Assessment of the Water Resource of the Yodo River Basin in Japan Using a Distributed Hydrological Model Coupled with WRF Model

K.L. Shrestha and A. Kondo

Abstract The Yodo River basin provides water resource to the highly populated areas of Kinki, Japan. Similar to other river basins located elsewhere, the Yodo River basin is also vulnerable to negative impacts of climate change. Since accurate prediction of extreme events is essential for assessing the impact of climate change, any integrated monitoring and prediction system should be based on the hydro-meteorological system. For this goal, dynamic downscaling of the meteorological data by using coupled mesoscale hydrometeorological modeling approach to simulate the local and regional effects on water resources of the basin, has been attempted. Coupled model consisting of WRF mesoscale meteorological model and distributed hydrological model, along with a simplified dam model, at high-resolution was used to simulate the response of the Yodo River basin to atmospheric forcings in one-way coupling mode. The distributed hydrological model is shown to be capable of simulating the basin hydrology of the Yodo River basin by replacing the atmospheric forcings from observation station data with the high-resolution gridded hydrometeorological variables from WRF mesoscale meteorological model.

Keywords Distributed hydrological model · Yodo River basin · Coupled model · WRF model

1 Introduction

The IPCC (2007) has projected a substantial impact of human-induced climate change on the water resources at global and regional scales. In river basins affecting the urban population, Owing to the urban pressures, the effects of climate change

K.L. Shrestha (✉)
Kathmandu University, Dhulikhel, Kavre, Nepal
e-mail: kundan@ku.edu.np

A. Kondo
Osaka University, 2-1 Yamadaoka, Suita, Osaka, Japan

Mu. Ramkumar et al. (eds.), *Environmental Management of River Basin Ecosystems*,
Springer Earth System Sciences, DOI 10.1007/978-3-319-13425-3_8

are more pronounced in river basins as the urban centres are usually concentrated along the river courses and the urban regions have high density of population and a limited supply of water. However, the local impacts of urban and meteorological forcings on the water cycles at the river basin scales are difficult to be estimated using the climate models of the global scale. The spatial resolutions of such models are very coarse and the fine spatial variability of the river basins cannot be represented in such models. The regional models can better represent the complex orographic features and land-use distribution of a river basin. Moreover, regional and local atmospheric phenomena like sea breeze, storm and mesoscale flows can also be represented in the regional scale models.

Basin-scale physically-based distributed hydrological models have been proposed (Freeze and Harlan 1969) for documenting the increasing complexities of land-use changes, anthropogenic activities, and vegetation changes etc. (Abbott et al. 1986). The distributed models require a large set of data related to soil, vegetation, geography, etc. and they are computationally more expensive than the lumped models. Computationally cheaper models have been developed to integrate the hydrological processes with water management strategies that directly affect water resource issues such as water supply, agriculture activities and water quality problems (Arnold et al. 1998). The physically-based distributed hydrological models are important to investigate land-use change scenarios (Cai 1999; Mango et al. 2011; Miller et al. 2002; Cornelissen et al. 2013) and climate change scenarios (Kiem and Verdon-Kidd 2011; Kim et al. 2010; Mango et al. 2011; Sato et al. 2012, 2013; Thompson et al. 2013; Todd et al. 2011). Information on future hydroclimatic changes have been provided by GCM to run different hydrological models (Todd et al. 2011; Thompson et al. 2013) to assess different hydrological changes in the future. Very high resolution GCMs have also been used to provide atmospheric forcing at the resolution of 20 km (Sato et al. 2012, 2013; Kim et al. 2010) to simulate the effect of climate change on river discharge and snow melt. For limited-area applications at regional scale, mesoscale atmospheric models have been coupled with different hydrological models to evaluate the extreme hydrological events as well as the impact of hydroclimatic changes on the hydrological cycle (Cornelissen et al. 2013; Kiem and Verdon-Kidd 2011).

The advances in distributed models have helped in the implementation of better water management plans (Hooper 2011; Liu et al. 2008). The basin-scale models have been simplified and made computationally cheaper by using conceptual hydrological models (Arnold et al. 1998; Malone 2014; Liu et al. 2008; Singh et al. 2005), and their applications in the water quality research at basin scale have contributed to water pollution abatement strategies (Cai 1999; Malone 2014; Abbott et al. 1986). Several regional modeling techniques have been employed to simulate the hydrological cycle and water balance for many purposes like flood forecasting, river discharge forecasting, reservoir operational management, rainfall-runoff relationship, effect of climate change on water resources and ecosystem, groundwater flows, water quality, orographic effect on basin discharge, urban drainage flow, etc. Prediction and forecasting systems for Japanese river basins (Sayama et al. 2005; Tachikawa et al. 2007) and physically-based distributed hydrological models have been used in the Yodo River basin (Shrestha et al. 2005; Tachikawa et al. 2007) and in other urbanized basins (Jia et al. 2001, 2002). Dam operation models have also been incorporated in the hydrological models (Sayama et al. 2005; Tachikawa et al. 2007). The hydrological processes in the paddy fields have also been incorporated in the hydrological models (Sakaguchi et al. 2014). Water quantity and water quality assessments (Ikebuchi et al. 2006; Kojiri et al. 2002, 2008; Nawahda et al. 2005) have been carried out in Japan using various hydrological models.

Many researchers have focused on how to effectively use atmospheric forcings like precipitation in high spatial resolution settings of the hydrological models (Mölders and Raabe 1997; Lin et al. 2006; Verbunt et al. 2006; Seuffert et al. 2002; Hong and Lee 2009). One-way coupling of meteorological and hydrological models is mostly used to drive hydrological models by the hydrometeorological variables like air temperature and precipitation generated by meteorological models (Mölders 2005). Due to the requirement of high resolution spatial and temporal scales for coupling atmospheric and hydrological model, many computational problems arise during such integrated hydrometeorological studies. These computational limitations are also being overcome with the use of more powerful computing resources and better atmosphere-hydrology coupling techniques. Examples of the coupled hydrometeorological models are: Integrated Regional Scale Hydrologic/Atmospheric Model (IRSHAM) (Yoshitani et al. 2001); "System for Prediction of Environmental Emergency Dose Information Multi-model Package" (SPEEDI-MP) with MM5 mesoscale meteorological model as the atmospheric model, Princeton Ocean Model (POM) as the oceanic model, and SOLVEG atmosphere—soil—vegetation model as the land surface model (Chino and Nagai 2003); WRF mesoscale model coupled with a hydrological model (Yoshikane et al. 2005); hydrostatic Swiss Model (SM) and non-hydrostatic Alpine Model (aLMo) coupled with Precipitation Runoff EVApotranspiration Hydrotope (PREVAH) distributed hydrological model (Verbunt et al. 2006); Canadian atmospheric Mesoscale Compressible Community Model (MC2) coupled with the Chinese Xinanjiang hydrological model (Lin et al. 2006); integrated Hydrologic Model System (HMS) (Yu 2000); Hydrologic Model System (HMS) coupled with Regional Climate Model (RCM) (Yu et al. 2002); MM5 mesoscale meteorological model coupled with Distributed Hydrology Soil Vegetation Model (DHSVM) (Westrick and Mass 2001); MM5 mesoscale meteorological model coupled with Soil and Water Assessment Tool (SWAT) (He et al. 2009); MM5 mesoscale meteorological model coupled with distributed Water Simulation Model (WaSiM) (Kunstmann and Stadler 2005); and integrated land surface and atmosphere using MM5 mesoscale model (Kunstmann and Jung 2003).

Japan is facing several water related problems due to the impacts of climate change. The Ministry of Land, Infrastructure, Transport and Tourism (2008), Japan has reported that the snow cover in upstreams of many of the major rivers of Japan will decrease and consequently the water reservoir levels will decrease. The frequencies and intensities of floods are also projected to increase due to the anticipated higher intensities of precipitation. For example, in a future environmental scenario, yearly average maximum daily rainfall is predicted to increase by 11 %

under the A1B scenario (2080–2099 compared with 1979–1998) in Tokyo and surrounding regions.

