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Integrated Assessment of Hydro-Climatology Variability in Kamo River Basin: Confronting Climate and Extremes

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Abstract

One of the most urgent global issues of our time is how to build a sustainable society to cope with climatic changes and associated water-related hazards. Understanding how changes in precipitation, temperature and evapotranspiration impact runoff yield, and the resulting discharge, is significant for the sustainable management of water resources. The Hydrological Predictions for the Environment (HYPE) model and statistical methods were employed to evaluate the effects of climate and extremes on water resources in Kamo River Basin (KRB). Climate change has been taking place in recent decades in KRB, as reflected by a decrease in annual and seasonal precipitation amounts, while an increase in the annual and seasonal mean temperatures has also been observed. In addition, extreme short-term precipitation became less frequent and smaller, as indicated by the lowering of extreme indices from 1951 to 2010. The HYPE-simulated hydrological variables presented large variations, possibly due to the influence of climate change. Annual and seasonal surface runoff and stream-flow have shown a decreasing tendency. There was a decrease of more than 60mm in the mean annual and flood seasonal (March to October) surface runoff in the period 1981-2010, in comparison to the period 1951-1980. The variations in hydrological extreme indices indicate that extreme short-term flood became less frequent and smaller from 1951 to 2010. In addition, precipitation had more influence on evapotranspiration than temperature at annual and flood seasonal timescales. The annual and flood seasonal evapotranspiration had the same declining trends as precipitation. The findings of hydro-climatic characteristics in KRB indicate that the main problem for water sustainable management in the area relates to how to mitigate the increasing probability of drought.

***Keywords:** Climate change; Extreme indices; Hydrology; HYPE; Statistic.*

Abbreviations:

KRB	:	Kamo River Basin
HYPE	:	Hydrological Predictions for the Environment
NSE	:	Nash-Sutcliff Efficiency

1. Introduction

Ongoing climate change processes have been significantly affecting water resources distribution and the intensities and frequencies of hydro-meteorological extreme events [1, 2]. It is very likely that there have been statistical significant increases in the number of heavy precipitation events over most of the mid-latitude land masses and wet tropical regions, as mentioned in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (5AR IPCC). Extreme climate events and their changes are highly related to human society, as emphasized in the Special Report on Extreme Events of IPCC. Understanding how changes in precipitation, temperature and evapotranspiration impact runoff yield, and the resulting discharge, is a significant problem for the sustainable water management [3, 4].

To date, a number of studies have been conducted to ascertain evidence and the impacts of climate change on hydro-climatology in the world [5-8]. Decreasing rainfall and rising temperature in south-western Australia have resulted in surface water being less used on a proportional basis compared with groundwater, and this substitution of sources is likely to increase in future [9]. Öztürk et al. (2013) [10] reported that the water budget was most sensitive to variations in precipitation and conversion between forest and agricultural lands in the Bartin spring watershed, Turkey. Mann and Gleick (2015) [11] analyzed California drought in the early 21st century and reported that it is likely that the droughts California will experience in the future will become more severe due to climate change. A decrease in wet and warm seasonal stream-flow (and annual stream-flow) due to climate change over the past decades was found in the upper Yellow River Basin, China by Cuo et al. (2013) [5]. However, most studies have so far focused on long-term average hydrological changes in terms of annual, seasonal or monthly characteristics. Assessments of water resources changes from the perspective of extremes are not

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Detection and Indices (ETCCDI) developed 27 core indices to describe and estimate climate extremes [17]. The ETCCDI climate change indices have been widely used for assessing extreme changes due to their robustness and fairly straightforward calculation and interpretation [17-19].

