Simulating hydrological impact of environmental change in the Abukuma watershed, Japan

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Abstract The WEP model was applied to the Abukuma watershed in Japan (5400km^2). The model is validated with observed discharges at several locations in 2002, and then applied to simulations for 2003 and 2004 in a time step of 1 hour and a grid cell size of 500m. The simulation results showed good agreements with observed in both low streamflow and flood hydrographs. The hydrological impacts of possible future environmental changes in the watershed, i.e. increase in air temperature, rainfall intensity and patterns, land use alteration and urbanization, are simulated using the WEP model. Evaporation, surface runoff and groundwater recharge are found sensitive to the environmental changes, and the hydrographs are also modified.

Key words WEP model; Abukuma watershed; environmental change; global warming; land use; water budget

INTRODUCTION

Water resource management in watersheds is essential for both sustainable human society and nature conservation. However, growing economy, populations and urbanization have been direct and indirect pressures on the basin-scale hydrological cycles in many watersheds. Most significant indirect pressure would be the climate change caused by the global warming. Water-related hazards may increase in humid climate regions, while droughts are more threats in dry zones. Land use is also the direct control factor of hydrological cycle in the watershed and is dominated by human activities and climatic conditions. Under these changing conditions, physically distributed modeling is highly required for hydrological prediction in watersheds with heterogeneous land surfaces, soils and aquifers under uneven distribution conditions of rainfall to better estimate the impacts of future environmental changes such as land use alteration, urbanization and climate change. The WEP model (Water and Energy transfer Processes model), a grid-based distributed hydrological model developed by Jia et al. (2001), has a great potential for sustainable water resource management on the watershed level. In this study, we applied the WEP model to the Abukuma Watershed, Japan, for assessing hydrological impacts of possible climate change and land use alteration in the future.

DESCRIPTION OF THE ABUKUMA WATERSHED

Geographical, geological and meteorological conditions

The Abukuma River watershed is located in the northeast of Japan mainland, and has an area of 5,400km^2 of which forest and agricultural land use accounts for 79% and 18%, respectively. Most of the mainstream runs in the middle of the watershed from the south to the north. Many tributaries run eastward or westward. The headwater starts from the Asahidake (elevation of 1,835m) and reaches down to the Pacific Ocean. The elevation of the watershed ranges from the sea level to more than 2,000m on the west side, where a volcanic mountain range is located. On the contrary, a peneplane is dominant on the east side of the mainstream, forming mountains of low elevation and gentle river slope.

Geological conditions of the watershed are characterized by the granite and the granodiorite extending on the east side and complex mixtures of the metamorphic rock, andesite and granite on the west side. Diluvium and alluvial soils are developed on the west side due to the erosion of volcanic products. Two ravines in the mainstream provide magnificent landscapes, but limit the flood flow capacity of the mainstream channel.

The watershed is located in the temperate zone. Mean annual precipitation is as much as 1,500mm on the west side because of high elevation and snowfall, but less on the east side (1,200mm) and the plain in the north area (1,100mm). Precipitation in some mountainous areas exceeds 2,000mm.

