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Paleo-hydrology and Paleo-flow Reconstruction in the Yodo River Basin

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Synopsis

Uncertainties related to flood events are not yet well characterized, specifically with respect to historical records and future predictions. Paleo-hydrological studies can help us understand the historical effects from environmental change as well as climate change. This paper presents a review of the history of paleo-hydrology on a world-wide scale and compares this history with the history of paleo-hydrology in Japan. It reconstructs the paleo-flow in the Kamo River basin, a tributary of the Yodo River basin under two different land use conditions by using a Grid-based Distributed hydrological model.

Keywords: Paleo-hydrology, Yodo River basin, land use, CDRMV3

1. Introduction

The Japanese megacities, Osaka and Kyoto, are located in the Yodo River basin, which plays an import role in Japan’s economy, culture and politics. Over the past 1700 years, Japan suffered frequent flood events. The earliest recorded flood control construction was called Mamutanotsutsumi field bank and was built by the Emperor Nintoku (A.D.257-339) in the Yodo River basin. Paleo-hydrology is the study of hydrologic systems and past conditions including the occurrence of flood events, historical flows, etc.

Paleo-hydrological studies tend to focus either on global scale or local scales. The International Union of Geological Sciences (IUGS) and the International Geological Correlation Programme (IGCP) achieved some global continental paleo-hydrological projects focused on lake level changes and reconstruction of fluvial regimes. At the local scale, the Late Quaternary Paleo-hydrology study focused on the Gulf of St. Lawrence, Québec, Canada (Lapointe, 2000) and the Madre de Dios River, southwestern Amazon River basin, Peru (Rigsby et al., 2009). Previous research also focused on the paleo-hydrology of lakes at the local scale including the glacial Lake Oshkosh, Wisconsin, USA (Clark et al., 2009) and the upper Laurentian Great Lakes (Breckenridge and Johnson, 2009). The approaches of integration of facies and isotopic geochemistry are applied in local paleo-hydrological studies (Paz and Rossetti, 2006).

Hydrological models are widely applied and the application of physically based hydrological models such as SWAT (e.g. Luo et al., 2011) and SHETRAN (Ewen et al., 2000) to large catchments is restricted by the vast amount of high quality and fine resolution data needed in order to reliably model the physical processes taking place in the catchment (Beven, 1989). The approach of grid-cell based rainfall runoff models provides a physical process with the spatial distribution. For example, the SLURP (Simple LUmped Reservoir Parametric) model (Kite, 1978) subdivides the catchment into units of different land cover and other sub-units (Grouped Response Units). AFFDEF (A spatially distributed grid based rainfall runoff model for continuous time simulations of river discharge) requires extensive information in terms of historical hydrological data or geomorphology of the contributing area with the strength of computational efficiency (Moretti et al., 2007). Kojima (1997) developed a grid-cell based distributed Kinematic Wave Runoff (KWR) model in 1997.

The Cell Distributed Rainfall Runoff Model Version 3 (CDRMV3) was selected for simulating the hourly paleo-flow in our study site. It is a physically-based hydrologic model developed at Innovative Disaster Prevention Technology and Policy Research Laboratory, DPRI, Kyoto University. CDRMV3 model solves the Kinematic wave equation using the Lax Wendroff scheme on every node of each cell (Kojima et al., 2003). Monte Carlo simulation technique was used to evaluate the rainfall-sediment-runoff model based on the grid-cell-based KWR model (Sayama et al., 2003). Based on CDRMV3, a lumped sediment model at spatial and temporal scale was applied and calibrated by Apip et al. (2010).

The main purpose of this paper is to review the history of paleo-hydroly at global and local scales and simulate the hourly paleo-flow in the Kamo River basin considering land use change.

2. Study Site and Data

In this study, we selected the Kamo River basin in the Yodo River basin (YRB) for the simulation study site.

