determined using the sequent-peak method (Thomas and Burden, 1963). The reservoir yields included surface water for consumption and for the maintenance of instream minimum flows. It was assumed that the surface water consumption demand was from two sources. First, 10% of the annual surface water demand was assumed to be a constant demand throughout the year to meet urban and industrial uses. This is less than the approximately 5% of present total consumptive demand, but allowing for increased urban and industrial demands in the future relative to irrigation, 10% is a reasonable value to use for the planning periods of 2055 and 2085. The remaining 90% of the annual surface water demand was distributed throughout the year for irrigation purposes using the same demand coefficients as ground water. It was decided to model the dynamic monthly demands because it was found that the estimate of the required storage was sensitive to the monthly demands. Based upon the guidance provided in Falkenmark et al. (1989), if annual withdrawals exceed 20% of mean annual flow, large water management and environmental problems may occur; hence the minimum monthly flows during the dry season were set at 80% of the average virgin monthly streamflow before ground water consumption, and during the wet season (considered to be the 4 months with highest flows) the minimum flow was set at 60% of average monthly virgin flows before ground water consumption to allow for excess water to be stored for dry periods.

To obtain the storage requirements for each of the basins the 95-year time series was split into two sets; the first set spanning from 1901 to 1950 and the second set from 1951 to 1995. The modified sequent-peak algorithm was used to model the two time series independently and the average storage requirement of the two time series was reported as the storage requirement. This value was assumed to be an

TABLE VI
Comparison of model consumption to estimated

Region	Consumption (this study) (billion m^3)	Consumption (estimated from water use data) (billion m^3)	Percent difference
Northeastern	28	25.9	8
Combined Hai He-Luan He, Huai He, Huang He, Chang Jiang	154.07	158.49	−3
Southern	38	37.86	0
Southeastern	27	15.67	72
Southwestern	10	3.95	153
Interior	4.7	36.56	−87
Total	261.77	278.43	−6

accurate estimate of the storage required to meet consumption and instream flow requirements with a reasonable level of reliability.

The net loss of water due to inundation of land behind a reservoir is the difference between PET and actual evapotranspiration. It was found that evaporation had a small, yet significant, effect upon the storage requirements for the basin. In a recent global study of large dams, Takeuchi (1997) determined a relationship between the gross capacity and the inundated area of a reservoir. This relationship was used in combination with assumptions about the surface area of a typical reservoir, and the number of active reservoirs to determine the net evaporation losses from reservoir storage in each basin. PET was estimated using the Priestly Taylor method (Shuttleworth, 1993) and actual evapotranspiration was calculated in the abcd model.

As a basis for comparison with our yield results, the present consumption of water in each of China's major river basins was estimated by multiplying the withdrawals of water by the three largest water use sectors in each basin by consumption data by sector from Shiklamonov (2000). This estimate of consumption of water was then compared to the estimate of basin consumption determined from our method using estimates of the current active water supply storage from ICOLD (1984, 1988). The comparison is shown in Table VI. As can be seen, the analysis provides reasonably accurate estimates of water consumption in the major water consuming and transferring basins in China. The Hai He–Luan He basins, Huai He, Huang He and Chang Jiang basins were combined because the review of literature regarding water use in the Northeast basins indicated that there is a large amount of water transferred between basins. The water transfer is from the water-rich regions in the South to the drier regions in the North. When these basins are combined together the deviation from the total consumption data derived from the United Nations is only 3%. The poor agreement in the Southeastern region may occur because the amount of storage reserved for flood storage could have been

TABLE VII
Ground water costs in the United States

Ground water depth (m)	Capital costs for 1,000 m^3/day	Annual maintenance costs for 1,000 m^3/day	Annual operation costs (per MCM)
10	$47,186	$1,255	$3,630
12	$56,624	$1,507	$4,356
15	$70,779	$1,883	$5,445
20	$94,373	$2,511	$7,260
50	$184,016	$5,781	$167,938
100	$316,116	$11,065	$6,215,490
120	$379,339	$13,278	$7,458,588

Source: Normand Provencher, personal communication, Pembroke Water Works (2000).

underestimated in our analysis, which would result in an overestimation of water supply storage capacity. As was found in the previous section on the calibration of the abcd model to the river basins, the reason for the large deviations in the Interior and Southwestern basins is probably the spatial averaging of the climate data and insufficient data to calibrate the model in these regions. Our methodology seems to accurately account for approximately 90% of all water consumption in China and improvements are not possible without more hydrologic and socioeconomic data.

6. Ground Water Development Costs

The capital, maintenance and operation costs were estimated for typical 1,000 cubic meters per day wells in the United States (U.S.A.) for the depths given in Table VII using information provided by Provencher (Normand Provencher, personal communication, 2000), and then adjustments were made for Chinese costs using a factor of 70% (Engineering News Record [ENR], 2000).