The Water Resources Development Promotion Law, Ministry of Land, Infrastructure and Transport (Ministry of Land, Infrastructure, Transport and Tourism, Japan 2008) has termed the river systems needing water supply measures due to urban and industrial development as "river systems for water resources development and encouraged application of integrated resource management in these river systems. Seven such river systems have been identified and one of them is the Yodogawa or the Yodo River system (Fig. 1) in the Kinki region of Japan. It is situated in the southcentral region of Honshu, and has a densely populated urban region. The Kinki region includes many big cities like Osaka, Kyoto and Nara. Yodo River originates from the Lake Biwa (670.4 km^2), which is the biggest freshwater lake in Japan. The Yodo River is 75 km long and the Yodo River basin covers an area of 8,240 km^2.

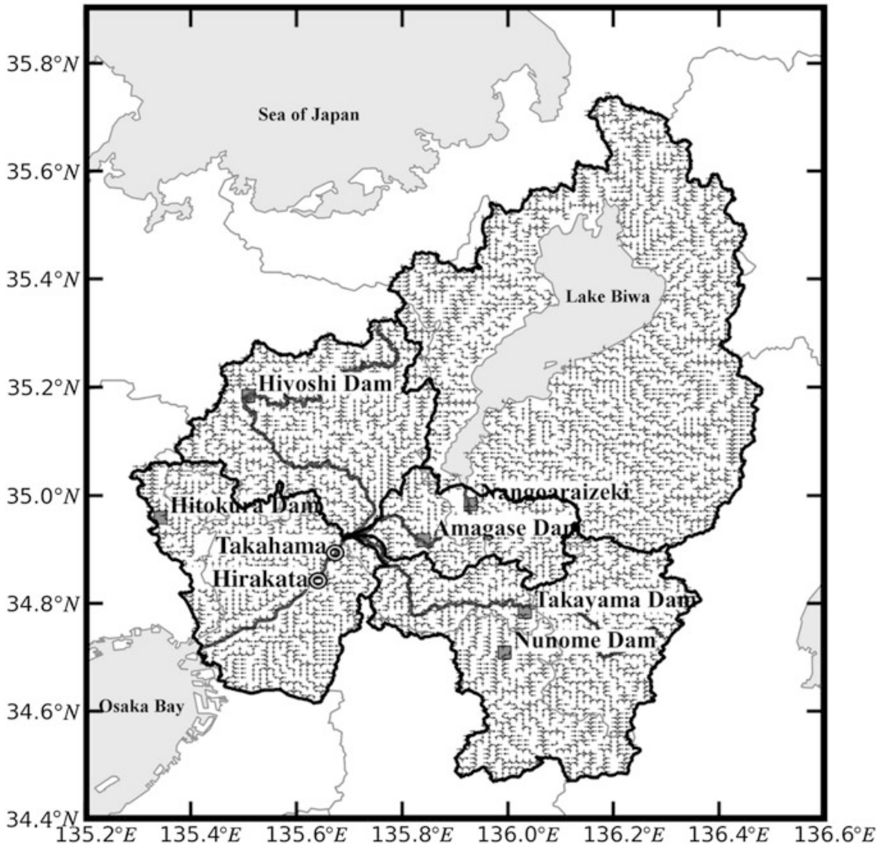

Fig. 1 Yodo River basin grid structure with flow directions. Square symbols are dams and circles represent two observation stations

There are several important factors affecting the water resources of the Yodo River basin. The Yodo River basin experiences many seasonal typhoons and heavy rainfall. Discharge in the Yodo River basin is also affected by snow melting. The Yodo River basin has also witnessed several cases of water supply shortage. Water demand has also increased due to urbanization and regional development. The Kinki region is located mostly below the river water levels and hence the risk of embankment collapse and flood is substantial. Nearly 95 % of the highly urbanized region of Osaka City has risk of flooding. These characteristics necessitate integrated water resource management study of the Yodo River basin. In this paper a hydrometeorological prediction system to simulate water cycle of the Yodo River basin has been attempted through the coupled modeling approach. The coupled model considers the land-use distribution in Yodo River basin and includes a conceptual linear storage model for subsurface transport, a tank model for paddy fields, and a simple dam model to simulate the operations of the complex dam network. This model is also coupled with the WRF mesoscale atmospheric model at high-resolution to enable the application of the model to future hydroclimatic scenarios, water resource assessment and water quality research.

2 Models and Modeling Methods Used in the Study

2.1 WRF Mesoscale Model

The Weather Research and Forecasting (WRF) is a fully compressible and non-hydrostatic mesoscale numerical weather prediction and atmospheric simulation system. It has a terrain-following hydrostatic pressure coordinate system and a flexible, modular and portable code design. It is a successor to the widely used MM5 model (Skamarock et al. 2005). The WRF can be applied at local scales to global scales, and many options of cumulus parameterization, microphysics, radiation, land surface, boundary layer are available in this model. This model was adapted for high-resolution meteorological modeling of the Yodo River basin.

2.2 Hydrological Modeling

2.2.1 Distributed Hydrological Model

The Yodo River basin is a mesoscale river basin. Hence, the impacts of meteorological and climate changes on the water resources can only be studied by high-resolution hydrological modeling. The mesoscale hydrological modeling requires finer spatial and temporal resolutions than the large-scale hydrological modeling. The land-use and precipitation data are also required to have high resolution.

For the present study, high-resolution distributed hydrological modeling approach was used to simulate the water flow and river discharge in response to the changing hydrometeorological variables in the basin. River flow, surface runoff, sub-surface groundwater flow, water intake, and dam reservoir operations in the Yodo River basin were modeled using a high-resolution distributed hydrological model based on a rainfall-runoff model known as Hydrological River Basin Environment Assessment Model (HydroBEAM) (Kojiri et al. 2002).

In the hydrological model (Fig. 2), the basin has been divided into terrain grids (that acted as a single unit basin) with horizontal resolution of 1 km × 1 km. The grids also acted as river flow network (Fig. 1) in which corresponding upstream grids were allocated for each of the downstream grids. The surface runoff in each grid flow into the corresponding downstream river grid. The terrain grid was divided into five land-use categories (fields, forest, urban, paddy and water) (Fig. 3). The basin units or the grids were vertically divided into four soil layers (A, B, C, and D from top to bottom respectively). Surface energy balance model (Sect. 2.2.2) was applied at each grid to estimate the rainfall, snowmelt and evapotranspiration. The surface runoff, runoff from paddy fields, ground water flow, water intake and release, and lateral water flows were simulated by HydroBEAM. The lateral movement of water in soil layers, except the layer D, flow into the river channel. The sewerage network, wastewater and irrigation canals in paddy fields were also included in the model.