2.1 Study Site

The Yodo River basin includes six sub-basins including the Lake Biwa basin (3,802 km^2), the Uji River basin (506 km^2), the Kizu River basin (1,647 km^2), the Katsura River basin (1,152 km^2), the lower Yodo River basin (521 km^2) and the Kanzaki River basin (612 km^2). YRB extends over the six prefectures of Shiga, Kyoto, Osaka, Hyogo, Nara and Mie. Lake Biwa is Japan’s largest fresh water lake with surface area of 670 km^2 and volume of 27.5×10^9 m^3. Over 400 streams (including small rivers) flow into Lake Biwa. The Lake Biwa basin is joined by the Uji River through the Seta River. The Katsura River, Kizu River and Uji River meet at Kyoto Prefecture and connect with the lower Yodo River going to the sea of Osaka bay. The length of the main-stem of the YRB is 75 km. The YRB is covered by 71.9% mountainous area and 28.1% flat area. The mean annual precipitation of the Lake Biwa, the Katsura River, the Kizu River, and the lower Yodo River basins are about 1,880 mm, 1,640 mm, 1,590 mm, and 1,400 mm respectively. Mean annual precipitation of YRB is 1387.8 mm (1976 ~ 2000) and mean annual runoff of YRB is 270.8 m^3/s (1952 ~1998) at Hirakata.

Fig.1 The location and area map of Yodo River basin (Source: Japan Water Agency)

The Kamo River basin is a sub basin of the Katsu River basin. The Kamo River passes through Kyoto City, the capital of Japan during Heian period (794AD-1868AD). The riverbank of the Kamo is popular with tourists and residents for many activities such as sightseeing during Sakura (cherry blossoms) blooms, fishing and walking. There are some pathways around this river which are opened for public access during the dry season. During heavy rainfall season, many activities cannot be done because the pathways are flooded. Near the upper stream of the KRB, there is the Sajikigatake mountain area which is the boundary of Kumogahata village and Keihoku village in the northern ward of Kyoto. The length of the Kamo

River is about 31 km. The area and highest elevation of the KRB is around 210 km^2 and 896 m. Flood control activities at the KRB were started in 824 AD when flood prevention became a government official position.

2.2 Data

In this study, we collected spatial and hydrologic data from the Kamo River basin including Digital Elevation Model (DEM), land use, soil type, channel network, observed discharge and Automated Meteorological Data Acquisition System (AMeDAS) data from the Japan Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The 50-m resolution DEM data (Fig.2) and 100-m mesh land use data sheets from 2006 (Fig.3) and 1976 (Fig.4) were obtained from the National and Regional Planning Bureau of MLIT. The DEM map was up-scaled from 50 m to 100 m. The real river channel used in this study (Fig.5) was downloaded from the website of MLIT and modified by ArcGIS. Table 1 shows the detail information of land use types in 1976 and 2006.