The capital costs included drilling, hydraulic testing, parts and labor. Operation costs were based upon pumping energy requirements of the well, and the maintenance included replacement and redrilling of the well. Well costs were applied to each basin, based upon the optimum well depths reported in Table I.

7. Surface Water Development Costs

These were estimated based upon the past work of Löf and Hardison (1966). They developed storage cost curves for 11 size classes and 10 physiographic zones in the United States. The cost curves were then modified by Wollman and Bonem (1971) by normalizing by the average unit cost over all physiographic zones and class sizes. Thus by assuming that the relationship between physiographic zone, size and relative unit storage cost remains the same in the United States and China, the cost

TABLE VIII
Reservoir storage capital costs

ID	Basin	Average cost/MCM of additional storage ($)
A	Heilong Jiang	109,867
B	Lao He	204,272
C	Luan He	177,124
D	Hai He	778,833
E	Chaoba	645,455
F	Huai He	323,100
G	Huang He	455,351
H	Chang Jiang	349,972
I	Dong Jiang	233,747
J	Xi Jiang	558,899
K	SE Coastal	365,869
L	Langcan Jiang, Yauan Jiang	212,512
M	Yarlung, Zangbo	108,321
N	Inner basins	168,061

of any size reservoir can be estimated using information on the physiography of the region. In more detail, the physiographies of Chinese basins were correlated to their slopes. Then published data on the cost of the Three Gorges dam and the slope of the Chang Jiang basin were used to estimate what the average unit cost of storage in China is, such that application of the method would result in the Three Gorges cost. The national average unit storage cost was compared to other estimates of reservoir costs to verify whether it was a reasonable value. A digital elevation model was then used to calculate the average slopes of the regional topographies. The final step was to multiply the normalized unit costs for each physiographic zone by the average storage cost in China. Since the resulting unit costs shown in Table VIII include the total of active and dead storage (dead storage is the volume of reservoir storage that is below any outlets), the dead storage volumes must be added to the active storage requirements determined in the basin yield calculations. Since easily obtainable data on dead storage in China are not available, dead storage volumes were estimated from data for U.S. reservoirs in Wollman and Bonem (1971).

8. River Basin Yields and Total Development Costs

Using the previous data, capital, operation and maintenance costs of ground water and surface water supply were developed assuming a 50-year lifetime and a 3% discount rate for the basins. The cost curves for the Chang Jiang, Huang He and Xi

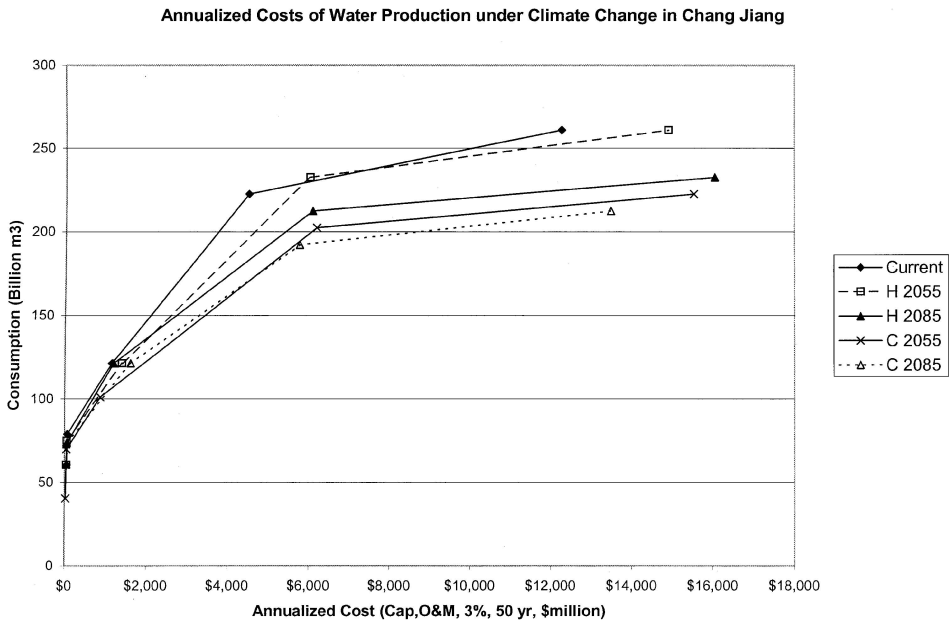

Figure 7. Annualized cost for water resources development for Chang Jiang (Yangtze).

Jiang rivers under current and climate change conditions (discussed subsequently) are shown in Figures 7–9. In each case, current water supply development was accounted for by not including the capital costs for current surface water storage and ground water facilities. Curves and data for other basins are available from the first two authors.

