LAND USE CHANGE ANALYSIS AND PALEO-FLOOD IN THE KAMO RIVER BASIN, KYOTO, JAPAN

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Human activities have led to changes in land use, environmental conditions and climate. Land use change has significant impacts on hydrology and other water related problems. In this study, the assessment of land use change is used to explore the effects of human activities on hydrologic response under the paleo-environment and the present conditions by using a grid-based distributed hydrologic model. According to the results of land use change analysis, forest area decreased, but the areas of building types A and B increased from 1843 to 1902. Due to increasing building area and decreasing forest area and rice fields, the peak discharge is increasing and arriving earlier. Projected rainfall-runoff hydrographs suggest that rainfall may peak early (in the third hour) leading to earlier peak discharge or rainfall could peak later (in the eighth hour), leading to larger and later peak discharge. This study offers guidance for future urban planning and flood risk management.

Key Words : *land use change, paleo-flood, hydrological response, paleo-land use, Kamo River,*

1. INTRODUCTION

Due to urbanization, environmental conditions and land use have changed significantly between the past and the present. The changes to land use and the environment have dramatic effects on flood frequency, water quality, climate, and ecosystem structure and function. Recent studies have focused on the impacts of land use change on catchment hydrology and hydrologic response^{1),2)}, and the assessment to quantify the influence of land use and water management on flows³⁾. An assessment of the long-term effect of land use change on hydrology and solute budgets was conducted on small catchments in Amazonia⁴⁾. A series of studies

assessed the impact of land use change on hydrology by ensemble modeling (LUCHEM)⁵⁾⁻⁸⁾. Wijesekara presented a study to extend the time scale of the assessment of the future and past period land use change impact on hydrologic processes⁹⁾. However, most previous studies of land use change impact assessment only consider the past several decades.

Land use change analysis considering long periods of paleo-environmental conditions is very important for understanding land use change in the context of changing socio-economic conditions. Land use change impacts on hydrologic response under the paleo-environment can be used to confirm and connect statistical analysis and discontinuous

historical evidence of paleo-floods. Research has shown that large-scale deforestation of basins has led to significant increases in mean discharge and flood frequency through long timescales under paleo-environmental conditions¹⁰.

Reconstruction of paleo-land use is essential for long period land use change analysis. Reconstruction of paleo-land use and environmental conditions includes reconstruction of the paleo-channel, the paleo-land landscape and the paleo-environment. The field observation approach is used as a foundation for paleo-environmental reconstruction¹¹. Ward¹⁰ described the reconstruction of paleo-land use based on CORINE data, census data, historical records, and pollen analyses. CORINE data is the dataset CORINE Land Cover 2000 (CLC2000)¹². There are some studies on historical census information in Belgium¹³, the Netherlands¹⁴ and France¹⁵. Pollen analysis was mainly used for simulating the period from 4000 to 3000 BP¹⁶. Based on previous studies, historical information such as old books, drawings, pictures and paper maps can be used to reconstruct paleo-land use.

The Cell-based Distributed Rainfall Runoff Model Version 3 (CDRMV3) 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 cell¹⁷. Monte Carlo simulation was used to evaluate the rainfall-sediment-runoff model based on the grid-cell-based KWR model^{18,19}.

In this study, we present the land use change analysis and representation of paleo-flood with the calibration results and the best parameter set of the CDRMV3 in the Kamo River basin, Kyoto, Japan. We reconstructed three paleo-land use periods for 1843, 1927 and 1902. The land use change impact on the hydrologic response under the paleo-land use is assessed with the historical recorded and designed rainfall in this study.

2. STUDY SITE AND DATA

(1) Study site

The Kamo River basin is a sub-basin of the Katsura River basin. The Kamo River passes through Kyoto City, which was the capital of Japan during 794AD-1868AD (Fig.1). 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, many activities are restricted 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 km² and 896 m. Flood control activities at the KRB were started in 824 AD when flood prevention became an official government position²⁰.

Fig.1 The location and DEM map of the Kamo River basin

(2) Data

In this study, we collected spatial and hydrologic data from the Kamo River basin including Digital Elevation Model (DEM), land use, channel network and observed discharge from the Japan Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The Automated Meteorological Data Acquisition System (AMeDAS) data at Kyoto station was obtained from the Japan Meteorological Agency (JMA). The 50-m resolution DEM data (Fig.1) and 100-m mesh land use data sheets of 1976 were obtained from the National and Regional Planning Bureau of MLIT. The historical geographical maps (HGMs) of 1927, 1902 and 1843 were obtained from the Japan Map Center (JMC). The observed discharge at Fukakusa monitoring station was used to calibrate the CDRMV3 in the Kamo River basin. Based on the 1976 land use data, the 1902 land use was reconstructed using the paleo-land-use reconstruction (PLUR) program introduced by Luo²¹. Based on historical information, the vector data (the delineation of the land-use changed areas) was built up and with the geometric correction was combined with the 1976 land use map. The land use changed areas in the 1976 land use map were replaced using the PLUR program, and finally the paleo-land-use data from years 1927, 1902 and 1843 were created from the PLUR program. Table 1 shows the classification and area of land use in 1976, 1927, 1902 and 1843 (Fig.2).