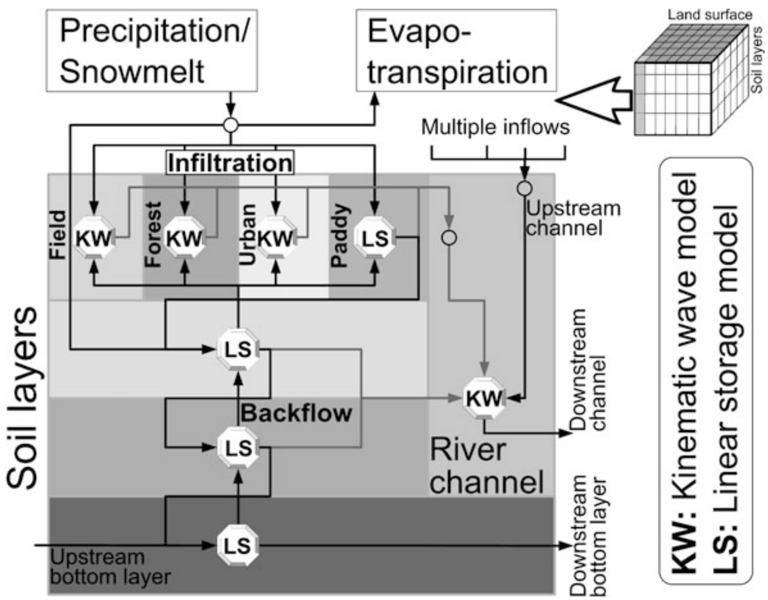

Fig. 2 Rainfall-runoff hydrological model framework

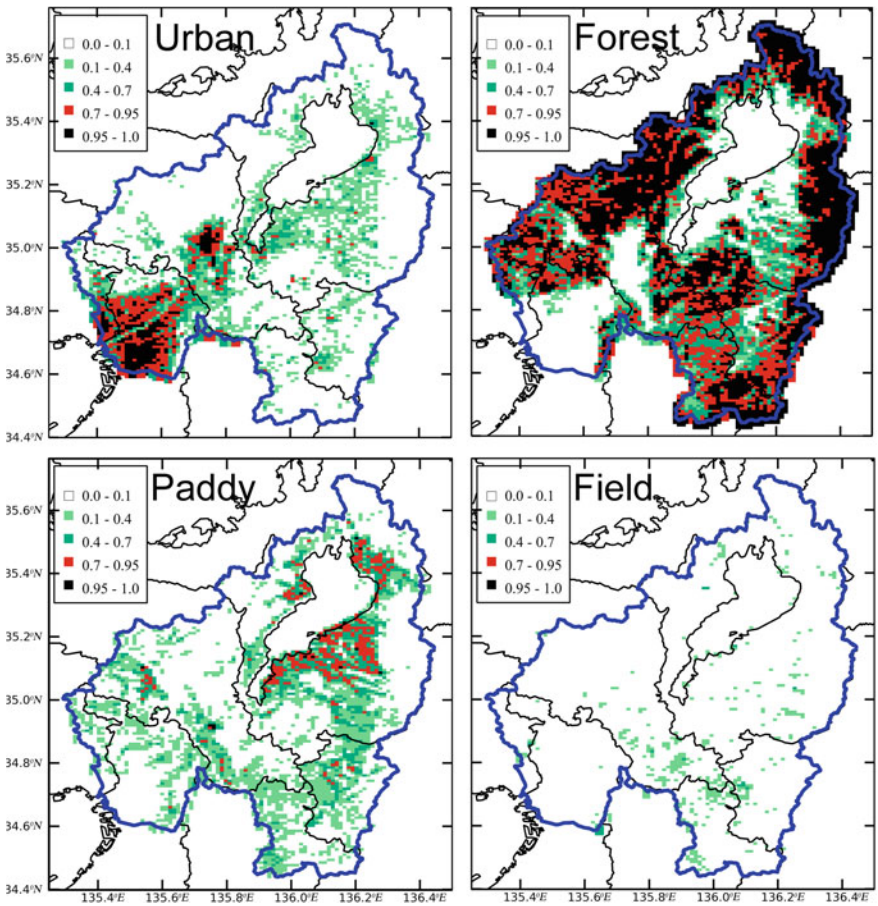

Fig. 3 Land use fraction of different land use categories in Yodo River basin

2.2.2 Surface Energy Balance Model

Using positive sign convention for incoming radiative fluxes and outgoing non-radiative fluxes from the surface, the surface energy balance equation for the basin was modeled with the bulk transfer approach to calculate the surface moisture flux. The ground heat flux was parameterized as having the diurnally averaged value of zero.

Snowfall and snowmelt were modeled by an energy balance at a single layer of snow. When near-surface air temperature was less or equal to the critical temperature, snowfall was assumed.

2.2.3 HydroBEAM Runoff Model

HydroBEAM (Kojiri et al. 2002) runoff model consists of gridded mesh structure with digital elevation data for each mesh and four soil layers namely, A, B, C and D to represent the surface layer and sub-surface layers and to facilitate the vertical water movement. The layer D represents the bottommost layer of the soil and does not contribute to the lateral water flow from the soil to the river channel of the corresponding mesh. Thus water has lateral movement in every single mesh of the basin from soil layers A, B, and C into the river channel. The direction of river channel flow was set for all the meshes of the river basin. In the HydroBEAM model, water intake and supply from various processes namely, domestic water supply, irrigation water supply, paddy field water storage and reservoir water storage systems are considered.

The surface discharges were calculated by the kinematic wave model in all the land-use categories except the paddy field. Soil layers B, C, and D were used for the simulation of the groundwater flow using linear storage model. For the paddy field, the tank model was used with three holes acting as upper ridge overflow, middle lateral ridge infiltration, and lower vertical ridge infiltration. Linear storage model equation for the soil layer D is similar to the equation for the soil layer C, but no return flow was allowed as it is the bottommost layer. Similarly, no vertical outflow from D was considered. The kinematic wave model was also used for each river grid in the hydrological model. The lateral inflow to the river grid contained flows from the A, B, and C soil layers and drainage discharge.

2.2.4 Dam Operation Model

The Yodo River basin is a multi-purpose river basin regulated with a network of dam reservoirs of various sizes that is used for flood attenuation, water supply and power generation. Six large dams have been selected for this study (shown in Fig. 1). The size and capacity of the six dams are shown in the Table 1.

Table 1 Database of six major dams of the Yodo River basin for 2006

Dams	Intake area (km^2)	Total volume ($\times 10^6$ m^3)	Flood control storage[a] ($\times 10^6$ m^3)
Nango-araizeki	3,848	27500.0	2221.0[b]
Amagase	4,200	26.3	20.0
Takayama	615	56.8	35.4
Nunome	75	17.3	6.4
Hiyoshi	290	66.0	42.0
Hitokura	115	30.8	17.5

[a] From normal water level at flooding season to surcharge water level

[b] Capacity of Biwa lake from standard water level of −0.3 m to design high-water level of 1.4 m

The effect of dam reservoirs was included as actual outflow boundary condition for the past scenarios. But this method cannot be used for the future scenarios. To develop a generalized dam model, a simplified operation rule was modeled to simulate the actual dam operation. Since the regulation of water flow in the rivers needs to be considered for correct prediction of the outflow of the rivers, a simple dam model with fluctuating water level was constructed, in which the desired water levels were set according to the normal water levels and flood water levels stipulated by the present dam operation rules (Table 2). The maximum allowed water level was the surcharge level and the water level was not allowed to decrease beyond the minimum level. According to the water levels set for the flooding and non-flooding seasons, the outflows of dams were adjusted to maintain the required water levels. The weather reports and forecasts are referred by dam operators to predict the floods according to the precipitation rate in the catchments of dams. Given cognizance to this, in the simplified dam model, the past and future precipitation forecasts were directly obtained from the meteorological input from the mesoscale model. The water levels were accordingly lowered to adjust for the flood. Though there are several modes of operation depending upon the intensity of precipitation and estimated flood (Sayama et al. 2005), in the present study, only a single operation rule was applied in the simplified model, so that the water level is adjusted if the precipitation intensity predicted by the meteorological model for the next day is more than 50 mm/day in the terrain grid of the dam.

Table 2 Different water levels of six major dams of Yodo River basin for 2006

Dams	Water levels (EL m)[a]	Normal (non-flooding)	Normal (flooding)[b]
	Surcharge		
Nangoaraizeki	1.4	0.3	−0.2 BSL m
(6/16–8/31)			
−0.3 BSL m			
(9/1–10/15)			
Amagase	78.5	78.5	72.0
Takayama	135.0	135.0	117.0
Nunome	287.3	284.0	280.6
			(6/16–8/15)
			279.2
			(8/16–10/15)
Hiyoshi	201.0	191.4	178.5
Hitokura	152.0	149.0	135.3

[a] From Dam database of ministry of land, infrastructure and transport, Japan
[b] Flooding season is 6/16–10/15 if not stated

2.3 Input Data for the Hydrological Model

2.3.1 Observed Precipitation Data

Thiessen polygon method (Thiessen 1911) was used for the regions having precipitation observation network. This method may underestimate the overall rainfall in the regions having a complex terrain and orographic precipitation. There are many relations used to find correlation between the precipitation, elevation (Daly et al. 1994; Drogue et al. 2002; Mölders et al. 1996; Running et al. 1987), and wind (Suzuki et al. 2003). To generate gridded precipitation for distributed hydrological modeling, the SDP (Surface Daily Product) observation station data archived by the Japan Meteorological Agency were processed. The SDP observation data also contained other hydrometeorological variables namely, air temperature, wind speed, water vapor pressure, sunshine duration, etc. Ten observation stations were used to calculate the Thiessen polygons. Then the daily average precipitation data were calculated using the Thiessen polygon method. Terrain height correction method was then used to obtain the areal average precipitation data having 1-km resolution. The corrected SDP precipitation data is termed as 'SDP data' in this paper.

2.3.2 Other Input Data for Evapotranspiration Model

Besides precipitation, near-surface air temperature, near-surface wind speed, surface pressure, water vapor pressure, and incoming shortwave radiation flux at surface are required to run the evapotranspiration model. The input data needed for all these input variables were also gridded into the Yodo River basin domain by using the Thiessen polygon method.