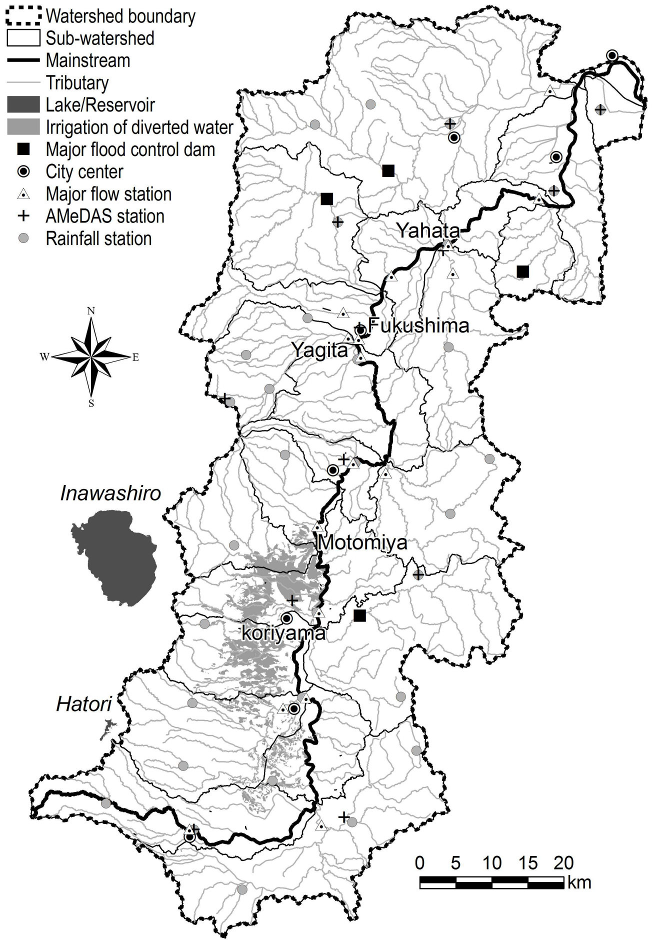

Fig. 1 Study area showing the Abukuma watershed and two lakes located outside the watershed.

Socio-economic condition

The total population in the watershed is 1.38 million. Large urban cities were developed on the fluvial basins nearby the mainstream, probably due to the access to the main water. At present, these cities utilize the mainstream for wastewater discharges, rather than domestic and industrial water uptake. Certain amount of drinking water depends on tributary rivers.

Problems in the Abukuma River watershed

The Abukuma River watershed experienced several devastating floods in the past, such ones happened in August 1986, August 1998 and July 2002. Following the flood in August 1998, which resulted in 20 deaths and injuries, 3,590 inundated households, and 69 collapsed houses, an intensive river improvement project was conducted by the embankment, dredging, installation of drainage pumps, etc. to raise the safety level against flooding. However, the river is still vulnerable to floods due to low flood flow capacity in middle to upper reaches and some bottleneck reaches. Furthermore, the recent trend of intensified rainfall is likely to cause flood damages along tributaries. In addition, the Abukuma River is recognized as one of the worst quality stream among major watersheds located in the Tohoku region (Kinouchi & Musiake, 2006). Water resources are not abundant, as the precipitation is less than the Japan's average and water use in some areas are dependent on the diversion from outside the watershed.

MODEL APPLICATION

Input data and parameters

WEP model requires a variety of input data as listed in Table 1. For each computational mesh (500m by 500m), thirteen land use types are reclassified into five categories; tall vegetation (forest and urban trees), short vegetation (grassland, paddy and other agriculture), bare soil land, water body, and impervious area (structures and ground), referring to previous studies (Jia et al., 2002, Jia et al., 2005).

Table 1 List of main input data used for WEP model simulation

Category	Item	Source
Land surface conditions	Watershed boundary Topography Land use Soil type Soil depth	Digital map* (250m by 250m DEM) National digital information* (100m by 100m raster data of 13 land use types, 1km resolution for soil types) Geologic map (borehole data)
Meteorological and hydrological conditions	Precipitation (31 stations) Relative humidity (3 station) Air temperature, Wind velocity, Sunshine duration (12 stations)	Hourly data from MLIT** and AMeDAS***
River network and hydraulic dimensions	Stream channel River profiles	Digital Map, National digital information, Survey by the MLIT
Water use	Diverted water volume Area for diverted irrigation	Report of daily water diversion from the Inawashiro Lake and the Hatori Lake Irrigation districts map
Anthropogenic conditions	Population	National census data by the Ministry of Internal Affairs and Communications

*Products of the Geographic Survey Institute, **Ministry of Land, Infrastructure, Transport and Tourism
***Automated meteorological data acquisition system by the National Meteorological Agency

The Thiessen polygon method was applied to determine precipitation and other meteorological variables of each grid cell from gauged values. Air temperature at each grid was corrected from measured one using the lapse rate (0.65°C/100m) and the elevation of the grid. No correction was made for the precipitation. The degree-day snowmelt method was included in the WEP model with the melt factor and the base temperature being 1.0mm/°C/day and 2°C, respectively.