The steep initial parts of the curves in each of Figures 7–9 are indicative of existing water resources development in each basin where only increases in operation and maintenance costs are necessary to meet demand. The nearly horizontal parts of the ends of the curves represent maximum yields possible. Therefore the Chang Jiang and Xi Jiang basins have considerable development potential available whereas the Huang He does not.

9. Influence of Global Climate Change upon Water Resources and Water Supply Yield and Production Costs in China

9.1. CLIMATE CHANGE SCENARIOS

In this study the results from Hadley Center HadCM2 (Johns et al. 1997) and the Canadian Centre for Climate (CCC) Modelling and Analysis CGCM1 (Flato et al., 2000) Generalized Circulation Models (GCMs) were used to determine the possible effects of climate change on water supply and production costs in China. These models were chosen because of their use in the United States National

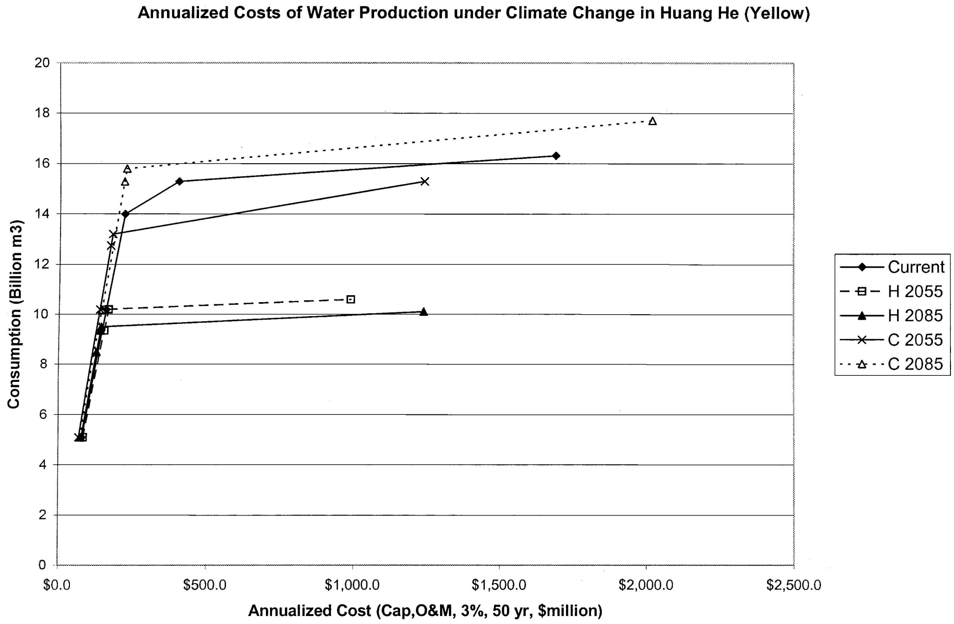

Figure 8. Annualized cost of water resources development in Huang He (Yellow River).

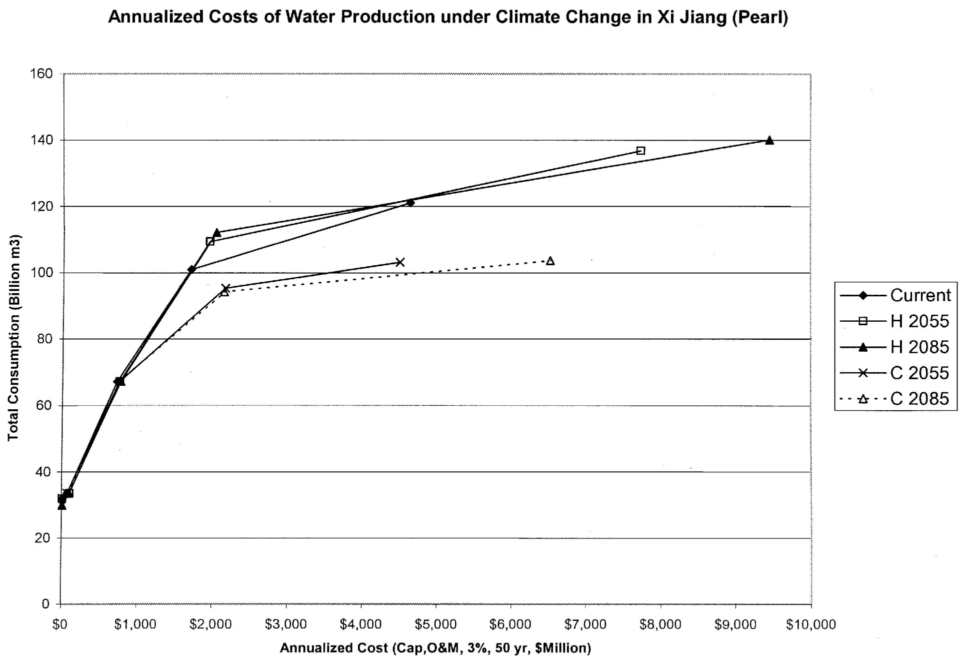

Figure 9. Annualized cost of water resources development in Xi Jiang (Pearl River).