Near-surface air temperature data recorded at the SDP observation stations were provided by the Japan Meteorological Agency. These were used for the calculation of sensible heat flux and latent heat of vaporization. As in the case of precipitation, terrain height correction was applied to air temperature data. The correction coefficient used to consider the effect of terrain on air temperature was 0.65 K per 100 m. Water vapor pressure was also obtained from the SDP observation data, and it was used in the calculation of air density and near-surface specific humidity in the bulk transfer equation for moisture.

Actual sunshine duration obtained from SDP observation data was used to calculate daily incoming shortwave radiation flux at surface. Empirical relationship between incoming solar radiation at surface and extraterrestrial radiation is:

$$R_S\downarrow \; = \; R_{S0}\downarrow(a + b\,N/N_0) \tag{1}$$

where, $R_S\downarrow$: Incoming shortwave radiation $R_{S0}\downarrow$: Extraterrestrial radiation, N: Actual sunshine hours, N_0: Day length, a and b: Empirical numerical parameters.

Table 3 Parameters for evapotranspiration model in Yodo River basin

Land-use	Bulk transfer coefficient	Evaporation efficiency	Albedo
Forest	0.002	0.7	0.1
Paddy—irrigation period	0.005	0.7	0.15
Paddy—non-irrigation period	0.0008	0.3	0.2
Crop field	0.0008	0.2	0.2
Urban	0.0001	0.2	0.3
Water bodies	0.001	1.0	0.06

Irrigation period 120–270th days of a year

The regressional parameters *a* and *b* were set at 0.244 and 0.511 respectively. The data on actual sunshine hours were provided in the SDP observation station data. $R_{S0}\downarrow$ is the assumed amount of solar radiation coming to the surface without the influence of the atmosphere. N_0 is day length, or the theoretical maximum duration of the sunshine between dawn and sunset. Near-surface speed was also obtained from the SDP observation data, and it was used in the bulk transfer equation for moisture.

Few important parameters for the five types of land-use surfaces used in the surface energy balance equation of the evapotranspiration model are shown in the Table 3. Since the surface properties of the paddy fields change during irrigation and non-irrigation periods, different sets of parameters were used for these two periods. For the Yodo River basin, the irrigation period was estimated as 120–270 days of a year. Anthropogenic heat flux was set at an average value of 80 Wm^{-2} for the Yodo River basin area.

2.3.3 Data and Parameters for Runoff Model

Precipitation and evapotranspiration quantities simulated by the evapotranspiration model were used as input data in the HydroBEAM runoff model. Water intake and release for water supply, water use, hydroelectric plants, and irrigation purposes were also used as inputs into the runoff model. The sewerage and wastewater flow data were used for the corresponding grids. Dam operation rules (Sect. 2.2.4) were used to control the water level and storage in the six majors dams (Fig. 1). Important soil layer and model parameters used in the runoff model are shown in the Table 4.

2.4 Domain and Grid Structures

The Yodo River basin was gridded into 8,242 square grids each having an unit area of 1 km × 1 km resolution (Fig. 1). Each grid in the basin contains terrain data and

Table 4 Soil layer and model parameters for runoff model in Yodo River basin

Parameter		Value
Equivalent roughness ($m^{-1/3}s$)	Paddy	–
	Crop field	0.300
	Forest	0.700
	Urban	0.030
	River channel	0.035
Direct runoff percentage from surface	Paddy	1.0
	Crop field	0.21
	Forest	0.3
	Urban	0.737
Soil layer depth (m)	A	0.3
	B	1.0
	C	2.5
	D	10.0
Porosity (%)	All soil layers	10.0
Linear storage model constant (1/d)	B soil layer horizontal runoff coefficient	0.03
	C soil layer horizontal runoff coefficient	0.007
	D soil layer horizontal runoff coefficient	0.0039
	B soil layer vertical runoff coefficient	0.11
	C soil layer vertical runoff coefficient	0.013
	D soil layer vertical runoff coefficient	0.0
Tank model constant	A1: runoff coefficient (1/d)	1.0
	Z1: hor. runoff boundary height (mm)	300.0
	A2: hor. runoff coefficient	0.17
	Z2: hor. runoff boundary height	DPD[a]
	A3: hor. runoff coefficient	0.0
	Z3: hor. runoff boundary height	0.0

[a] Desired ponding depth

river network flow direction that channels water flowing in the rivers. The evapotranspiration model was used to solve surface energy balance in each of the basin grids. As the lake model has not been used to simulate the hydrodynamics of the Lake Biwa. So, in the rainfall-runoff model, only 7,557 grids, excluding those of Lake Biwa, were used in the simulation. The tributaries of the Lake Biwa were directly let out from the outlet of the lake.

The distributed hydrological model was used to simulate the response of the Yodo River basin to meteorological forcings for one-year period (the year 2006) using the evapotranspiration model, rainfall-runoff model and dam reservoir model. The simulation period was selected due to the availability of reliable observation data during that period.

2.5 Coupled Hydrometeorological Modeling

2.5.1 Coupling Approach

The modeled hydrometeorological data are the inputs to the hydrological model. One simple way of obtaining the hydrometeorological data is to directly downscale the global climate data obtained from the General Circulation Models (GCMs). However, the very fine spatial resolution required by the hydrological models cannot be realistically obtained from the very coarse GCM outputs. To circumvent this problem, atmospheric models with better spatial and temporal resolutions could be utilized. Regional and mesoscale meteorological models are better suited for providing more accurate and high-resolution input data to the distributed hydrological models. Thus the regional and mesoscale models dynamically downscale the global climate variables to regional and local scales.

Since the Yodo River basin has a mesoscale basin structure, the distributed hydrological modeling at a spatial scale of 1 km × 1 km was found to be satisfactory. The WRF model was used to produce all the meteorological variables required by the hydrological model. The hydrological simulation of the Yodo River basin was then carried out for 2006 by coupling the WRF model with the distributed hydrological model.

WRF mesoscale model was coupled one-way in offline mode with the hydrological model of the Yodo River basin. WRF mesoscale model was first run to simulate the hydrometeorological variables namely, air temperature, precipitation, surface pressure and incoming solar radiation. Then, the required hydrometeorological variables were downscaled and converted into the data format required by the hydrological model.

2.5.2 Parameters and Input Data

The options used in the WRF model are shown in the Table 5. The US NCEP (National Centers for Environmental Prediction) Global Analyses data, available on 1.0 × 1.0° grids continuously at every 6 h since the year 1999 (http://dss.ucar.edu/datasets/ds083.2/), were chosen as boundary and initial conditions for the WRF simulations along with the SST data. NCEP Global Analyses data for the Yodo River basin were dynamically downscaled to 3-km grid domain (Fig. 4).

All the input variables were made available from the WRF output except the water vapor pressure. Air temperature at 2 m was used as near-surface air temperature. Similarly, horizontal wind vector components, u and v, at 2 m were used to calculate the near-surface wind speed. From the WRF output, surface pressure (P) and water vapor mixing ratio at 2 m (q) were extracted, and then water vapor pressure was calculated. In the hydrological model, sunshine duration was used to calculate daily incoming shortwave radiation flux at the surface. Horizontal wind vector components, u and v, at 2-m height were used for the calculation of

Table 5 Specifications of the WRF model

Parameter/option	Value
Nesting	One-way with 3 domains
Domain-1 size	50 × 50 mesh with 27-km mesh size
Domain-2 size	46 × 46 mesh with 9-km mesh size
Domain-3 size	52 × 52 mesh with 3-km mesh size
Vertical grid	35 full levels with top level at 5 kPa
Microphysics	WSM 3-class simple ice
Cumulus	Kain-Fritsch scheme
Planetary boundary layer	YSU scheme
Land surface	Noah land surface model
Longwave radiation	RRTM scheme
Shortwave radiation	Dudhia scheme