The topsoil in the watershed is classified into ten types based on the national digital information. The hydraulic properties of each type are given from the soil sample test and sensitivity check (Fig. 2, Table 2). Exceptions are set for the topsoil overlaid on some geological types such as granite, loam and gravel (Fig. 2). Spatial distribution of the thickness and stratigraphy of the ground was given from the hydrogeological maps and borehole data at 986 locations within the watershed (Fig. 3). The extent of the ground was considered as unconfined aquifer because no distinct aquitard was found. Permeability and storage coefficient are aggregated, giving those values for each ground soil layer.

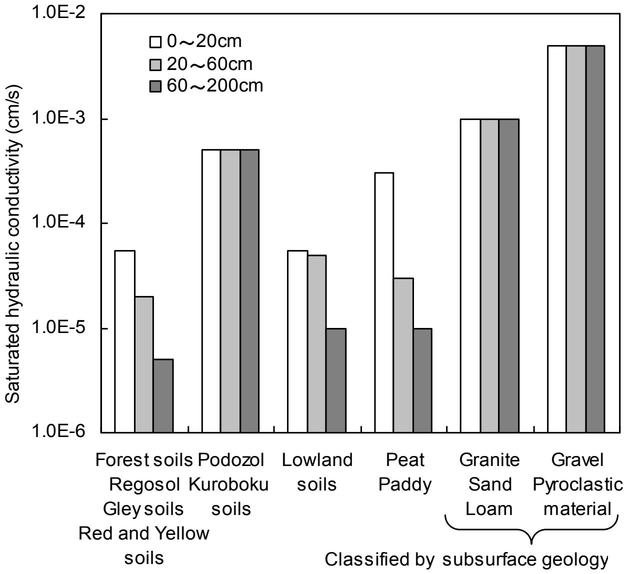

Fig. 2 Soil physical parameters (1).

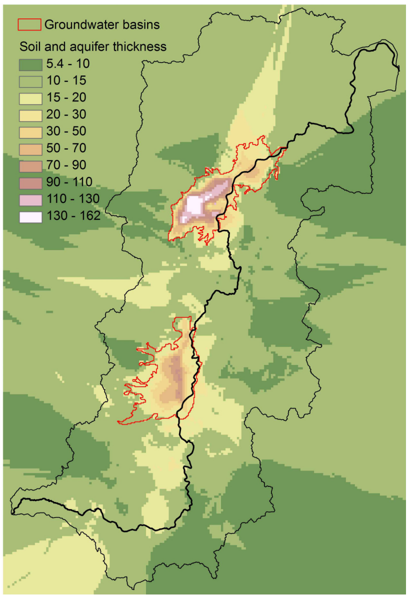

Fig. 3 Distribution of soil and aquifer depths.

Table 2 Soil physical parameters (2).

Soil or land category	Saturated and residual moisture contents		
	0–20cm	20–60cm	60–140cm
Forest soils, Gley soils, Red and yellow soils, Regosol, Podozol, Lowland soils	0.70 / 0.40	0.55 / 0.20	0.55 / 0.20
Kuroboku soils	0.70 / 0.30	0.70 / 0.30	0.70 / 0.30
Peat, Paddy	0.80 / 0.44	0.80 / 0.44	0.39 / 0.12
Urban	0.80 / 0.44	0.80 / 0.44	0.80 / 0.44

The Manning's roughness of overland flow is given as a harmonic average of the roughness coefficient for each land use type (Table 3). The overland flow is routed along the steepest downward one among eight directions to its adjacent cells using the kinematic wave method. The Manning roughness values of the mainstream are the estimates based on the inverse simulation of observed floods (Table 3), and the value for the remaining streams is set to 0.033. Dam operation rules are incorporated into the model. Unit water volume for irrigation and household is set to 200m^3/ha/day and 300litter/person/day, respectively. Irrigation water is provided from local streamflow, except for two districts where irrigation water is diverted from two lakes located outside of the Abukuma watershed (see Fig. 1).