TABLE IX
Summary table for climate change parameter data

		Annual average		
ID	Basin	T (°C)	P (mm/yr)	PET (mm/yr)
A	Heilong Jiang	0.12	498.83	496.17
B	Lao He	5.83	538.41	637.40
C	Luan He	5.17	442.42	627.94
D	Hai He	9.27	487.33	692.75
E	Chaoba	10.96	517.09	741.88
F	Huai He	14.43	799.95	794.66
G	Huang He	6.68	418.71	648.43
H	Chang Jiang	11.67	989.63	703.88
I	Dong Jiang	20.48	1789.07	918.69
J	Xi Jiang	19.21	1421.24	847.97
K	SE Coastal	17.78	1583.48	852.09
L	Langcan Jiang, Yauan Jiang	7.09	916.06	642.89
M	Yarlung, Zangbo	−1.28	773.02	728.52
N	Inner basins	2.63	183.06	884.00

Note. Base case scenario. LINK climate data set for 1901–1995.

Assessment. Both assume a 1% increase in greenhouse gases per annum (IS92a scenario). Model results with and without the effects of sulphate aerosols were used to provide a range of climate change results, because the impacts of not including aerosols drives the model outputs to extremes. Therefore while on annual basis the CGCM1 scenario is warmer and drier than the HadCM2 scenarios with aerosols (see Tables X–XIII), the CGCM1 scenario is even warmer and drier without aerosols and the HadCM2 scenario is wetter than with aerosols and warmer, though still not as warm as CGCM1 with aerosols. We do not present the results of the GCMs without aerosols to keep the paper length reasonable.

We have chosen to use coupled GCMs for our climate change scenarios instead of fabricated sensitivity analyses. As noted in Chapter 8 of Working Group 1 (WG1) of Intergovernmental Panel on Climate Change (IPCC, 2001), "coupled models can now provide credible simulations of both annual mean climate and the climatological seasonal cycle over broad continental scales for most variables of interest for climate change" (p. 511). WG1 (IPCC, 2001) also states that most models agree qualitatively and it is best to use several models. Chapter 9 of WG1 of IPCC (2001) presents information to compare GCMs on global and regional bases. One of the global parameters is transient climate response (TCR), which measures the global mean temperature change from the present climate that occurs at the time of atmospheric CO_2 doubling for the case of 1% annual increase of

TABLE X
Climate change scenarios from CGCM1 model with sulfate aerosols

	Annual average (2055)			Annual average (2085)		
Basin	delta T (°C)	delta P (%)	delta PET (%)	delta T (°C)	delta P (%)	delta PET (%)
Heilong Jiang	2.01	0.94	1.07	3.32	0.96	1.10
Lao He	2.29	0.94	1.15	3.84	0.95	1.26
Luan He	2.72	1.01	1.15	4.89	1.07	1.27
Hai He	3.45	1.04	1.17	5.87	1.18	1.27
Chaoba	2.85	1.05	1.13	5.18	1.13	1.22
Huai He	2.48	0.93	1.09	4.38	0.98	1.15
Huang He	3.24	0.97	1.14	5.53	1.05	1.23
Chang Jiang	2.67	0.89	1.11	4.76	0.90	1.19
Dong Jiang	1.36	0.94	1.05	2.88	0.92	1.09
Xi Jiang	1.73	0.93	1.07	3.61	0.94	1.11
SE Coastal	1.31	0.84	1.05	2.59	0.82	1.09
Langcan Jiang, Yauan Jiang	2.52	0.90	1.10	4.27	0.90	1.17
Yarlung, Zangbo	2.03	0.88	1.10	4.02	0.80	1.20
Inner basins	3.30	0.95	1.14	5.93	0.92	1.26

CO_2. Another is the equilibrium climate sensitivity (ECS), which measures the global mean temperature change from the present climate resulting from the equilibrium climate having a doubling of CO_2. A higher value means that the model has weaker feedback in it to increased climate changing entities; that is, the radiative forcing change. The HadCM2 and CGCM1 models have mid-range values of these parameters compared to the other approximately 20 models summarized in IPCC (2001), WG1. In terms of temperature changes in Eastern Asia in 2085 compared to the present for 1% annual increase in CO_2, WG1 (IPCC, 2001) reports that CGCM1 is generally at the high end of the temperature changes and HadCM2 is at the low end of the five GCMs reviewed for both the *with* and *without aerosols* scenarios. Thus the CGCM1 and the HadCM2 models cover the range of simulated temperature changes. The simulated precipitation changes of CGCM1 during the summer period, which is during the dominant Chinese wet season from April through July, are the maximum decreases in precipitation of all reviewed models and the increases of HadCM2 are less than the highest values of the reviewed models. During the winter (generally a drier period), the simulated changes of CGCM1 and HadCM2 of precipitation are the extremes of decreases and increases of the reviewed models. Therefore generally the temperature and precipitation changes simulated by these models are at the extremes of changes simulated by other models.