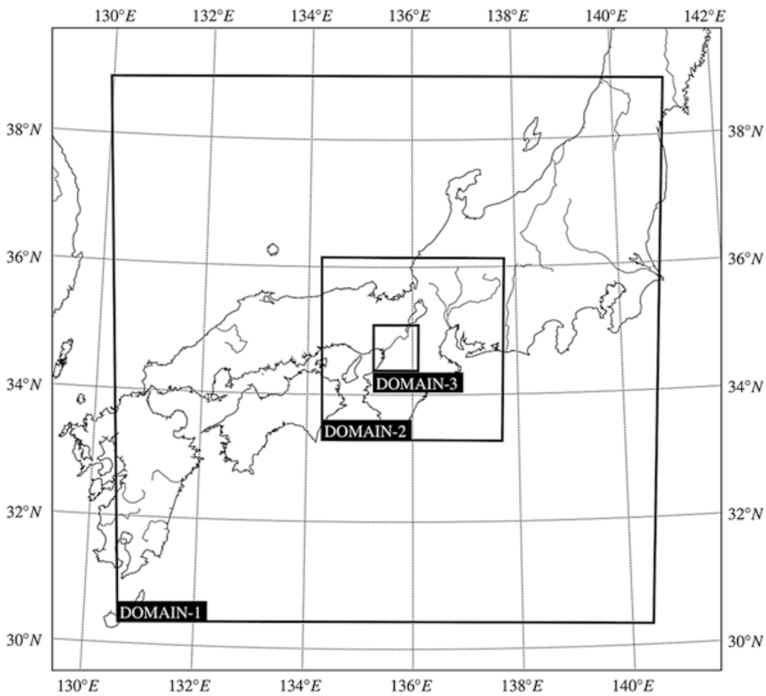

Fig. 4 Nesting of three domains in WRF model (The total area is Domain-1,'d02' is Domain-2 and 'd03' is Domain-3)

near-surface wind speed. First, the 10-m wind vector components were used to find wind speed at 10-m height. Then, using the wind profile based on the Monin and Obukov similarity theory, 10-m wind speed was converted to 2-m wind speed (as followed in the work of Högström 1988).

2.5.3 Data Processing

The grid structure of the Yodo River basin in the hydrological model is represented by nearly 1 km × 1 km GIS grid system, which is also known as Japanese 3D Mesh. In the hydrological model, each grid was given a unique Mesh ID to represent the sequence of channel flow in the basin. Besides a Mesh ID, these grids have 3D Mesh ID as well. A list of Mesh ID and 3D Mesh ID for 8,242 grid mesh of the Yodo River basin was created. Using GRASS GIS (http://grass.itc.it/), geographical coordinates (latitude/longitude) of the basin grid meshes were tabulated against corresponding Mesh ID using the 3D Mesh ID data.

A Fortran program called read_wrf_nc (described in http://www.mmm.ucar.edu/wrf/OnLineTutorial/Tools/read_wrf_nc.htm) is available in the WRF software to look into the NetCDF binary format (http://www.unidata.ucar.edu/software/netcdf/) output data produced by the WRF. This program is slightly modified to obtain X/Y coordinates of WRF for each of the grid mesh of the Yodo River basin. The latitude/longitude information from the previous step for each Mesh ID of the Yodo River basin were used as input to read_wrf_nc program to produce a list containing Mesh ID and corresponding WRF X/Y coordinates.

The required output data from the WRF were extracted from the WRF output files using a Python program that utilizes Climate Data Management System (CDMS, http://www2-pcmdi.llnl.gov/cdat) library to access the NetCDF variables. Since the WRF precipitation data Domain-3 (Fig. 4) were at 3-km resolution, they were downscaled to 1-km resolution required by the hydrological model. Other variables were obtained at basin grids corresponding to the nearest grid in the WRF output data. Then the hourly meteorological data for all the 1-km × 1-km grid mesh of the Yodo River basin were averaged into daily average values and then written into the input data files required by evapotranspiration model of the hydrological model.

3 Results and Discussion

3.1 Validation of the Hydrological Model

3.1.1 Validation of the River Discharge

Table 6 shows the comparison between the modeled and observed annual outflow from the six major dams in the Yodo River basin. The observed outflows from the dams have been provided by Ministry of Land, Infrastructure and Transport, Japan (http://www2.river.go.jp/dam/index.html, in Japanese). The outflow for the Nangoaraizeki dam has not been included because of data unavailability. The hydrological model reasonably reproduced the actual observed outflows in all the dams. The dam outflows were slightly overpredicted at the Hiyoshi and Nunome dams but some underpredictions of the outflows we observed at the Amagase and Hitokura dams.

Table 6 Comparison of modeled and observed annual outflow from dams in Yodo River basin in 2006

Dam	Outflow ($m^3 \times 10^6$)	
	Observed	From model
Amagase	3523.7	3494.2
Hiyoshi	360.9	396.2
Takayama	474.6	474.3
Nunome	56.5	61.6
Hitokura	95.2	50.3

The slight overpredictions in the annual outflow amount at Hiyoshi and Nunome dams can also be visualized from the hydrographs in Fig. 5 (shown by SDP lines). The overall slight overprediction of outflow at the Hiyoshi and Nunome dams can be attributed to some peaks larger than the observed discharge peak values in the rainy season (June and July). The largest peak discharge at the Nunome has been overpredicted by nearly 20 m^3/s.

At the Amagase dam, though the annual discharge has been slightly underpredicted by the hydrological model, the maximum discharge peak in July has been overpredicted by more than 1,000 m^3/s and the ensuing low discharge periods were also generally overpredicted by the model. Some of the overpredicted peak discharges shown by the hydrological model may be attributed to the under-representation of peak attenuations during actual dam operations at Nangoaraizeki and Amagase dam reservoirs that regulate the outflow from the Lake Biwa into the Uji River. Another reason for the overprediction in the Amagase dam peak discharges may be that the lake hydrodynamics of the Lake Biwa has not been considered in the present model, and hence, the outflow from the Lake Biwa is possibly overpredicted due to the lack of consideration of residence time in the lake. Though the peak discharge in July has also been overpredicted at all the dams except at the Hitokura dam, most of the peak discharges were modeled by the hydrological model within the acceptable limits of error.

The Water Information System database provided online by the Ministry of Land, Infrastructure and Transport, Japan (http://www1.river.go.jp/, in Japanese) contains many observation stations in the Yodo River basin. But, most of the observation stations had missing data in the year 2006. Hence, only two observation stations, viz., Hirakata and Takahama (Fig. 1) were validated with the observed data. In the Hirakata station, only the high discharge peak in July 2006 was available in the observed river discharge data.

Takahama station is situated in the Yodo sub-basin and receives river discharge from Biwa, Uji, Katsura and Kizu sub-basins (Fig. 6). Hirakata station lies further downstream than the Takahama station in the Yodo River. Though the maximum river discharge in July could not be compared with the observed data at the Takahama station, rest of the river discharge in the year 2006 is well-simulated by the hydrological model in the Takahama station with some slight underpredictions in the spring season. The highest peak discharge during July 2006 has been reasonably predicted at the Hirakata station with the observed discharge being overpredicted by nearly 1,000 m^3/s. This overprediction in maximum peak discharge in