Table 3 Equivalent roughness of each land use type.

Land use	Forest	Grassland Cropland	Paddy	Bare lands	Urban	Inland water	Stream channel
Manning's n	0.13	0.08	0.05	0.10	0.02	0.01	0.022–0.037

Validation and application

The model was run for a simulation from 2002 to 2004 in a time step of 1 hour (except for overland flow and river flow routing with a time step of 10 minutes) and a grid cell size of 500m×500m. River channels are divided into computational elements with the longitudinal length of 395 - 770m. Hourly flow discharge at representative water level measurement sites is compared with simulated results. Principle parameters are manually validated for the simulation results of 2002.

Annual and flood hydrographs Variations in simulated hourly streamflow agreed well with simulated at most measurement stations throughout years (Fig. 4). Due to snowmelt, the spring streamflow At Yagita station of the Ara river increases in both simulation and measurement (Fig. 6). Biggest floods during the simulation periods are compared between simulation and measurement (Fig. 5 and 7). The peak discharge at each station is also well reproduced. The difference is attributable to the flooding along the mainstream, as the model does not represent the flooding phenomenon. The flood in July 2002 caused inundation in large areas, which resulted in detaining and reducing flood discharge.

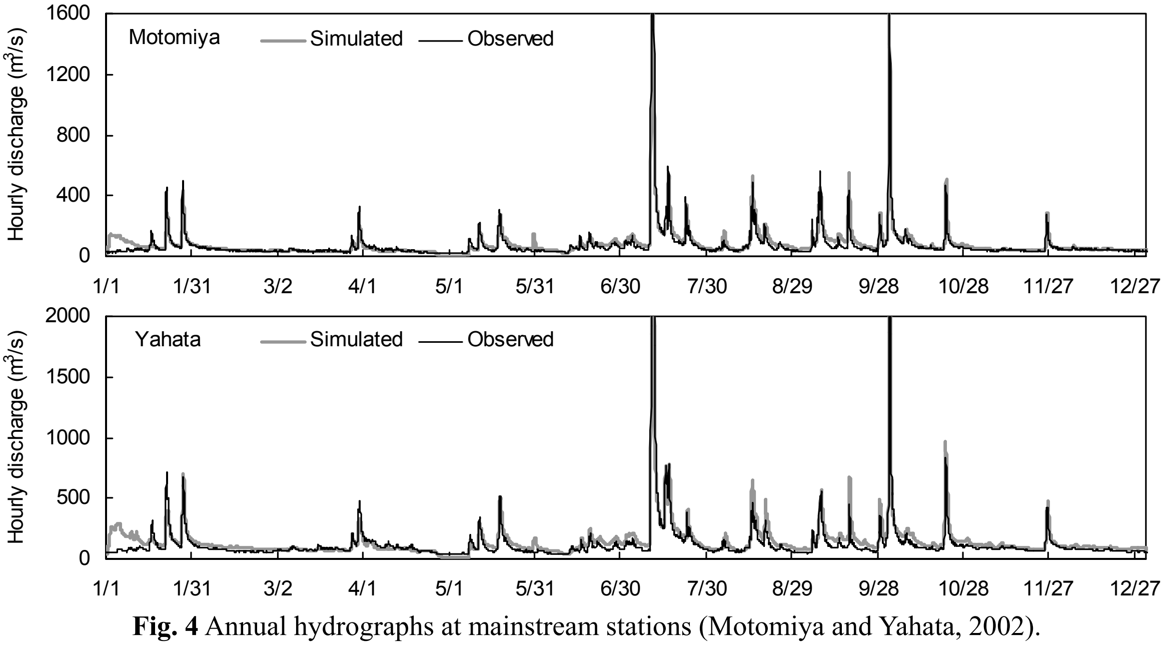

Fig. 4 Annual hydrographs at mainstream stations (Motomiya and Yahata, 2002).