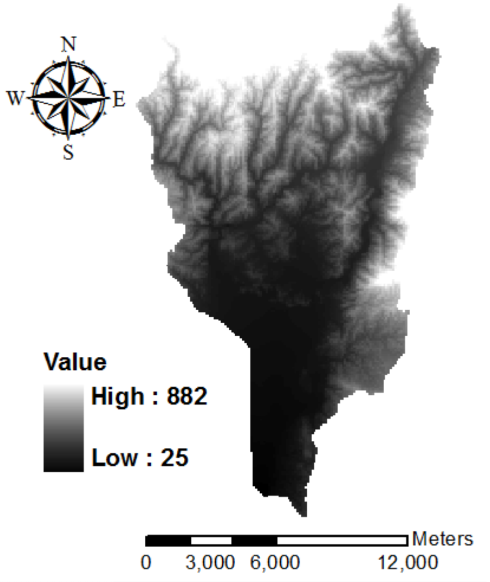

Fig.2 DEM of Kamo River basin

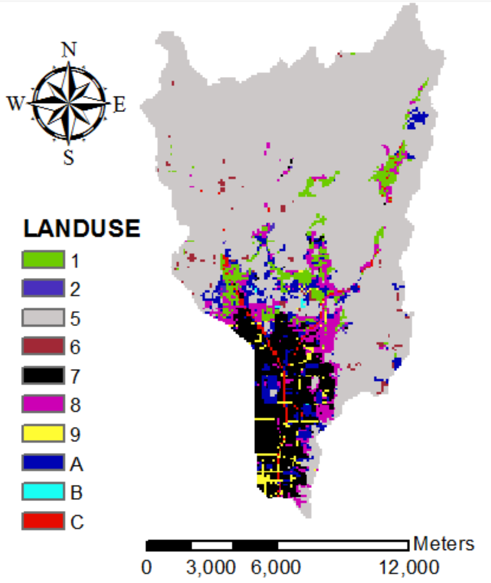

Fig.3 1976 Land use of the Kamo River basin

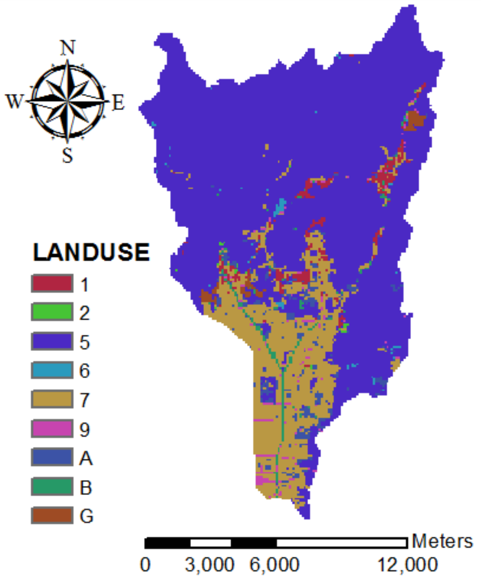

Fig.4 2006 Land use of the Kamo River basin

Table 1 Landuse classification for two years.

1976		2006	
Code	LU name	Code	LU name
1	Rice field	1	Rice field
2	Other Fields	2	Other Fields
5	Forest	5	Forest
6	Waste Land	6	Waste Land
7	Building site A	7	Building site
8	Building site B	9	Arterial traffic sites
9	Arterial traffic	A	Other sites
A	Other sites	B	Inland water areas
B	Lake and marsh	G	Golffield
C	River area		

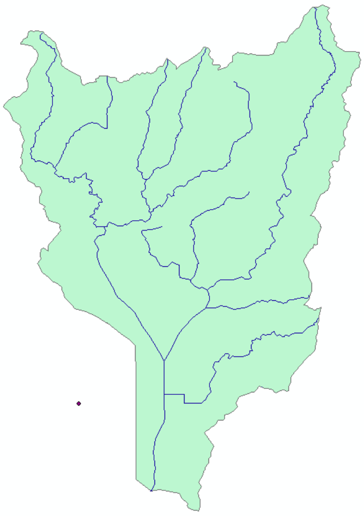

Fig.5 Real river channel of the Kamo River basin.

3. Methods

3.1 Grid-based hydrological model

This study uses CDRMV3, which provide the surface and subsurface hydrological process in each grid cell. This model is based on the kinematic wave method. The model includes a stage-discharge, q-h relationship for both surface and subsurface runoff processes:

$$q=\begin{cases} v_m * d_m * (\frac{h}{d_m})^{\theta} & 0\le h\le d_m \\ v_m * d_m + v_a * (h-d_m) & d_m\le h\le d_a \\ v_m * d_m + v_a * (h-d_m)+\alpha * (h-d_a)^m & d_a\le h \end{cases} \qquad (1)$$

$$v_m = k_m i, v_a = k_a i, k_m = \frac{k_a}{\theta}, \alpha = \sqrt{i}/n$$

$$d_m = D\theta_m, d_a = D\theta_a$$

where q is the discharge per unit width, h is the water depth, i is the slope gradient, k_m is the saturated hydraulic conductivity of the capillary soil layer, k_a is the hydraulic conductivity of the non-capillary soil layer, d_m is the depth of the capillary soil layer, d_a is the depth of capillary and non-capillary soil layer, and n is the roughness coefficient based on the land cover classes.