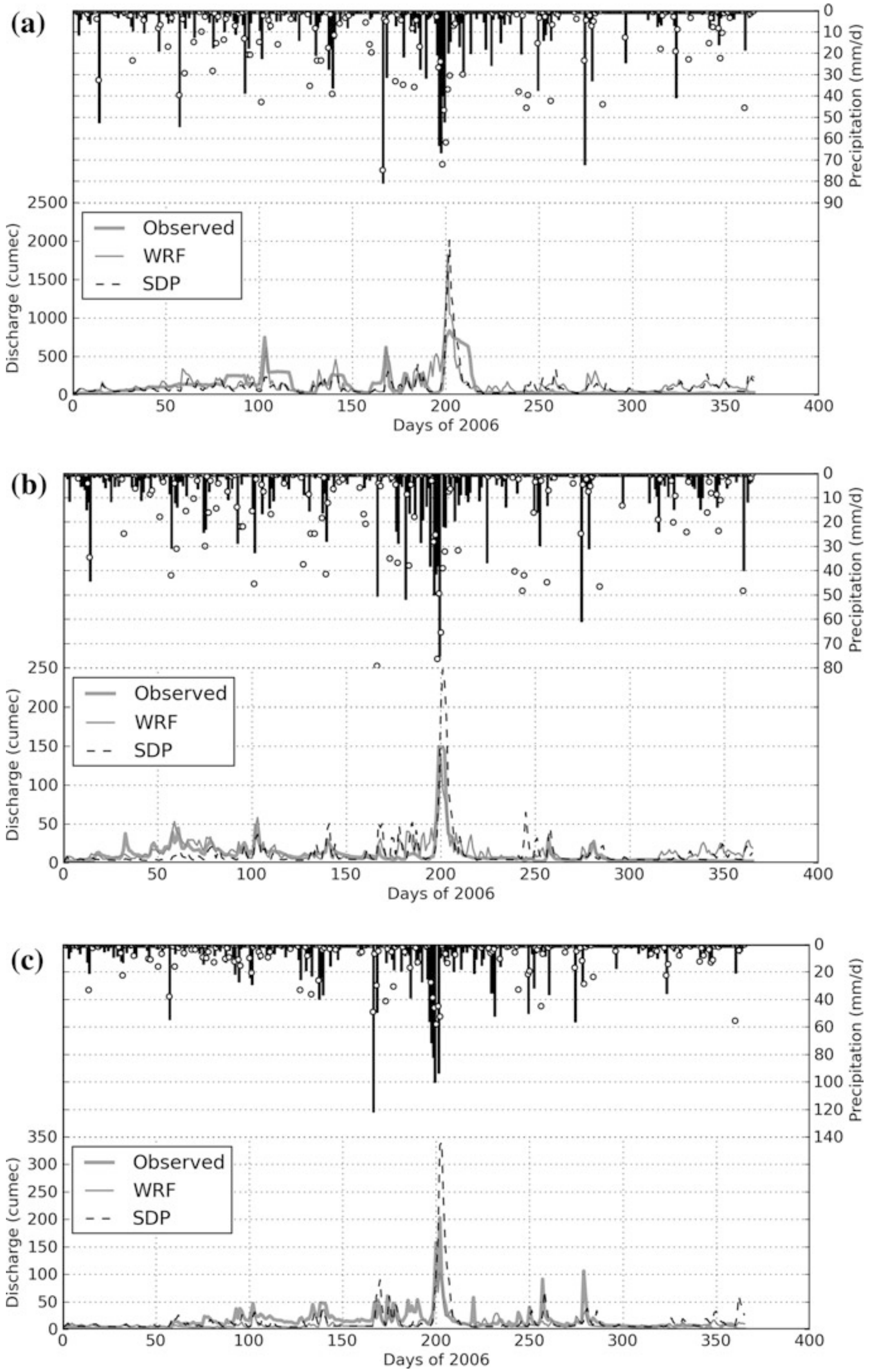

Fig. 5 Hydrographs for dams in Yodo River basin using coupled hydrometeorological model (Circles represent observed precipitation and bars represent precipitation from WRF model.) **a** Amagase dam, **b** Hiyoshi dam, **c** Takayama dam, **d** Nunome dam, **e** Hitokura dam

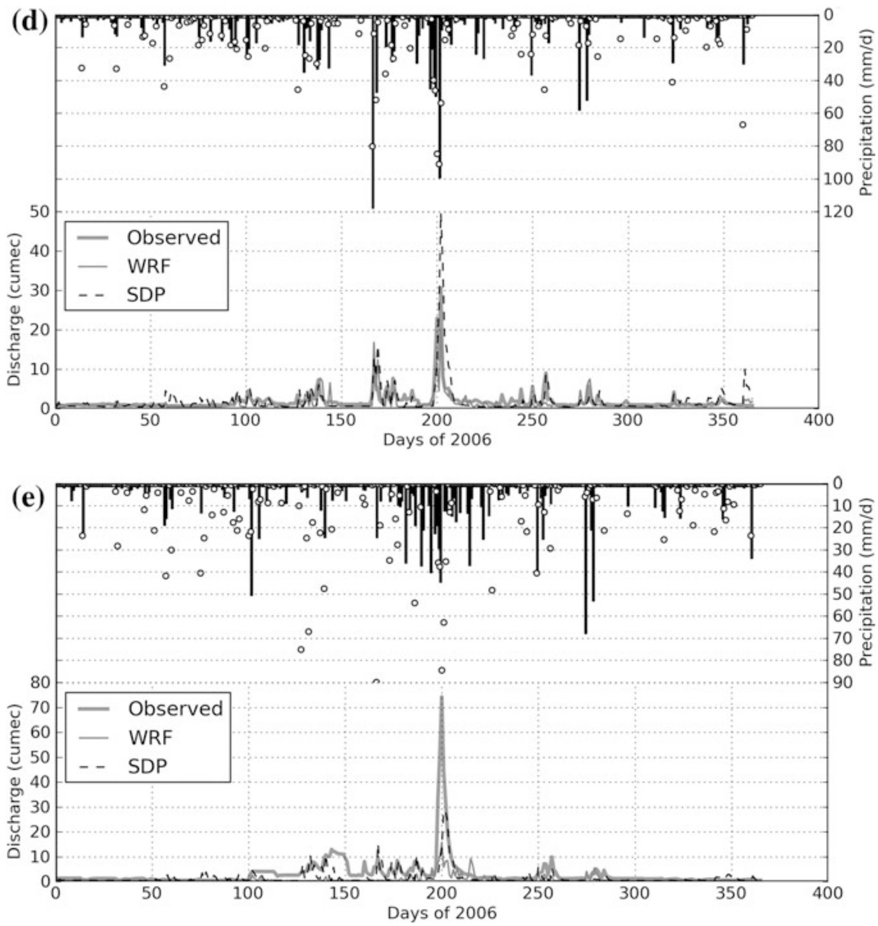

Fig. 5 (continued)

July is most probably due to the overprediction of dam outflow from the Amagase dam located at upstream.

3.1.2 Validation of the Dam Model

To validate the simplified dam model used in the hydrological model to simulate the reservoir operation in six major dams of the Yodo River basin, the observed water levels at those dams (http://www2.river.go.jp/dam/index.html, in Japanese) were compared with the simulated water levels (Fig. 7). The patterns of water level fluctuations in all these dams were well-simulated. The change in water levels during the transition period between the flooding and non-flooding seasons was also predicted with sufficient accuracy. Since the actual dam operations are complex and

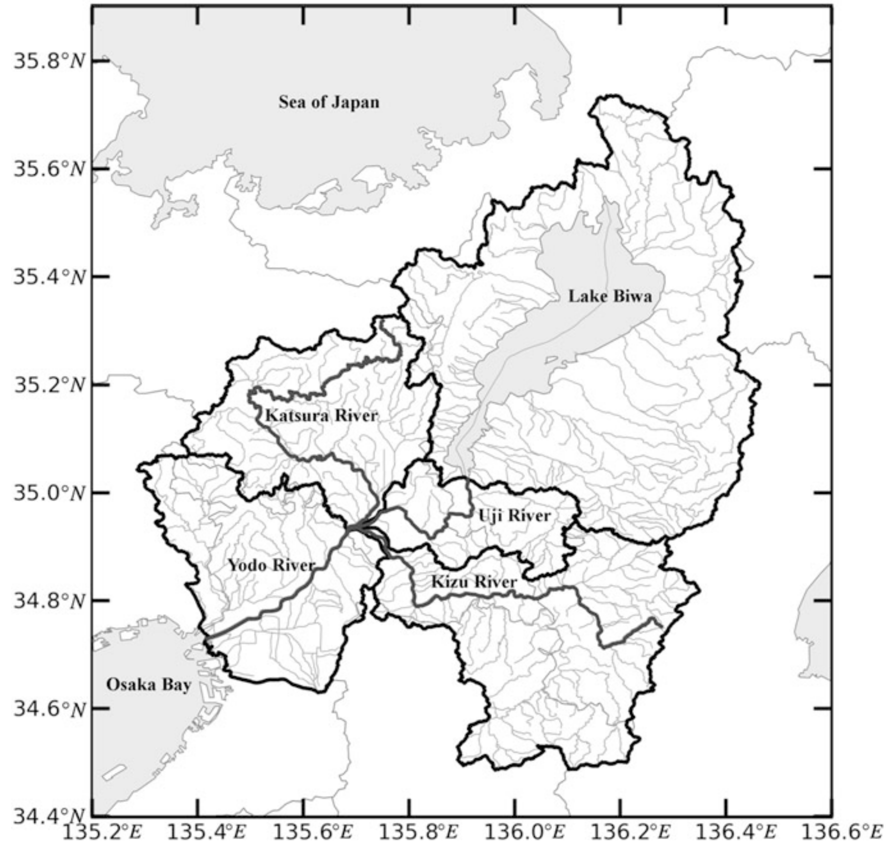

Fig. 6 Sub-basins of Yodo River basin with major rivers (*Thick black lines* are the boundaries of the sub-basins)