There is abundant evidence of the impact of climate change on hydro-meteorology in Japan [20]. Water-related disasters are likely to occur more frequently because of abnormal changes of temperature and precipitation [21-23]. However, hydrological responses to climate change are different from place to place. It is necessary to conduct a study of hydrological variation under climate change on regions where few studies have been previously carried out, in order to provide information that can guide the sustainable water management practices. Kamo River, which flows through Kyoto city, eventually empties into Katsura River, supporting about 1.5 million residents. The Kamo River Basin (KRB), considered the historical political, socioeconomic and cultural center of Japan, is an important tourist attraction and many landscape cultural activities in the area rely on its water resources. Also, the basin is vulnerable to floods and suffered several disastrous flooding events in history. In addition, Kamo River is an important habitat of freshwater fish, which are sensitive to changes in water level [24]. Furthermore, the Kamo River bank is a popular place for sightseeing. There are open pathways along the river during the dry season. The variations of water resources in Kamo River associated with climate change are likely to have great impact on the river ecosystem and tourist economy. The effects of climate change on stream-flow variations in KRB were analyzed by using a hydrological model by Hu et al. [25]. However, this research only discussed annual and seasonal variations and neglected the changes in hydrological variables related to climate extremes.

Therefore, this study, using the work of Hu et al. [25] as its starting point, aims to identify climate extremes changes by the use of "extreme indices" and quantify water resources variations related to climate change, especially extremes changes in hydrology. The ultimate goal is to provide information for water resource managers that can help to understand hydrology variations and plan decisions associated with water related environmental change.

2. Study Area

The KRB, located around the area of Kyoto city in the western part of Japan, is a sub-basin of the Yodo River Basin (Fig. 1). It has a total area of about 210 km^2, with mountain terrain comprising about 70% of the surface. The average annual precipitation (1951-2010) was about 1580mm and the mean daily air temperature was around 15.6℃.

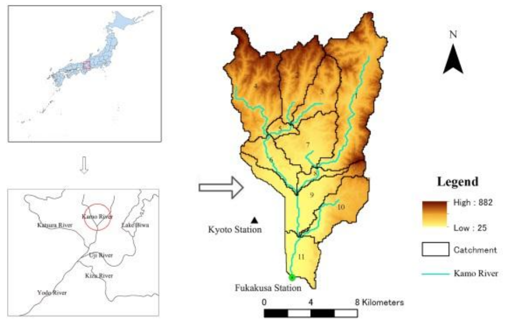

Figure 1 The location and DEM of Kamo River Basin

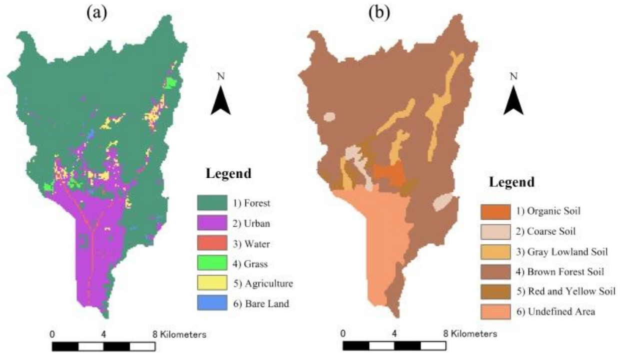

Figure 2 (a) Land use map of KRB (b) Soil type map of KRB

3. Data and Method

3.1 The Hydrological Predictions for the Environment (HYPE) model

The Hydrological Predictions for the Environment model [26, 27] was applied to investigate the effects of climate change on the hydrology of KRB. HYPE is a semi-distributed, dynamical hydrological model forced with time series of precipitation and air temperature, typically on a daily time step. It can simulate water flows in the landscape at the catchment scale. A pre-study has confirmed that HYPE can adequately simulate KRB [25]. In addition, a number of studies also reported a good performance of HYPE on simulating stream-flows in a range of climate conditions and resolutions [26-30].

In a HYPE model set-up the basin is divided into sub-basins, which are further divided into fractions based on, for example, land use and soil type. These are called hydrological response units (HRUs). HYPE calculations are based on the water balance in the soil profile and the following functions are simulated (note that the list is not exhaustive): precipitation and snow pack, soil moisture and evapotranspiration, surface and soil runoff. The detailed calculation method of each model component can be found in literature [26].