3.2 Monte Carlo simulation technique

Monte Carlo simulation is a technique for calibration and uncertainty analysis of hydrologic models. Based on the idea of approximating stochastic processes by a large number of equally probable realizations, Monte Carlo simulation is used to describe all the model inputs and parameters in a statistical manner with the model running hundreds or thousands of times to generate multiple outputs, including runoff flows for a catchment. This Monte Carlo approach (MCA) is used to calibrate the hydrologil rainfall-runoff model to study the first-order analysis of climate change effects on flood frequencies (Muzik, 2002).

MCA generates a large number of realizations of model parameters according to their corresponding probability distributions with lower and upper bounds that are assumed to represent the variation of calibration parameters. After each realization, MCA calculated the values of the mean and standard deviation of the output statistics (mean model efficiency, mean volume error, mean peak flow and mean objective function) by using the Nash-Sutcliffe coefficient (NS):

$$NSE = 1.0 - \frac{\sum_{j=1}^{M}(O_j - S_j)^2}{\sum_{j=1}^{M}(O_j - \overline{O})^2} \qquad (2)$$

where M is the number of ordinates in an event, O and S are the observed and simulated output variables, respectively, while $\overline{O}$ is the average of observed values.

4. Review of paleo-hydrology

A brief review of paleo-hydrology is given for both the global and local scale. We also give a comparison of the paleo-hydrological techniques used in Japan and in other countries.

4.1 Paleohdrology at global scale

Paleo-hydrology at the global scale is an examination of hydrologic balances. It is very import to predict future global water budgets and hydrologic cycles by assessing hydrologic change during past periods. There are two requirements for paleo-hydrology studies at global scales. First, paleo-hydrologic studies should consider the change in geography, land use and hydrologic cycles at the global scale. Second, the time scale of paleo-hydrologic studies is not limited to past and recent periods but can also be extended to future periods (Starkel, 1990). It can be used to examine the reconstruction of hydrology in the present and forecast the flood frequency for the future.

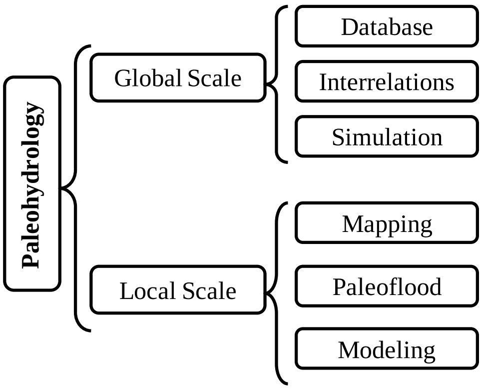

Fig. 6 Framework of Paleo-hydrology

The most important component (Fig.6) is the data source for paleo-hydrologic studies. To build the database for lakes, rivers, glaciers and groundwater is a substantial undertaking necessary for the examination of water balances and hydrological cycles at the global scale. There are some existing databases for paleo-hydrologic studies and they are described below.

[1] IGCP 158 project. It includes some paleo-hydrological changes during the past 15000 years.

[2] Cooperative Holocene Mapping Project (COHMAP). It includes paleo-climatic change and environmental change data. The lake level change database of open and closed lakes in North America and Europe is also included.

[3] Paleo-hydrology of Africa (Palhydaf).

[4] Global Paleo-hydrology Database (GPHD). It is powered by ArcView internet Map sever to provide online browsing of data related to paleo-hydrology and paleo-evironmental maps.