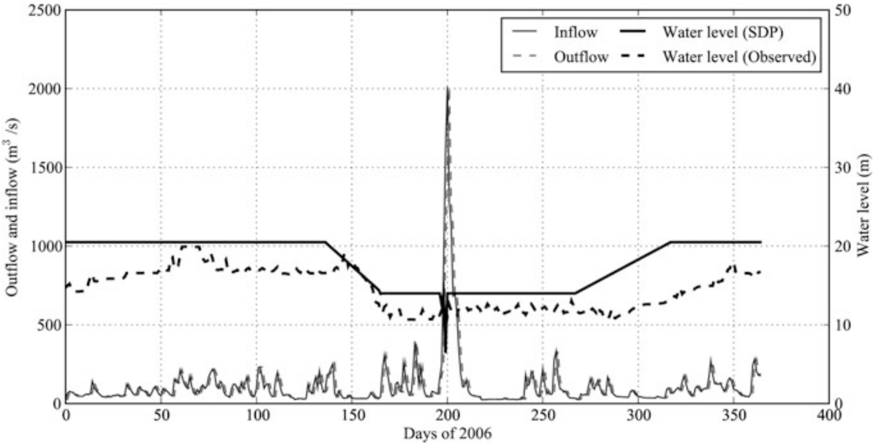

Fig. 7 Inflow, outflow and water level for Amagase dam in 2006

are manually changed according to the weather conditions, the water levels from the simplified dam model used in this study do not exactly fit with the observed water levels. Some short-period changes in water levels may not be reproduced at all by the present dam model. For example, some of the periodic fluctuations in the water levels at the Amagase dam are smoothed by the dam model. Similarly, at the Hiyoshi dam, the sudden increase in dam water level at highest peak discharge in July 2006 could not be reproduced by the dam model. Again, the temporary drop in water level in the second half of August 2006 in the Hiyoshi dam was also not reproduced. The reason for this non-reproducibility might be the simple precipitation limit used in the model to determine flooding (Sect. 2.2.4). It should also be noted that the transition periods between flooding and non-flooding seasons have regular patterns in the modeled water levels, but the actual dam operations may differ from this somewhat idealized but expected transition in the dam water levels.

The overall trend of dam water levels are sufficiently well-reproduced by the simplified dam model for the application of the hydrological model in the assessment and prediction of water resources at mesoscale.

3.2 River Discharge from the Coupled Model

The WRF hydrometeorological variables were used as input data in the the coupled hydrometeorological model instead of observation data. This has validated the use of high-resolution gridded data from WRF to be used in the hydrological model and the future basin scenarios can also be studied using the projected variables from WRF mesoscale model. The limited availability of observation data in the Yodo River basin were overcome by coupling the WRF mesoscale model in one-way mode to drive the basin-scale hydrological simulations.

Since the observation data were limited to dam data and two observation stations, the validation was done only with these available data. Table 7 shows the comparison of total annual outflow discharges from five dams in 2006 between

Table 7 Comparison of annual outflow from dams in 2006 between observed data, hydrological model using SDP data, and coupled hydrometeorological model

Dam	Outflow ($m^3 \times 10^6$)		
	Observed	SDP[a]	WRF[b]
Amagase	3523.7	3494.2	4348.2
Hiyoshi	360.9	396.2	442.7
Takayama	474.6	474.3	302.8
Nunome	56.5	61.6	41.7
Hitokura	95.2	50.3	29.2

[a] "SDP" column is the result of hydrological model using SDP observation data

[b] "WRF" column is the result of coupled hydrometeorological model

observed data, hydrological model using SDP data, and the coupled hydrometeorological model. All the dam outflows are comparatively similar between the hydrological model using SDP data and the coupled hydrometeorological model. The Amagase dam shows slightly larger overprediction in the coupled model than the hydrological model using SDP data. These overpredictions can also be observed from some larger peaks in coupled model output in Fig. 5. The coupled hydrometeorological model is found to be better at predicting the maximum peak discharge of July 2006 at most of the places than the original hydrological model using SDP data. At the Hiyoshi, Takayama and Nunome dams, the maximum peak discharges in July were better represented by the coupled hydrometeorological model. But at the Hitokura dam, the maximum peak discharge in July is found to be highly underpredicted by the coupled model than the hydrological model using SDP data. Moreover, May-June peak discharges at Hitokura dam were also underpredicted by the coupled model than the hydrological model using SDP data.

In the case of two observation stations used in the validation of coupled hydrometeorological model, the maximum peak flow at the Hirakata station and the overall annual discharge at the Takahama station were predicted by the coupled model without any appreciable deviation from the performance of the original hydrological model using SDP data. In fact, the maximum discharge peak in July 2006 at Hirakata has been simulated more precisely by the coupled hydrometeorological model.

4 Conclusions

As a solution to the need of a comprehensive integrated water resource management in the Yodo River basin, a coupled mesoscale hydrometeorological modeling approach was attempted.

The response of the Yodo River basin to atmospheric forcings was simulated for the year 2006 by using a distributed hydrological model containing an evapotranspiration model and a rainfall-runoff model. The hydrometeorological input such as precipitation and air temperature were obtained from the SDP observation data of the Yodo River basin and were gridded into the mesh structure of the hydrological model using Thiessen polygon method. A simplified reservoir model was also used to simulate inflow, outflow and water level at major dam reservoirs in the Yodo River basin. Outflow from the dams, basin discharge and river peak discharge in the observation stations were found to be fairly well-predicted by the hydrological model.

Instead of the traditional observation data used as atmospheric input data in the hydrological model, the high-resolution meteorological data from WRF model were used as the atmospheric forcings in the hydrological model. The coupled mesoscale meteorological—hydrological modeling system overcomes several problems associated with observation data from basin stations. Foremost, the sparse distribution of the observation stations in the basin limits the level of regional and mesoscale features that can be reproduced by the hydrological model. The coupled hydrometeorological modeling system mostly overcomes this spatial problem by producing high-resolution regular gridded meteorological data that is equivalent to a highly dense network of observation stations placed at very close proximity. The upshot of using the coupled hydrometeorological modeling system is that the local and regional variabilities inherently present in the meteorological data are better reproduced by virtue of high-resolution and physically-based modeling of the atmospheric processes. The comparison and validation of the coupled hydrometeorological model results against the observed river discharge and dam outflow data indeed reinforces the notion that regional modeling approach for water resource assessment is imperative for integrated management of river basins.

References

Abbott M, Bathurst J, Cunge J, O'Connell P, Rasmussen J (1986) An introduction to the European hydrological system—systeme hydrologique Europeen, "SHE", 1: history and philosophy of a physically-based, distributed modelling system. J Hydrol 87:45–59

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development. JAWRA J Am Water Resour Assoc 34(1):73–89

Cai X (1999) A modeling framework for sustainable water resources management. PhD thesis, The University of Texas at Austin

Chino M, Nagai H (2003) Numerical research of regional environment on IT based laboratory. In: International symposium of the Kanazawa University, Kanazawa University, vol 1, pp 186–189

Cornelissen T, Diekkrüger B, Giertz S (2013) A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment. J Hydrol 498:221–236

Daly C, Neilson RP, Phillips DL (1994) A statistical-topographic model for mapping climatological precipitation over mountainous terrain. J Appl Meteorol 33(2):140–158

Drogue G, Humbert J, Deraisme J, Mahr N, Freslon N (2002) A statistical-topographic model using an omnidirectional parameterization of the relief for mapping orographic rainfall. Int J Climatol 22(5):599–613

Freeze R, Harlan R (1969) Blueprint for a physically-based, digitally-simulated hydrologic response model. J Hydrol 9(3):237–258

He H, Zhang Q, Zhou J, Fei J, Xie X (2009) Coupling climate change with hydrological dynamic in Qinling mountains, China. Climatic Change 94(3):409–427

Högström U (1988) Non-dimensional wind and temperature profiles in the atmospheric surface layer: a re-evaluation. Bound-Layer Meteorol 42(1):55–78

Hong SY, Lee JW (2009) Assessment of the WRF model in reproducing a flash-flood heavy rainfall event over Korea. Atmos Res 93(4):818–831

Hooper BP (2011) Integrated water resources management and river basin governance. J Contemp Water Res Educ 126(1):3