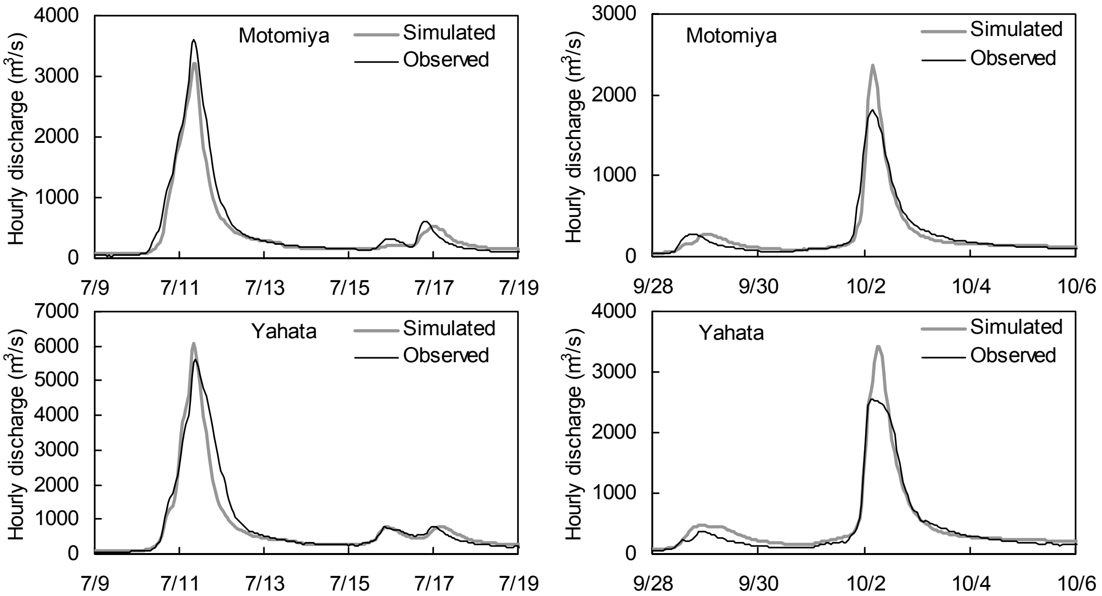

Fig. 5 Flood hydrographs at mainstream stations in July and October 2002.

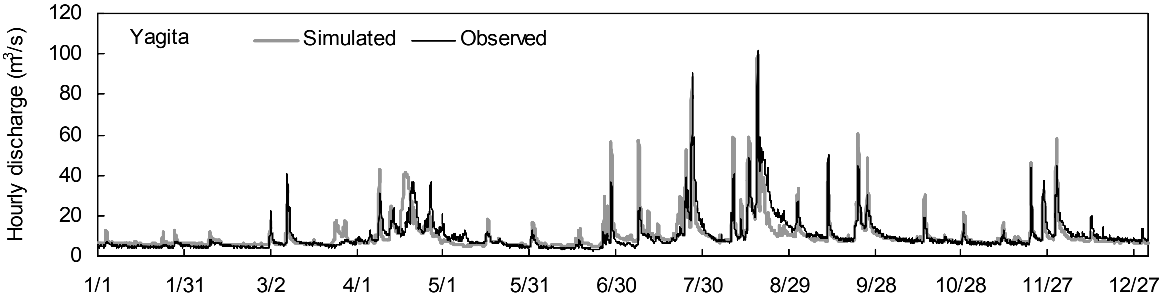

Fig. 6 Annual hydrograph at Yagita, Ara river in 2003.