3. METHODS

(1) Cell-based Distributed Rainfall Runoff Model

CDRMV3 provides the surface and subsurface hydrologic processes in each grid cell. This model is based on the kinematic wave method. The model simulates three lateral flow mechanisms including (1) subsurface flow through capillary pores, (2) subsurface flow through non-capillary pores and (3) surface flow on the soil layer. At each grid-cell, when the water depth is lower than the equivalent water depth for unsaturated flow ($0 \leq h \leq d_m$), flow is simulated by Darcy's law with an unsaturated hydraulic conductivity k_m . Surface flow is simulated as a function of the Manning roughness coefficient. The flow lines are parallel to the slope and the hydraulic gradient is equal to the slope. The kinematic wave model assumes the rainfall intensity is always lower than the infiltration capacity. It does not consider the vertical water flow, and the input rainfall data is added directly to subsurface flow or surface flow according to the water depth at the rainfall location. The model includes a stage-discharge, q - h relationship for both surface and subsurface runoff processes eq.(1):

$$q = \begin{cases} v_m d_m \left(\frac{h}{d_m}\right)^\theta, & 0 \leq h \leq d_m \\ v_m d_m + v_a (h - d_m), & d_m < h \leq d_a \\ v_m d_m + v_a (h - d_m) + \frac{\sqrt{i}}{n} (h - d_a)^m, & d_a < h \end{cases} \quad (1)$$

$$v_m = k_m i, v_a = k_a i, k_m = \frac{k_a}{\theta}, d_m = D\theta_m, d_a = D\theta_a$$

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 the capillary and non-capillary soil layer, v_m and v_a are the flow velocities of unsaturated and saturated subsurface flows respectively, θ is a non-dimensional parameter for unsaturated flow, θ_a is the effective porosity of soil layer (D), θ_m is the effective porosity of unsaturated layer, and n is the roughness coefficient based on the land cover classes. Eight parameters are used in this study, including n (the roughness coefficients for land use parameters of the forest (Nw), building area ($Nu1$), other area ($Nu2$), paddy field ($Nf2$) and river area (NRv)), total soil depth (d_a), hydraulic conductivity in saturated layer (k_a), and θ . The characteristic of each land use type, which is represented by Manning's roughness

Fig.2 Land use map of 1976,1927, 1902 and 1843

Table 1 Classification and the area for each land use type for 1976, 1927, 1902 and 1843.

ID	Land use	Area (km2)			
		1976	1927	1902	1843
1	Forest	134.1	138.21	139.81	143.59
2	Building type A	16.76	13.77	8.89	8.25
3	Building type B	9.07	3.45	1.51	0.95
4	Arterial traffic area	2.26	2.08	1.44	1.36
5	River area	1.53	1.53	1.53	1.53
6	Other sites	7.94	6.9	6.64	6.64
7	Lake and marsh	0.14	0.14	0.14	0.14
8	Waste Land	1.38	1.12	0.73	0.71
9	Rice field	6.84	12.83	19.33	16.85
10	Other Fields*	0.34	0.34	0.34	0.34

* The area of other fields is supposed to be not changed.

coefficient, affects the flux of surface flow. However, the model does not consider detailed information of each land use type such as irrigation system of the paddy field land use type.

Initial conditions at each grid-cell were assumed to be in steady-state. Given the observed discharge at the catchment outlet, the discharge from every grid-cell was assigned in proportion to each of the grid-cells upstream to it, and the assigned discharge in each grid-cell was converted to the value of the water depth according to the stage-discharge relationship eq.(1) ¹⁹.

Building type A is residential with high density population such as residential streets, the free-standing buildings and housing area with side

lengths of more than 50 m, as well as other tall and large buildings. Building type B is residential with median or low population, including free-standing buildings and housing with side lengths less than 50 m.

(2) Monte Carlo simulation technique

Monte Carlo (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):

$$NSE = 1.0 - \frac{\sum_{j=1}^M (Y_j - S_j)^2}{\sum_{j=1}^M (Y_j - \bar{Y})^2} \quad (2)$$

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

4. RESULTS AND DISCUSSIONS

In this paper, we present the land use analysis and the reconstruction of paleo-floods under 1976, 1927, 1902 and 1843 land-use scenarios, respectively.

(1) Result of Calibration

In this study, we calibrated the CDRMV3 model using rainfall data from the 1953 extreme flood event because we lacked observed discharge data. Fig.4 shows that the simulation results bracket the observed discharge very well. The Nash-Sutcliffe coefficient for this calibration is around 0.95. The peak discharge of the simulation is somewhat lower than the observed discharge. The simulation discharge during 12:00 to 16:00, 18:00 to 20:00 and after 23:00 is slightly higher than the observed discharge. The low flows of the simulation results bracket the observed discharge well (Fig.3).