Calibration of HYPE is automatically carried out based on a Monte Carlo simulation method, which is a module of the model. To assess the performance of the model calibration, the Nash-Sutcliff efficiency (NSE) and correlation coefficient (CC) between observations and simulations are calculated. NSE measures the efficiency of a model by relating the errors to the variance in the observations [27]. Larger NSE values indicate better model performance and a perfect fit corresponds to NSE =1.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O-S)^2}{\sum_{i=1}^{n}(O-\overline{O})^2} \qquad (1)$$

Where O and S are the observed and simulated data, respectively, and n is the total number of data records [27].

3.2 Dataset

The dataset contains daily precipitation and temperature from 1951 to 2010 at Kyoto station obtained from the Japan Meteorological Agency. No missing and unrealistic records were found in the climatic data. The 50m DEM of KRB, land use map of 2006, and soil type stemmed from the Nation and Regional Planning Bureau of the Japan Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The land use map is presented in Fig. 2(a), which shows that KRB is occupied mostly by forest (74.25%), urban (21.26%), water (1.06%), grass (0.74%), agriculture (2.26%), and bare lands (0.43%). Fig. 2(b) shows the soil map and its percentage distribution: 1) Organic Soil (1.7%), 2) Coarse Soil (2.4%), 3) Gray Lowland Soil (5.4%), 4) Brown Forest Soil (72.1%), 5) Red and Yellow Soil (3.2%), and 6) Ungauged Area (15.2%).

In order to drive the HYPE simulations, the DEM, land use and soil type data were processed in a Geographic Information System (GIS). First, according to the 50m DEM the basin was divided into 11 sub-basins (Fig. 1) by means of a hydrological analysis. Then, the land use and soil maps were combined to create hydrological response units.

Daily stream-flow data at Fukakusa station (34°57'58"N, 135°45'33"E) was obtained from MLIT. However, the data was less than 10 years long and there was a discontinuity in it (1991-1995 and 2002-2005). In addition, there were 50 days missing in 2002. The observed stream-flow data were used to calibrate and validate HYPE.

3.3 Analysis of hydro- climatology changes

In a previous study by Hu et al. [25] the variables of annual and seasonal precipitation and temperature were used to evaluate climate change. However, the variables employed in the study by Hu et al. [25] cannot demonstrate changes in climate extremes. Thus, in the present study five indices (Table 1) were selected to estimate extremes, recommended by the study of Duan [31] and the ETCCDI [17]. Moreover, indices of stream-flow corresponding to extremes were also developed.

Trend analysis was carried out using the Mann Kendall Test (MKT) for monotonic trends to determine whether statistical trends exist in the measures of extremes in the time series. MKT is a non-parametric hypothesis test for statistical procedures [32]. The null hypothesis is that the data used for test is independent and randomly ordered. If the statistics results provided by MKT have a value of less than 0 this implies a decreasing trend, and if more than 0 an increasing trend.

Table 1 Definitions of hydro-climatology indices used in this study

	ID	Indicator name	Definitions	Units
Indices of climate extremes	RX1day	Max 1-day precipitation amount	Annual maximum 1-day precipitation	mm
	CDD	Consecutive dry days	Maximum consecutive days with DR <1mm	d
	R20mm	Heavy rainfall days	Annual count of days when DR>=20mm	d
	TX1day	Max 1-day mean temperature	Annual maximum 1-day mean temperature	℃
Indices of hydrological extremes	SRX1day	Max 1-day surface runoff amount	Annual maximum 1-day surface runoff	mm
	SX1day	Max 1-day mean stream-flow	Annual maximum 1-day mean stream-flow	m^3/s

DR is daily rainfall.

In addition, the time series from 1951 to 2010 was equally divided into two periods, 1951-1980 (P1) and 1981-2010 (P2). The differences of climatic and hydrological variables between the two periods were calculated to evaluate climate and hydrological changes.