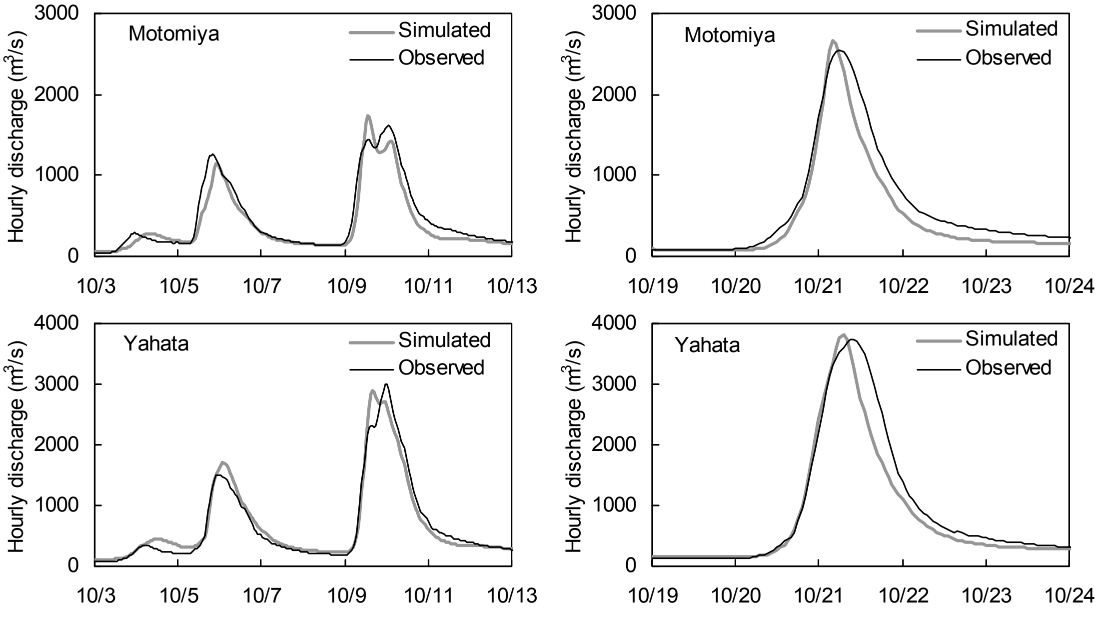

Fig. 7 Flood hydrographs at mainstream stations in October 2004.

Low flow, accumulated runoff and annual water budget Low flow is well simulated by considering the snowmelt, irrigation water diversion, and spatial distribution of ground soil characteristics. Accumulated runoff is a little overestimated due partly to the initial variable settings. Annual water budgets in 2003 and 2004 are shown in Fig. 8. Subsurface flow is larger than other components, which implies the contribution of runoff from forested lands. Surface runoff and groundwater outflow are almost comparable. Diverted water for irrigation is small in the annual budget, but it should be noted that the irrigation period is limited to about 4 months and the impact of diversion should be large in the irrigation periods.

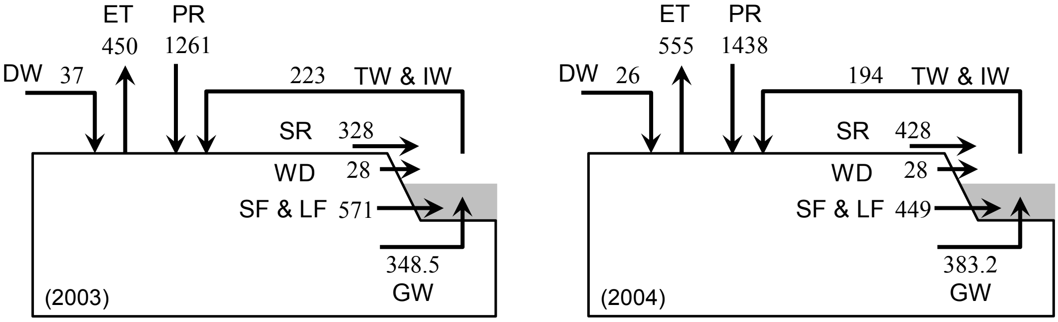

Fig. 8 Schematic of annual water budgets in the Abukuma watershed (left: 2003, right: 2004, unit: mm). ET: evapotranspiration, PR: precipitation, DW: diverted water, TW&IW: tap water and irrigation water, SR: surface runoff, WD: wastewater discharge, SF&LF: subsurface and lateral flows, GW: groundwater outflow.