TABLE XI
Climate change scenarios from HadCM2 model with sulphate aerosols

Basin	Annual average (2055)			Annual average (2085)		
	delta T (°C)	delta P (%)	delta PET (%)	delta T (°C)	delta P (%)	delta PET (%)
Heilong Jiang	2.24	1.12	1.11	3.62	1.19	1.16
Lao He	1.47	1.27	1.06	2.70	1.29	1.12
Luan He	1.04	1.19	1.06	2.09	1.23	1.11
Hai He	1.00	1.12	1.05	2.25	1.18	1.11
Chaoba	0.95	1.14	1.06	2.09	1.06	1.12
Huai He	1.00	1.08	1.07	1.92	1.04	1.11
Huang He	1.24	1.01	1.07	2.52	1.05	1.12
Chang Jiang	1.20	0.99	1.08	2.25	0.99	1.13
Dong Jiang	0.94	1.06	1.07	1.67	1.08	1.11
Xi Jiang	1.06	1.03	1.08	1.77	1.04	1.13
SE Coastal	0.95	1.06	1.06	1.63	1.05	1.10
Langcan Jiang, Yauan Jiang	1.20	0.95	1.07	2.36	1.00	1.11
Yarlung, Zangbo	1.43	0.95	1.10	2.56	1.11	1.14
Inner basins	1.86	1.11	1.07	3.16	1.20	1.11

Mean monthly values of climate parameters from the GCMs were obtained for the "control" climate period of 1961–1990 and for scenarios for the periods 2040–2069 and 2070–2099, the latter referred to as 2055 and 2085. The values from GCM grids were then spatially averaged to represent the climates in the 24 basins used in the streamflow modeling. The results of the 24 basins were then aggregated to the 14 major basins in Figure 1.

Since the temperature, precipitation and the PET of the control periods of the GCMs do not agree with the present climate, the results from climate change scenarios must be adjusted or downscaled. This has always been one of the challenges of impact analysis and we used one of the most direct methods. Other methods such as regional modeling and weather typing may be more accurate, but they require more resources than we had for this analysis. The monthly precipitation values for a specific climate change scenario were calculated by multiplying the present values of the monthly precipitation time series by the fractional monthly changes in control period precipitation estimated by the GCM. Monthly scenario temperatures were calculated by adding the monthly scenario change to the present monthly time series. Monthly scenario PETs were calculated by multiplying the present values of the monthly PET time series by the fractional monthly changes in control period PET estimated from the GCM. Using these methods, 95-year time series of monthly climate data suitable for the abcd model were generated for each GCM scenario.

TABLE XII
Climate change scenario with CGCM1 model without sulphate aerosols

	Annual average (2055)			Annual average (2085)		
Basin	delta T (°C)	delta P (%)	delta PET (%)	delta T (°C)	delta P (%)	delta PET (%)
Heilong Jiang	3.11	0.99	1.07	5.18	0.90	1.13
Lao He	3.42	0.96	1.22	5.66	0.90	1.37
Luan He	3.92	0.99	1.21	6.95	0.96	1.37
Hai He	4.69	1.05	1.22	7.96	0.99	1.37
Chaoba	4.09	1.03	1.18	7.14	0.97	1.30
Huai He	3.65	1.05	1.11	5.72	1.05	1.18
Huang He	4.53	1.08	1.18	7.58	1.05	1.32
Chang Jiang	4.01	1.05	1.13	6.21	1.03	1.21
Dong Jiang	2.79	0.93	1.06	4.52	1.01	1.11
Xi Jiang	3.43	1.16	1.07	5.37	1.25	1.12
SE Coastal	2.35	0.87	1.07	4.02	0.95	1.11
Langcan Jiang, Yauan Jiang	3.53	1.00	1.12	5.44	0.98	1.19
Yarlung, Zangbo	3.62	0.94	1.15	5.70	1.01	1.24
Inner basins	4.63	1.01	1.19	8.34	0.94	1.35

Table IX shows the current annual average temperature, precipitation and PET for the 14 basins using the spatially averaged LINK data. Table X to XIII show the values of the parameters under the Hadley and CCC scenarios. Tables XIV and XV show the resulting modeled mean annual streamflows in the 14 basins.