4. Result

4.1 Model calibration and validation

The HYPE model was calibrated and validated in the study by Hu et al. [25], which showed that the methodology employed by those authors could accurately simulate the KRB (Table 2). Thus, the values of the parameters used in the present study were the same as those calibrated by Hu et al. [25]. There were over 15 parameters calibrated in the study by Hu et al. [25] and the 6 parameters that had highest sensitivity to model outcomes are shown in Table 3.

Table 2 Statistics in the calibration and validation

	Periods	NSE	Correlation Coefficient
Calibration	2003-2005	0.72	0.87
Validation	1993-1995	0.69	0.83

Table 3 Some of calibrated parameters and their values in the hydrological simulation

Parameter	Description	Optimal Value
CEVP	Evapotranspiration factor	Land-use dependent (0.1-0.21)
WCWP	Wilting point as a fraction	Soil-type dependent (0.08-0.1)
WCFC	Field capacity (mm/depth)	Soil-type dependent (0.07-0.33)
WCEP	Effective porosity (mm/depth)	Soil-type dependent (0.06-0.24)
RRCS1	Recession coefficient for top soil layer	Soil-type dependent (0.14-0.5)
RIVVEL	Peak velocity of stream (m/s)	General (1.68)

4.2 Climatic changes

Trend analysis was conducted for annual, flood (from March to October) and dry (from November to next February) seasonal rainfall and mean temperature, and all indices of extremes. The results are shown in Fig. 3 and Table 4. All temperature indices had significant increasing trends with time. Annual and flood seasonal precipitation amounts tended to rise, while a non-statistic decreasing trend also appeared for dry seasonal precipitation. Variations in the extreme indices of maximum daily precipitation (RX1day) and heavy precipitation days (R20mm) showed a decreasing trend. As a consequence of this the index of consecutive dry days (CDD) increased.

Table 4 Trend analysis for changes in climate

Item	Z	P	Item	Z	P
Annual Precipitation	-2.66	Y	Annual Mean Temperature	5.73	Y
Flood seasonal Precipitation	-3.01	Y	Flood seasonal mean Temperature	5.38	Y
Dry seasonal Precipitation	0.1	N	Dry seasonal mean Temperature	3.9	Y
RX1day	-1.18	N	TX1day	4.9	Y
CDD	1.7	Y	R20mm	-2.09	Y

Z are statistics from MKT; Y means significant at the level of P=0.05

Table 5 Differences in climatic indices between P1 (1951-1980) and P2 (1981-2010)

Item		1951-1980	1981-2010	Changes Value	Percentage (%)
Mean precipitation (mm)	Annual	1668.9	1491.3	-177.6	-10.6
	Flood season	1424.6	1253.4	-171.2	-12
	Dry season	244.3	237.9	-6.4	-2.6
Mean Temperature (℃)	Annual	15.2	15.9	0.7	4.6
	Flood season	19.5	20.2	0.7	3.6
	Dry season	6.6	7.2	0.6	9.1
Average RX1day (mm)		118.2	108.7	-9.5	-8

Table 5 illustrates the relative changes of precipitation and temperature between the periods of 1951-1980 (P1) and 1980-2010 (P2). It is clear that the variances correspond to the results of the trend analysis except average dry seasonal rainfall, which decreased 2.6mm from P1 to P2. Average annual and flood seasonal rainfall reduced more than 10%. A warming trend was obvious during the dry season, increasing by about 9%. The average extreme annual maximum 1-day precipitation decreased 9.5mm.

4.3 Impacts of climatic change

In order to illustrate how water resources respond to climate change, the variables of stream-flow, surface runoff and evapotranspiration and the hydrological extreme indices (listed in Table 1) were analyzed. The results of the trend analysis were presented in Table 6 and Fig. 4. Annual and flood seasonal surface runoff tended to rise, while there was a non-statistic significant decreasing trend for dry seasonal runoff. All variables of stream-flow had decreasing trends. Dry seasonal evapotranspiration seemed to increase, whereas there was a non-statistical significant decreasing trend for annual and flood seasonal evapotranspiration. Variations in the extreme indices of SRX1day and SX1day indicated a decreasing trend.