Ikebuchi S, Kojiri T, Hagiwara Y, Tomosugi K, Takemon Y, Tanaka K, Hamaguchi T (2006) Water resources and environment assessment in river basin based on hydro-BEAM. Annuals of Disaster Prevention and Research Institute, Kyoto University, Uji-Shi, vol 49 C, pp 113–118

IPCC (2007) Impacts, adaptation and vulnerability: contribution of working Group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jia Y, Ni G, Kawahara Y, Suetsugi T (2001) Simulation of hydrological cycle in an urbanized watershed and effect—evaluation of infiltration facilities with WEP model. J Hydrosci Hydraul Eng 19(1):43–52
Jia Y, Ni G, Yoshitani J, Kawahara Y, Kinouchi T (2002) Coupling simulation of water and energy budgets and analysis of urban development impact. J Hydrol Eng 7(4):302–311
Kiem AS, Verdon-Kidd DC (2011) Steps toward "useful" hydroclimatic scenarios for water resource management in the Murray-Darling basin. Water Resour Res 47(12):W00G06
Kim S, Tachikawa Y, Nakakita E, Takara K (2010) Hydrologic evaluation on the AGCM20 output using observed river discharge data. Hydrol Res Lett 4:35–39
Kojiri T, Kinai Y, Park J (2002) Integrated river basin environment assessment on water quantity and quality by considering utilization processes. In: Proceedings of the international conference on water resources and environment research, pp 397–401
Kojiri T, Hamaguchi T, Ode M (2008) Assessment of global warming impacts on water resources and ecology of a river basin in Japan. J Hydro-Environ Res 1:164–175
Kunstmann H, Jung G (2003) Investigation of feedback mechanisms between soil moisture, land use and precipitation in West Africa. IAHS-AISH Publication 280:149–159
Kunstmann H, Stadler C (2005) High resolution distributed atmospheric-hydrological modelling for alpine catchments. J Hydrol 314(1–4):105–124
Lin CA, Wen L, Lu G, Wu Z, Zhang J, Yang Y, Zhu Y, Tong L (2006) Atmospheric-hydrological modeling of severe precipitation and floods in the Huaihe River Basin, China. J Hydrol 330(1–2):249–259
Liu Y, Gupta H, Springer E, Wagener T (2008) Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management. Environ Model Softw 23(7):846–858
Malone TM (2014) Streamflow modeling of Johnson creek subwatersheds using the precipitation runoff modeling system. Civil and environmental engineering master's project reports. Portland State University, Portland
Mango L, Melesse A, McClain M, Gann D, Setegn S (2011) Land use and climate change impacts on the hydrology of the upper Mara river basin, Kenya: results of a modeling study to support better resource management. Hydrol Earth Syst Sci 15(7):2245–2258
Miller SN, Kepner WG, Mehaffey MH, Hernandez M, Miller RC, Goodrich DC, Kim Devonald K, Heggem DT, Miller WP (2002) Integrating landscape assessment and hydrologic modeling for land cover change analysis. JAWRA J Am Water Resour Assoc 38(4):915–929
Ministry of Land, Infrastructure, Transport and Tourism (2008) Climate change adaptation strategies to cope with water-related disasters due to global warming (policy report). url: http://www.mlit.go.jp/river/basicinfo/english/pdf/policyreport.pdf (Provisional Translation)
Ministry of Land, Infrastructure, Transport and Tourism, Japan (2008) Integrated water resource management addressing climate change and other risks. Technical Report (Interim Report)
Mölders N (2005) Coupled models for the hydrological cycle: integrating atmosphere, biosphere and pedosphere, Springer, Berlin, pp 192–208 (Chap Feedbacks at the hydrometeorological interface)
Mölders N, Raabe A (1997) Testing the effect of a two-way-coupling of a meteorological and a hydrologic model on the predicted local weather. Atmos Res 45(2):81–107
Mölders N, Raabe A, Tetzlaff G (1996) A comparison of two strategies on land surface heterogeneity used in a mesoscale meteorological model. Tellus 48:733–749
Nawahda A, Kojiri T, Kaihotu I (2005) Assessment of global warming impacts on water resources and ecology of a river basin in Japan. J Jpn Soc Hydrolo Water Resour 18(3):293–305
Running S, Nemani R, Hungerford R (1987) Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. Can J For Res 17(6):472–483
Sakaguchi A, Eguchi S, Kato T, Kasuya M, Ono K, Miyata A, Tase N (2014) Development and evaluation of a paddy module for improving hydrological simulation in SWAT. Agric Water Manag 137:116–122

Sato Y, Kojiri T, Michihiro Y, Suzuki Y, Nakakita E (2012) Estimates of climate change impact on river discharge in Japan based on a super-high-resolution climate model. Terr Atmos Oceanic Sci 23(5):527–540

Sato Y, Kojiri T, Michihiro Y, Suzuki Y, Nakakita E (2013) Assessment of climate change impacts on river discharge in japan using the super-high-resolution MRI-AGCM. Hydrol Process 27(23):3264–3279

Sayama T, Tachikawa Y, Takara K (2005) Assessment of dam flood control using a distributed rainfall-runoff prediction system. In: Proceedings of monitoring, prediction and mitigation of water-related disasters, pp 59–64

Seuffert G, Gross P, Simmer C, Wood EF (2002) The influence of hydrologic modeling on the predicted local weather: two-way coupling of a mesoscale weather prediction model and a land surface hydrologic model. J Hydrometeorol 3(5):505–523

Shrestha RK, Sayama T, Tachikawa Y, Takara K (2005) Use of disaggregated rainfall data for distributed hydrological modeling in Yodo River basin. Annuals of Disaster Prevention and Research Institute, Kyoto University (48 B)

Singh J, Knapp HV, Arnold J, Demissie M (2005) Hydrological modeling of the Iroquois river watershed using HSPF and SWAT. JAWRA J Am Water Res Assoc 41(2):343–360

Skamarock W, Klemp J, Dudhia J, Gill D, Barker D, Wang W, Powers J (2005) A description of the advanced research WRF version 2, NCAR technical note. Technical Report, NCAR/TN-468 + STR

Suzuki Y, Nakakita E, Ikebuchi S (2003) Numerical study of rainfall-topography relationships in mountainous regions of Japan using a mesoscale meteorological model. In: Weather radar information and distributed hydrological modelling, international association of hydrological sciences, Sapporo, Japan, vol 282, pp 43–50

Tachikawa Y, Sayama T, Matsuura H, Yamazaki T, Yamaji A, Michihiro Y (2007) Development of a real-time runoff forecasting system using a physically-based distributed hydrologic model and its application to the Yodo River basin. J Nat Disaster Sci 26(2):189–201 (In Japanese)

Thiessen AH (1911) Precipitation averages for large areas. Mon Weather Rev 39(7):1082–1089

Thompson J, Green A, Kingston D, Gosling S (2013) Assessment of uncertainty in river flow projections for the Mekong river using multiple GCMs and hydrological models. J Hydrol 486:1–30

Todd M, Taylor R, Osborn T, Kingston D, Arnell N, Gosling S (2011) Uncertainty in climate change impacts on basin-scale freshwater resources-preface to the special issue: the QUEST-GSI methodology and synthesis of results. Hydrol Earth Syst Sci 15:1035

Verbunt M, Zappa M, Gurtz J, Kaufmann P (2006) Verification of a coupled hydrometeorological modelling approach for alpine tributaries in the Rhine basin. J Hydrol 324(1–4):224–238

Westrick KJ, Mass CF (2001) An evaluation of a high-resolution hydrometeorological modeling system for prediction of a cool-season flood event in a coastal mountainous watershed. J Hydrometeorol 2(2):161–180

Yoshikane T, Ma X, Kimura F, Hara M (2005) Regional climatic simulation for hydrological model using WRF model around Yellow River basin. In: 6th WRF/15th MM5 users' workshop, National center for atmospheric research, 3.11

Yoshitani J, Kavvas M, Chen ZQ (2001) Coupled regional-scale hydrological-atmospheric model for the study of climate impact on Japan. Soil-Veg-Atmos Transfer Schemes Large-Scale Hydrolo Models 270:191–198

Yu Z (2000) Assessing the response of subgrid hydrologic processes to atmospheric forcing with a hydrologic model system. Global Planet Change 25(1–2):1–17

Yu Z, Barron EJ, Yarnal B, Lakhtakia MN, White RA, Pollard D, Miller DA (2002) Evaluation of basin-scale hydrologic response to a multi-storm simulation. J Hydrol 257(1–4):212–225