9.2. CLIMATE CHANGE IMPACTS UPON REGIONAL YIELDS AND COSTS

The streamflows resulting from the climate change scenarios were used to generate cost yield curves for the scenarios using the previous procedures. The ratios of urban and industrial demand to irrigation demands and of ground water to surface water withdrawals were assumed constant in the future because we could find no literature suggesting major changes. It is also reasonable that surface water withdrawals will continue to dominate in most basins and for the country's major water demand to remain irrigation. Monthly irrigation demands for each climate scenario were based upon the difference of potential evaporation and precipitation. Further research could investigate the influence of the ratios upon the yields and costs.

Figures 7 to 9 show the cost yield curves for the Chang Jiang, Huang He and Xi Jiang under the CCC and Hadley scenarios with aerosols. These are representative of the impacts. Current consumption is noticeable on a curve where a curve abruptly

TABLE XIII
Climate change scenario with HadCM2 model without sulphate aerosols

	Annual average (2055)			Annual average (2085)		
Basin	delta T (°C)	delta P (%)	delta PET (%)	delta T (°C)	delta P (%)	delta PET (%)
Heilong Jiang	2.91	1.13	1.13	3.90	1.27	1.16
Lao He	2.64	1.12	1.11	3.50	1.25	1.17
Luan He	2.26	1.19	1.10	3.18	1.28	1.14
Hai He	2.32	1.32	1.10	3.35	1.49	1.14
Chaoba	2.22	1.26	1.10	3.17	1.30	1.15
Huai He	2.11	1.00	1.12	2.82	1.11	1.16
Huang He	2.46	1.18	1.11	3.53	1.21	1.15
Chang Jiang	2.21	0.99	1.11	3.20	0.97	1.16
Dong Jiang	1.69	0.96	1.10	2.35	1.05	1.13
Xi Jiang	1.69	1.05	1.09	2.39	1.02	1.13
SE Coastal	1.73	1.00	1.10	2.37	1.06	1.12
Langcan Jiang, Yauan Jiang	2.29	0.99	1.10	3.47	1.02	1.14
Yarlung, Zangbo	2.44	1.13	1.12	3.94	1.25	1.16
Inner basins	2.84	1.20	1.09	4.19	1.28	1.14

shifts from almost vertical to sloped; the vertical area marks the present yield where only operation and maintenance costs are necessary. Generally, the costs of providing water for consumption and low flows in a basin are related to the mean annual flows of the scenarios shown in Table XIV. For example, the 2085 Hadley scenario flow for the Huang He river in Table XIV is slightly less than the 2055 value, which is less than the present flow. Therefore these curves are "under" the present cost curve in Figure 8, with the Hadley 2085 curve slightly under the Hadley 2055 curve, because to supply a given quantity of water costs more under climate change than in the present. The minor exception to this is in the Chang Jiang in Figure 7 where the CCC 2055 scenario shows slightly less costs than does the CCC 2085 scenario, even though the 2055 scenario has slightly less annual flow than the 2085 scenario has. The explanation for this is that the 2085 CCC scenario demand and flow have more variation than does the 2055 scenario flow and demand, and require more storage than the 2055 scenario to achieve the same yield.

Several more observations can be drawn from these yield and cost curves. As can be seen by comparing the final or ultimate yield point for each scenario compared to the current case in Figures 7 through 9, the ultimate yield is sensitive to climate change. For example in the Chang Jiang (Figure 7), the ultimate yield is currently approximately 260 BCM. Under the Canadian Climate Center scenario for 2085 with aerosols, it can decrease to approximately 210 BCM. It can also be seen

TABLE XIV
Summary of mean annual flows under various GCMs (with sulphate aerosols)

		Mean annual flow (billion m^3)				
ID	Basin	Current climate	HadCM2, 2040–69	HadCM2, 2070–99	CGCM1, 2040–69	CGCM1, 2070–99
A	Heilong Jiang	151.3	135.0	149.7	115.5	133.4
B	Lao He	49.1	43.6	53.4	36.2	40.3
C	Luan He	5.6	5.6	7.2	5.8	6.4
D	Hai He	30.3	24.5	31.5	32.6	35.8
E	Chaoba	2.0	2.0	2.2	2.3	3.1
F	Huai He	98.5	119.4	103.1	100.3	133.7
G	Huang He	53.6	35.8	34.6	48.7	56.5
H	Chang Jiang	828.4	809.1	713.5	667.7	677.5
I	Dong Jiang	30.8	35.6	36.9	25.9	28.0
J	Xi Jiang	379.1	414.7	414.9	319.8	314.5
K	SE Coastal	244.8	282.1	273.6	178.8	183.1
L	Langcan Jiang, Yauan Jiang	317.3	254.7	219.0	275.7	302.7
M	Yarlung, Zangbo	85.6	68.4	79.8	74.4	63.1
N	Inner basins	14.5	16.0	17.5	11.2	9.0

that the impacts of the scenarios upon the ultimate yields are sensitive to regional location. For example, in the Xi Jiang river (Figure 9) unlike in the Chang Jiang, the ultimate yield significantly increases under a climate change scenario. The curves also show, as expected, that the investment costs to achieve a yield vary by basin. For example, to obtain a yield of approximately 120 BCM under the current climate is approximately $4.5 Billion in the Xi Jiang river, but less than $2 billion in the Chang Jiang basin.