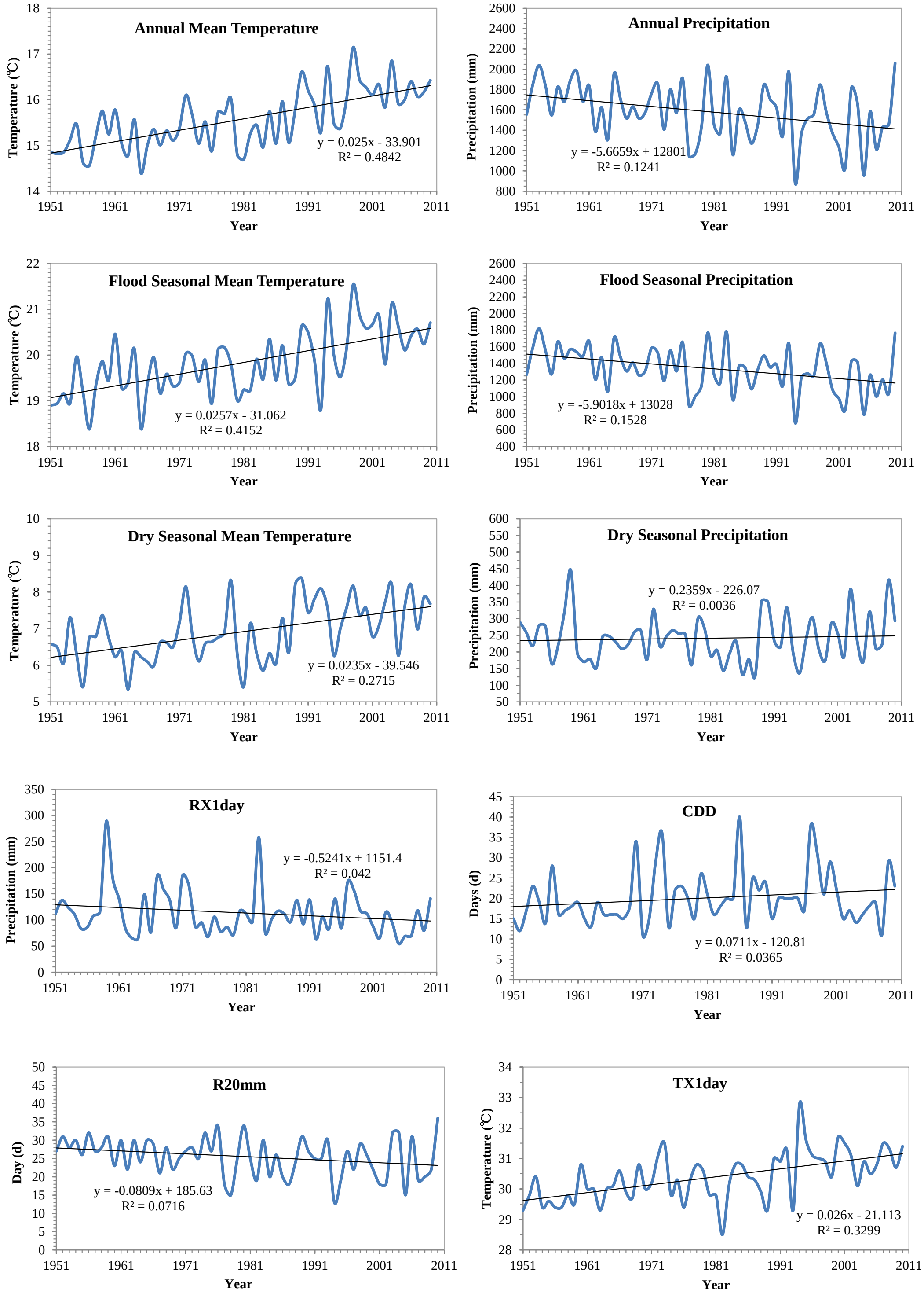

Figure 3 Linear trends in climatic change in the period 1951-2010

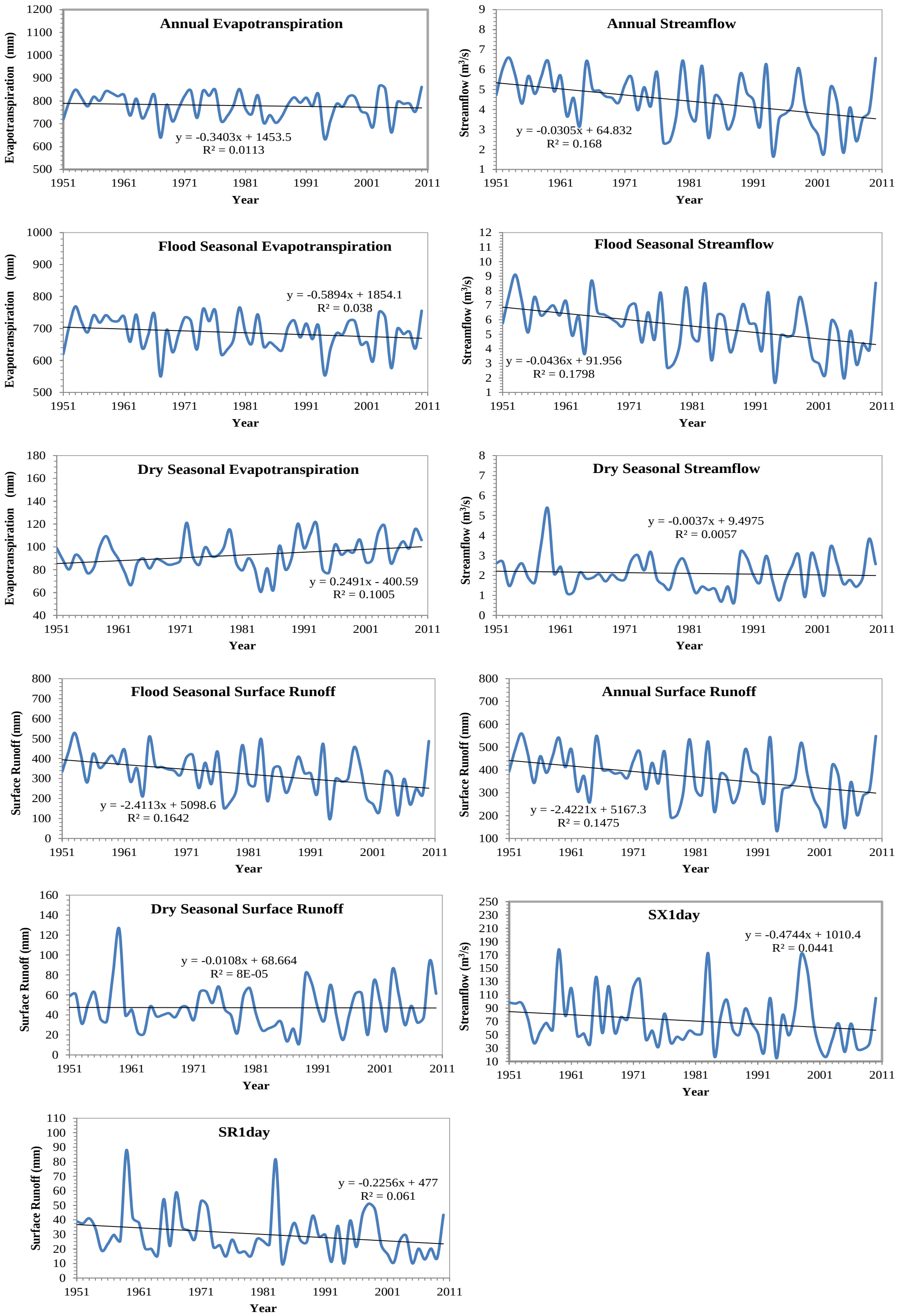

Fig. 4 Linear trends in hydrological change in the period 1951-2010

Table 6 Trend analysis for hydrological variables and extremes

Item	Z	P	Item	Z	P
Annual surface runoff	-3.16	Y	Annual seasonal stream-flow	-3.26	Y
Flood seasonal surface runoff	-3.3	Y	Flood seasonal stream-flow	-3.37	Y
Dry seasonal surface runoff	0.02	N	Dry seasonal stream-flow	-0.53	N
SRX1day	-2	Y	Annual evapotranspiration	-0.66	N
SX1day	-2.03	Y	Dry seasonal evapotranspiration	2.48	Y
Flood seasonal evapotranspiration	-1.36	N			