Another major undertaking (Fig.5) is finding the interrelationships within the hydrologic cycle. Reconstruction of water storage and hydrological cycles through time can be done in order to find relationships between hydrologic and environmental changes.

The last major objective (Fig.5) is to simulate the paleo-hydrology and paleo-climatic using the global hydrologic model and global climatic model. This can be used for simulating the continuous paleo-hydrologic and paleo-climatic data and for examining them with the historical recorded data. This approach can be use to evaluate the changes in hydrologic cycle and water storage at the global scale.

4.2 Paleo-hdrology at the local scale

Paleo-hydrology at the local scale focuses on the detailed evaluation of case studies.

The first approach of paleo-hydrology at the local scale is to map or reconstruct the paleo-geography and paleo-environment. This mapping approach is based on the CORINE data, census data, historical records, and pollen analyses (Ward, 2008). CORINE data is the dataset CORINE Land Cover 2000 (CLC2000) (EEA, Copenhagen, 2001). There are some studies on historical census information in Belgium (WL, 1994a), the Netherlands (Knol et al., 2004) and France (Dutoo, 1994). Pollen analysis was mainly used for simulating the period from 4000 to 3000 BP (Bunnik, 1995; Gotje et al., 1990; Henrard, 2003).

The second approach is to study paleo-flood hydrology, a method designed for this type of investigation (Kochel and Baker, 1982). Paleo-flood hydrology is the study of past or ancient flood events which occurred prior to the time of human observation or direct measurement by modern hydrologic procedures (Baker, 1987). The most popular technique of paleo-flood hydrology is the analysis of slackwater deposits and paleo-stage indicators (SWD-PSI). Research in this area has focused on: (1) geochronology, (2) hydraulic modeling, (3) flood-frequency analysis, and (4) climate (Baker et al., 2002). The most important methods of geochronology are tandem accelerator mass spectrometry (TAMS) radiocarbon analyses and optically-stimulated luminescence (OSL) dating (e.g. Stokes and Walling, 2003). Computational step-backwater analyses were introduced in the 1980s was improved for hydraulic modeling (O'Connor and Webb, 1988; Webb and Jarrett, 2002). The first introduction of paleo-flood data for flood-frequency analyses was advocated by Costa (1978), by Baker et al. (1979), and by Costa and Baker (1981).

The last method is modeling the paleo-climate and paleo-hydrology. In recent studies, the climate model ECBilt-CLIOVECODE, a three-dimensional coupled climate model consisting of three components describing the atmosphere, ocean and vegetation (Brovkin et al., 2002; Goosse and Fichefet, 1999; Opsteegh et al., 1998), was used for the paleo-climatic modeling. It was also designed for coupling with the hydrologic model STREAM (Aerts et al., 1999) to simulate Meuse palaeo-discharge (Ward et al., 2007, 2008; Renssen et al., 2007).

4.3 Comparison to paleo-hydrology in Japan

An introduction to fluvial geomorphology and paleo-hydrology in Japan was given by Oguchi et al. (2001). It emphasized: 1) abundant sediment yields from steep watersheds, 2) extensive sedimentation during the Holocene, 3) catastrophic hydro-geomorphological events, and 4) the impacts of increased heavy rainfall during the Pleistocene Holocene climatic change which highlight the meaning, framework and objective of paleo-hydrology at a national scale. Based on this introduction of paleo-hydrology, there were some previous studies on reconstruction the part of the Holocene large flood record for the Ara River in the central Japan (Grossman, 2001), spatiotemporally differential occurrence of rapid and slow mass movements of creep-type on segmented hillslopes which can be useful for the reconstruction of paleo-hydrology and its changes (Tamura et al., 2002). For the field works of paleo-hydrology, the slackwater deposits were investigated on the Nakagawa River, Tochigi Prefecture, Japan (Jones et al., 2001) and sedimentary evidence of a gigantic outburst flood was obtain from Towada caldera in northeast Japan (Kataoka, 2011).