Another observation from these figures is the current yield in each basin relative to the un-used potential under climate change scenarios. In the Chang Jiang basin (Figure 7), there is strong potential for development in the basin where approximately one third of the available water resources are being used depending upon future climate. The Huang He basin (Figure 8) is a strong contrast to the Yangtze basin. Much of the water has been developed in the basin and it is very expensive to develop additional water supply in the basin. In the Xi Jiang basin (Figure 9), where precipitation is abundant and current development low, moderate development is fairly insensitive to climate change. The curves also show the additional costs of meeting present demands under climate change. For example, Figures 7 and 9 show that there is not much increase in cost to meet the present demands under all climate change scenarios. Figure 8, however, shows that meeting the present demand of

TABLE XV
Summary of mean annual flows under various GCMs (without sulphate aerosols)

ID	Basin	Mean annual flow (Billion m^3)				
		Current climate	HadCM2, 2040–69	HadCM2, 2070–99	CGCM1, 2040–69	CGCM1, 2070–99
A	Heilong Jiang	151.3	169.4	199.7	142.8	101.8
B	Lao He	49.1	57.7	73.7	39.6	29.1
C	Luan He	5.6	5.5	7.3	5.0	5.0
D	Hai He	30.3	30.6	37.6	32.6	28.4
E	Chaoba	2.0	1.9	2.4	2.4	2.0
F	Huai He	98.5	68.8	98.6	104.6	112.9
G	Huang He	53.6	48.4	44.0	60.4	60.8
H	Chang Jiang	828.4	717.3	658.3	923.2	874.6
I	Dong Jiang	30.8	30.3	35.3	27.5	31.3
J	Xi Jiang	379.1	417.3	411.0	482.4	543.8
K	SE Coastal	244.8	240.5	271.0	182.2	212.7
L	Langcan Jiang, Yauan Jiang	317.3	221.2	201.7	332.8	344.3
M	Yarlung, Zangbo	85.6	84.8	93.3	79.0	84.8
N	Inner basins	14.5	19.0	19.7	11.9	7.7

approximately 14 billion m^3 meters will increase from approximately $200 million to $700 million under the CCC 2055 scenario and not be possible under the Hadley Center Scenarios.

10. Conclusions

The research has shown that use of a unique regional calibration approach to estimate the parameters of a water balance model coupled with a two-parameter snowmelt model resulted in a reasonable model of monthly streamflows in the hydrologically varying river basins of China. Inaccuracies in simulated flows occur in all basins because of short time series of data or no available data. Other inaccuracies occur because some basins have been heavily developed prior to 1950 or have precipitation with large spatial variations. A water balance model was combined with a simple ground water–surface water interaction relationship and reservoir storage yield and cost models to document the possible impacts of climate change on future water supply yields and water production costs by river basin. While the accuracy could be improved with additional or improved hydrologic and economic data, we believe that the cost curves have sufficient accuracy for analysis of water supply costs in integrated assessment models.

Acknowledgements

Although the research described in this article has been funded by the Office of Energy Research of the U.S. Department of Energy under Grant Number DE-FG02-98ER62665 to Tufts University, it has not been subjected to the Department's peer and policy review and does not necessarily reflect the views of the Department. Partial support for this research also came from the US National Science Foundation through its support of the Center for Integrated Assessment of the Human Dimensions of Global Change at Carnegie Mellon University under SB95-21914. We appreciate the support of ORD and NSF and also acknowledge the helpful research discussions we have had with William Fernandez, James Limbrunner, and A. Sankarasubramanian. We also appreciate the many insightful and helpful comments of an anonymous reviewer.

References

Alley, D.: 1984, 'On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance model', *Water Resources Res.* **20**(8), 1137–1149.

Engineering News Record (ENR): Fourth Quarterly Cost Report, December, 18, 2000.

Falkenmark, M., Lundqvist, J. and Widstrand, C.: November 1989, 'Macro-scale water scarcity requires micro-scale approaches', *Natural Resources Forum* **13**(4), 258–267.

Fernandez, W., Vogel, R. M. and Sankarasubramanian, A.: 2000, 'Regional calibration of a watershed model', *Hydrol. Sci. J.* **45**(5), 689–707.