Z are statistics from MKT; Y means significant at the level of P=0.05

Table 7 Differences in hydrological indices between P1 (1951-1980) and P2 (1981-2010)

Item		1951-1980	1981-2010	Changes Value	Rate (%)
Surface runoff (mm)	Annual	405.4	335.3	-70.1	-17.3
	Flood	355.8	290.3	-65.5	-18.4
	dry	49.6	45	-4.6	-9.3
Evapotranspiration (mm)	Annual	788.4	770.9	-17.5	-2.2
	Flood	697.7	676.2	-21.5	-3.08
	dry	90.7	94.7	4	4.4
Stream-flow (m^3/s)	Annual	4.9	4	-0.9	-18.4
	Flood	6.2	5	-1.2	-19.4
	dry	2.2	1.9	-0.3	-13.6
Average SX1day (mm)		75.6	66.1	-9.5	-12.6
Average SRX1day (mm)		32.3	28.1	-4.2	-13

Furthermore, the variations from period 1951-1980 (P1) to period 1981-2010 (P2) were calculated (Table 7). Average dry seasonal surface runoff in period 1981-2010 decreased 9.3% in comparison to 1951-1980, which contradicts with the result of trend analysis listed in Table 6. This phenomenon requires more analysis and future study, which is outside of the scope of this paper. Changes in other variables are in accordance with the results of trend analysis. Annual and seasonal stream-flow was reduced more than 10%, while dry seasonal evapotranspiration increased about 4%. There was a more than 60mm decrease in average annual and flood seasonal surface runoff. The average extremes of SRX1day and SX1day decreased more than 10%.

5. Discussion

5.1 Uncertainties analysis

Although the research of Hu et al. [25] demonstrated that HYPE can accurately simulate the KRB, uncertainties still exist in the simulated results. First, land use changes were neglected, which can have great influence on the HYPE-simulated results in KRB [25]. In addition, not all the HYPE parameters were calibrated, and some of those that were not can have a big effect on the water balance. Thus, there are biases between modeled results and actual values. These biases, however, should not compromise the analysis since results were based on a trend analysis of simulated results and the comparison of the results in different timescales, and did not directly use the calculated values for water resource management.

5.2 Implications of recent changes in climate

It is interesting to note that the result of trend analysis of dry seasonal precipitation contradicts with the result of variation analysis from period 1951-1980 to period 1981-2010. Also, there is a same problem in the analysis results of dry seasonal surface runoff. The probable reason is due to the biases in statistics. As at the 95% confidence level for dry seasonal precipitation and surface runoff the results are not statistically significant it is clear that the MKT method is not suitable for trend analysis of dry seasonal precipitation and surface runoff. Hence, variations in dry seasonal precipitation and surface runoff require more discussion and research in the future.

Another interesting finding is that both precipitation amounts and precipitation extreme indices decreased over the last 60 years. The reducing trend in R20mm and rising trend in CDD indicate that the annual precipitation was clearly reduced. Also, the decrease in RX1day indicates that the intensity of extreme short-term precipitation tended to decrease in the period 1951 to 2010. However, in most regions of Japan extreme short-term precipitation is becoming more frequent and much bigger [22, 31]. Changes in extreme short-term precipitation are of high relevance to the changes of temperature and saturation vapor pressure [22].