Some paleo-hydrologic studies in the Kamo River basin in Japan are reviewed. The paleo-hydrologic studies began with the reconstruction of river landscapes through several Meishiozue (guidebooks) (e.g. Kamo River, Kyoto in the Edo Era) (Yoshikoshi, 1993). Further studies using mapping the river bank environment of the Kamo River in the Edo Era was presented by Yoshikoshi, (1997). With the reconstruction of river conditions in the Kamo River basin, the changes in the hydrologic environment in urban areas (Kyoto city) generated an evaluative study on the reconstruction of the paleo-hydrologic cycle. A new approach to the determination of the flood zone using geologic information obtained from archaeological excavations was reported by Kawasumi (2004). Yoshikoshi (2005) has summarized the restoration methods of paleo-flood hydrologic by restoration from the earth surface, restoration from geologicl structure and restoration from historical records, including examples in the Kamo River basin. In recent years, a new research objective for the paleo-hydrology in the Kamo River basin which is the evaluation on Disaster Prevention Effect Accompanying the ‘Kanbun Era Bank’ Construction under the paleo-environment was presented by Yoshikoshi, 2006.

Three main points should be stressed in comparing paleo-hydrologic studies at global and lcal scales:

[1] Bulding Database. It is necessary to build the database systematically and organize the paleo-hydrologic, paleo-climatic and paleo-environmental data. To fill the historical flood records, some field works were done at the Ara River in central Japan (Grossman, 2001), slackwater deposits at Nakagawa River (Jones et al., 2001), and sedimentary evidence of a gigantic outburst flood in northeast Japan (Kataoka, 2011). The climatologists are studying quantitative climatic reconstruction based on historical Documents (Mikami, 1999) and recovery of nineteenth-century Tokyo/Osaka Meteorological data in Japan (Zaiki, et al., 2006).

[2] Modeling. Climate and geography data before the 18th century is not continuous and available in the study catchments. However, the modeling of paleo-climatic and paleo-geographic systems can be used to simulate the data during the past period and compare the simulated data to present recorded data. The modeling of paleo-discharge can help to evaluate the impact of human activities and climate change on paleo-hydrology. Ward et al. (2007, 2008) was successful in simulating Meuse palaeodischarge by using the hydrological model (STREAM) coupled with climate models (ECBilt-CLIOVECODE).

[3] Field work and statistical analysis. Slack water deposits method is applied worldwide. The method is used at Tochigi prefecture, northeast and central

Japan. It is necessary to apply this method in the other parts of Japan to obtain historical spatial and temporal data. Paleo-flood data must be analyzed statistically to characterize flood frequency in Japan. Using paleo-flood data for flood-frequency analyses was introduced by Costa (1978), by Baker et al. (1979), and by Costa and Baker (1981). The early research in this methodology was studied by the Panel on Scientific Basis of Water Resource Management, Geophysics Research Board (Baker, 1982). The standard procedure for flood-frequency analysis in the United States involves a method of adjusted moments for fitting the log Pearson type III distribution (U.S. Water Resources Council, 1982). Incorporating paleo-flood data into a flood-frequency analysis (Lane, 1987) (Stedinger and Cohn, 1986) (Stedinger and Baker, 1987; Jin and Stedinger, 1989; Cohn et al., 1997; Martins and Stedinger, 2001) was achieved by using likelihood functions in the analyses.

The paleo-hydrology in the Kamo River basin and Yodo River basin will focus on three directions i.e. the mapping of paleo-geography and paleo-land use, the modeling of paleo-climatic conditions and paleo-hydrology, and the statistical analysis of flood-frequency based on paleo-flood data.