HYDROLOGICAL IMPACTS OF ENVIRONMENTAL CHANGE

Impacts of future climate change were estimated giving possible scenarios of air temperature increase and precipitation variations in the future, which are based on GCM simulation results. 12% increase in evapotranspiration is predicted due to the 4°C air temperature increase alone (Fig. 9). By contrast, the groundwater recharge is reduced by about 10%, leading the reduction of runoff components (Fig. 9). More than 10% increases in groundwater recharge and surface runoff are simulated due to the 5.1% increase in annual precipitation, which was given based on the GCM derived ratios of monthly precipitation for 2091-2100 and 1991-2000. In case of the air temperature and precipitation increases, some offsetting relations are found for runoff components and evapotranspiration.

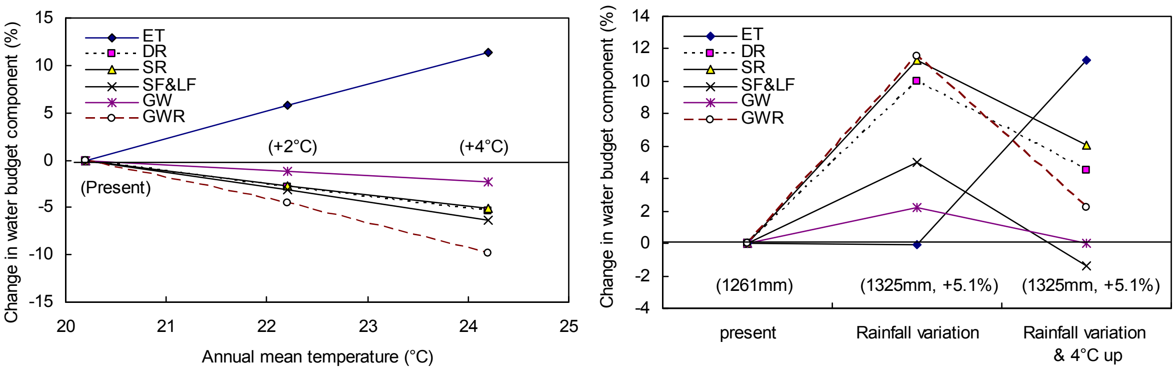

Fig. 9 Percentage of change in water budget components from those for the present case simulation result; Impacts of temperature increase (left), rainfall variations and their composite (right). DR: direct runoff (=SR+SF&LF), GWR: groundwater recharge. See Fig. 8 for other abbreviations.

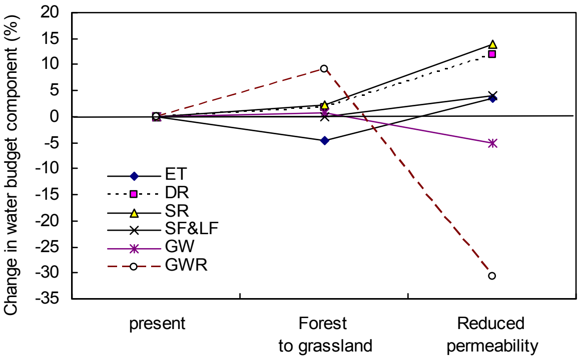

Fig. 10 Percentage of change in water budget components from those for the present case simulation result; impact of land use alteration. DR: direct runoff (=SR+SF&LF), GWR: groundwater recharge. See Fig. 8 for other abbreviations.

Impacts of deforestation, river improvement and urbanization were also simulated. As major cities in this watershed were developed over relatively permeable geological areas, significant hydrological impacts are found for surface runoff (not shown here). Channelization of tributaries is found to be one of responsible factors for quicker peak flood discharge, in addition to natural hydrological response due to geological and soil characteristics. Deforestation impact was simulated by assuming that all forested lands are turned into grasslands. Because of the reduced water consumption by transpiration of forets, groundwater recharge is increased (Fig. 10). Streamflow during floods tends to increase, but very little impact is found for the low flow. Assuming the permeability of the topsoil is reduced to one fifth, a significant increase in surface runoff was found to occur as a result of devastated forests.

CONCLUSION

This study investigated hydrological impacts of possible environmental changes in the Abukuma watershed in Japan. The WEP model was successfully applied to the watershed, and predicted the impacts of climate change and land use alteration on the water budget.

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