5.3 Implications of climate change impacts

The simulated and statistical results indicate that climate change might become an issue for future water supplies in KRB. The average annual surface runoff in the period 1951-1980 reduced by about 70mm in comparison to 1981-2010, resulting in a stream-flow decrease of about 20%. The extreme indices of surface runoff (SRX1day) and stream-flow (SX1day) decreased in accordance with the extreme index of precipitation (RX1day), which means that the extreme short-term flood seemed to be smaller. Also, Tachikawa et al. (2011) [13] found by conducting a runoff simulation that there is clear decrease in daily drought discharge (355th daily discharge in a year which have been sorted from greatest to least) in western Japan in the period of 2015-2039 and 2075-2099.

It is found that the variations in annual and flood seasonal evapotranspiration are not in accordance with the variations in temperature. This is because the impacts of decreased precipitation on evapotranspiration are larger than the impacts of increasing temperature. As shown in Table 5, the annual and flood seasonal precipitation decreased by more than 10% (more than 170mm), while the annual and flood seasonal temperatures increase less than 5% (0.7 ℃). Essentially, potential evapotranspiration depends on temperature but evapotranspiration is also limited by the availability of water in the soil.

5.4 Water resource management

KRB is vulnerable to floods and suffered several disastrous flooding events during its history. In addition, as an important cultural landscape and freshwater fish habitat, the variations of water resource in Kamo River are of great relevance to tourism and fish survival. Climate change will thus clearly pose a challenge for the sustainable management of the area due to the growing pressure on water resources from climate change, tourism demand and ecosystem services and protection. The results of this research indicate that the main future challenges due to climate change are likely to the decreasing precipitation and river discharge and increasing consecutive dry days. Although domestic water for the Kyoto area does not originate from KRB but from Lake Biwa, it is necessary to maintain water level for tourism and fish survival during dry season. Low impact development approaches (LIDs) may be good policies to aid sustainable water management, including rainwater harvesting, bio-retention, etc. The effectiveness of LIDs to store water and mitigate water security has been proved in literature [33-36].

In addition, according to the present research extreme, short-term flood events became rarer in the last 60 years. It means that the present flood management policies are adequate to ensure human security in terms of flooding in KRB. Also, the variation of extreme flood represents a significant difference to patters across most other regions of Japan [22, 31]. Apparently, hydrological responses to climate change are different from place to place at different scales. Scientific knowledge about the variations of hydrological cycle is thus clearly the first step in sustainable water management [37, 38], and the present study thus makes a significant contribution in this direction.

6. Conclusion

Sustainable water management is a concept that emphasizes the need to consider the long-term future as well as the present [3, 39]. Scientific knowledge about the variations of hydrological cycle can thus be considered the first step in sustainable water management. Climate variations in KRB during the past decades were characterized by evaluating annual and seasonal precipitation, temperatures and extremes indices. All temperature variables increased from 1951 to 2010. Precipitation amounts exhibited a decrease at both annual and flood season scales. Compared with the period of 1951-1980, the average annual and flood seasonal precipitation in the period of 1981-2010 were reduced by more than 170mm. The variations in dry seasonal precipitation require more discussion. The precipitation extremes indices of RX1day and R20mm indicated that the intensity of the extreme short-term precipitation became less frequent and smaller from 1951 to 2010.

The HYPE model was applied to calculate the stream-flow, surface runoff and evapotranspiration according to meteorological and topography data. Then, the changes in water resources and hydrology extremes related to climate and climate extremes changes were quantified. At the annual scale, the rising temperature and dropping precipitation resulted in declining stream-flow, runoff and evapotranspiration. At the seasonal scale, climate change has caused falling stream-flow and surface runoff, with evapotranspiration decreasing during the flood season and increasing during the dry season. For the extremes analysis, an obvious decline in SX1day and SRX1day was observed.

The authors thus conclude that present flood management policies in KRB are adequate to protect humans, due to a decreasing trend of extreme short-term flood events, removing the need to improve flood management defenses. However, improving the resilience of society to decreased water resources by following low impact development approaches (e.g. rainwater harvesting, bio-retention, etc.) may be necessary in order to ensure the sustainable water management of the basin.

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