5. Results and Discussions

5.1 Results of paleo-flow simulation

In this study, we simulated the paleo-flow in 1953 at the Kamo River basin by using CDRMV3. This model was calibrated using a Monte Carlo simulation. Fig.7 shows the best calibration result of 1000 times simulation using the 1976 land use map. The Nash-Sutcliffe coefficient of the best calibration is 0.9414.

To compare with the simulated result using 2006 land use, the parameters of the model were set with the values obtained from the best simulation parameters and the model was run again. Fig.8 shows a comparison of the simulation results under 1976 and 2006 land use (LU). The base flows of the two simulation results under 1976 and 2006 LU are quite close to each other. From 13:00 to 19:00 of December 25, 1953, the simulation result under 1976 LU is a little higher than that using 2006 LU. After 19:00 of December 25, 1953, the simulation result under 2006 LU is a little higher than that one under 1976 LU. Compared with the observed data, both simulated results under-estimated the peak discharge.

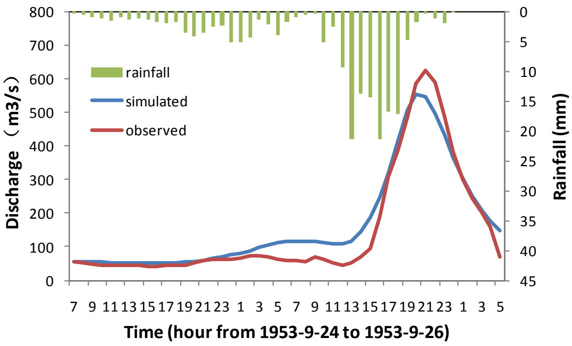

Fig.7 Best calibration result of stream flow under 1976 LU.

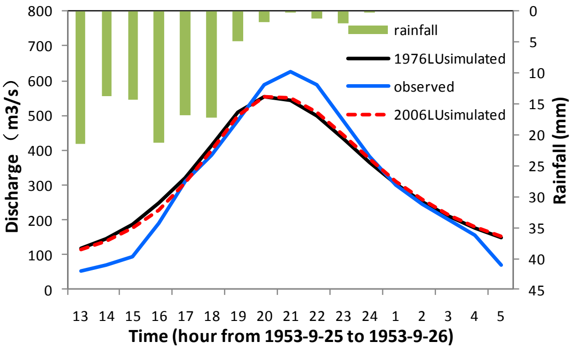

Fig. 8 Comparison of simulated discharge using landuse maps of 1976 and 2006.

5.2 Discussion

From the simulated results of paleo-flow in the Kamo River basin, the grid-based distributed hydrologic model can be used for the paleo-flow simulation in hour. The paleo-climatic data was collected from 1890-2008, but the paleo-flow observed discharge data is only available from present to 1953, and it is not continuous. For future research, it will be essential to obtain the historical flood data from historical documents and field works.

6. Conclusions

In reviewing the paleo-hydrology at global and local scales, we realized that there may have the evidence from the physical nature related with the historical extreme flood events. There are three components to paleo-hydrologic studies that need to be strengthened: building database, modeling, and field works and statistical analysis.

The paleo-flow simulation results in 1953 under the land use of 1976 works very well. The grid-based distributed hydrological model can be used for further paleo-hydrologic simulation and the reconstruction of the change in paleo-hydrology.

The future paleo-hydrology study in the Yodo River basin will focus on mapping the past land-use, reconstructing the paleo-discharge and flood frequency analysis.

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淀川流域における古水文現象の再現に関する研究

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要　旨

過去と将来の期間の洪水災害イベントの不確実性は，まだ完全に識別されていない。古水文研究では，過去の環境や気候の影響を理解するのに役立つ可能性がある。本稿では，世界規模で古水文研究の発展の歴史をレビューし，日本の古水文研究の歴史とそれらを比較した。また，グリッドベースの分布型水文モデルを用いて2つの土地利用条件の下で淀川の鴨川流域における古流れを再現した。

キーワード：古水文，淀川流域，土地利用，CDRMV3