Flato, G. M., Boer, G. J., Lee, W. G., McFarlane, N. A., Ramsden, D., Reader, M.C. and Weaver, A. J.: 2000 'The Canadian centre for climate modelling and analysis global coupled model and its climate', *Clim. Dynamics* **16**(6), 451–467.

Guowei, L. and Yifeng, C.: 1991, *The Water Balance of China and its Large River Basins, Hydrology for the Management of Large River Basins*, IAHS no. 201.

ICOLD: 1984, 1988, *World Register of Dams*, 1984 full edition and 1988 updating, International Commission on Large Dams, Paris.

Intergovernmental Panel on Climate Change (IPCC): 2001, *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, UK.

Johns, T. C., Carnell, R. E., Crossley, J. F., Gregory, J. M., Mitchell, J. F. B., Senior, C. A., Tett, S. F. B. and Wood, R. A.: 1997, 'The second Hadley centre coupled ocean-atmosphere GCM: Model description, spinup and validation', *Clim. Dyn.* **13**, 103–134.

Löf, George O. G. and Hardison, C.: 1996, 'Storage requirements for water in the United States', *Water Resources Res.* **2**(3) 323–354.

McCluskey, M.: September 2000, *Development of River Basin Water Supply Cost Curves for Integrated Assessment Models: A Case Study of China*, M.S. Thesis, Tufts University, Medford, MA.

Ministry of Water Resources: 1992, *Water Resources Assessment for China*, China Water and Power Press, Beijing.

Njssen, B., O'Donnell, G. M., Hamlet, A. and Lettenmaier, D. P.: 2001, 'Hydrologic sensitivity of global rivers to climate change', *Clim. Change* **50**, 143–175.

Republic of China: 1979, *Hydrologic Atlas of the People' Republic of China*, Peking, China.

Shiklomanov, I.: 2000, *World Water Vision Global Water Supply and Demand Database*, State Hydrologic Institute, St. Petersburg, Russia.

Shuttleworth, W. J.: 1993, '*Evaporation* in Maidmont, D. R. (ed.), *Handbook of Hydrology*, Chapter 4, McGraw-Hill, New York.

Takeuchi, K.: 1997, 'Least marginal environmental impact rule for reservoir development', *Hydrol. Sci. J.* **42**(4), 583–597.

Thomas, H. A.: 1981, *Improved Methods for National Water Assessment* (report), contract WR 15249270, U.S. Water Resources Council, Washington, DC.

Thomas, H. A. Jr., and Burden, R. P.: 1963, *Operations Research in Water Quality Management*, Harvard Water Resources Group, Cambridge, MA.

Thomas, H. A., Martin, C. M., Brown, M. J. and Fiering, M. B.: 1983, *Methodology for Water Resource Assessment*, Report to U.S. Geological Survey, Rep. NTIS84-124163, Natl. Tech. Info. Serv., Springfield, VA.

United Nations, China: 1997, *Water Resources and Their Use*, Economic and Social Commission for Asia and the Pacific, New York.

United Nations Educational, Scientific and Cultural Organization: 2003, *Water for People, Water for Life*, the United Nations World Water Development Report.

Vandewiele, G. L., Xu, C. and Ni-Lar-Win: 1992, 'Methodology and comparative study of monthly water balance models in belgium, China and Burma', *J. Hydrol* **134**(1–4), 315–347.

Viner, D., The Climate Impacts LINK Project: 2000, *Climate Data for the International Climate Change Research Community*. Retrieved from http://www.cru.uea.ac.uk/link/index.htm, University of East Anglia, United Kingdom.

Vorosmarty, C. J., Greeen, P., Salisbury, J., Lammers, R.: 2000, 'Global water resources: Vulnerability from climatic change and population growth', *Science*, **289**(5477).

Vorosmarty, C. J., Li, C., Sun, J. and Dai, Z.: 1998, 'Drainage basins, river systems, and anthropogenic change: The chinese example', in Galloway, J. and Melillo, J. (eds.), *Asian Change in the Context of Global Climate Change*, Cambridge, UK, pp. 210–44. Cambridge University Press.

Wollman, N. and Bonem, G. W.: 1971, *The Outlook for Water, Resources for the Future*, Inc., Johns Hopkins Press, Baltimore, MD.

World Water Resources Institute: 2003. Retrieved from www.wri.org. February 2003.

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

Yan, Jin and Xue, Q.: 1987, *Irrigation and Drainage in China*, China Water Resources and Electric Power Press, Beijing, China.

Yates, David, WatBal.: 1996, 'An integrated water balance model for climate impact assessment of river basin runoff', *Int. J. Water Res. Dev.* **12**(2).

Yoshino, Masatoshi, and Jilan, S.: 1998, *Temperate Asia: The Regional Impacts of Climate Change*, A Special Report of the IPCC Working Group II, Cambridge University Press, Cambridge, UK.

(Received 15 March 2002; in revised form 11 May 2004)