We use the best parameter Ψ based on the Monte Carlo simulation coupled with the CDRMV3 model: $Nw=0.51 \text{ m}^{-1/3} \text{ sec}$, $Nu1=0.14 \text{ m}^{-1/3} \text{ sec}$, $Nu2=0.19 \text{ m}^{-1/3} \text{ sec}$, $Nf2=0.47 \text{ m}^{-1/3} \text{ sec}$, $NRv=0.012 \text{ m}^{-1/3} \text{ sec}$, $d_a=105.43 \text{ mm}$, $k_a=0.0004 \text{ mm s}^{-1}$, and $\theta=7$.

(2) Land use change

Land use change analysis explored changes in land use types at snapshots from 1976, 1927, 1902 and 1843. Table 1 shows that the area of forest decreased from 1843 to 1976, and the area of forest

in 1843 was 3.78 km^2 larger than that in 1902. There are three land use types including river area, lake and marsh, and other fields which maintain the same area from 1843 to 1976. The land use types of waste-land and other sites did not change significantly from 1843 to 1976. The other sites in 1976 were reduced 1.04 km^2 from those in 1927 because of the construction of the golf field after 1946.

In Fig.4, we present four land use types including building types A and B, arterial traffic sites and rice field which had significant changes. The area occupied by building type A did not change much from 1843 to 1902, but it increased significantly between 1927 and 1976. The area occupied by building type B was very low in 1843 and 1902, but doubled by 1927 and quadrupled by 1976. The area of arterial traffic sites increased slightly from 1843 to 1976 due to the urbanization of Kyoto. For the area of rice field, it was 16.85 km^2 in 1843, increased 2.48 km^2 by 1902 because of the development of agriculture, and decreased from 1927 to 1976 due to urbanization.

(3) Hydrologic responses and paleo-floods

The land use change impact on hydrologic response was analyzed using the historic rainfall and the designed rainfall under the paleo-land use of 1843, 1902 and 1927, and the present land use of 1976. We assessed the land use change response after 10 hours under rainfall scenarios based on the 50, 100, and 200 year return period under two typical storm shapes based on the Area Rainfall Intensity Frequency Curves (AIDF)²² and historical recorded rainfall of this river basin.

Fig.3 Calibration result under 1976LU (1953/9/25-9/26)

Fig.4 Land use change among 1843, 1902, 1927 and 1976.

Fig.5 Results of hydrologic responses with the historical rainfall from 1930-7-31 to 8-1

Fig.6 Results of hydrologic responses with 10 hours designed rainfall of shape 1 for the 200 years return-period.

Fig.7 Results of hydrologic responses with 10 hours designed rainfall of shape 2 for the 200 years return-period.

In Fig.5, the peak rainfall arrived at 15:00 on July 31, 1930, and the discharge at this hour under the land use of 1843 is about $40 \text{ m}^3/\text{s}$ lower than that under the land use of 1976. The peak discharge under the land use of 1976 arrived at 20:00 on July 31, 1930 which is five hours later than the arrival of peak rainfall. The peak discharge under the land use of 1843 arrived at 21:00 which is delayed one hour and is $6 \text{ m}^3/\text{s}$ lower than that under the land use of 1976. The discharge under the land use of 1927 is located in the middle between the discharges under 1976 and 1843 land-uses, and the peak discharge arrived at 20:00, but it is $13 \text{ m}^3/\text{s}$ lower than that under the land use of 1976.

We present the results of land use change response with 10 hours designed rainfall of shape 1 and 2 for the 200 year return-period in Fig. 6 and Fig.7. These two distinct design rainfall events are based on historic rainfall events, such as the 1930 flood. For brevity, we have excluded the results with 50 and 100 years return period. The shapes of these

results are very similar to the results for the 200 year return period. In Fig.6, the peak rainfall arrives at the third hour. The discharge of the fifth hour shows a significant increasing trend from 1843 to 1976. The discharge after the fifth hour under the land use of 1843 increased very quickly and shows a big discrepancy. The discharge under the land use of 1976 showed a smoother curve, higher before arriving at the peak discharge at the seventh hour, and lower after the peak discharge. The discharge under the land use of 1927 is intermediate between that under the land use of 1976 and 1843, and showed a small discrepancy after the fifth hour.

In Fig.7, all of the discharge under the four land uses of 1976, 1927, 1902 and 1843 showed smoother curves than those in Fig.6. The peak discharge under all the four land uses arrived at the tenth hour, and the peak discharge under the land use of 1976 is about $3120 \text{ m}^3/\text{s}$. There is a significant difference in the discharge between the land uses of 1976 and 1843. The discharge under the land use of 1976 is higher before arriving at the peak discharge and lower after the peak discharge than that under the three other land uses.

(4) Discussions

Higher discharge and peak discharge, which are one hour earlier under the land use of 1976 as compared to the other land uses, resulted from decreased area of forest and rice field and increased area of building types A and B. These changes in land use led to the quick runoff in the ground and the reduced infiltration to the subsurface. Under the designed rainfall cases, we found similar results for the higher discharge with the historical rainfall case for the same reason. We found that there was a similar curve of the discharge presented around the fifteenth hour (Fig.5), the fifth hour (Fig.6), and the seventh hour (Fig.7). The high water storage function of forest and rice fields likely drives differences between the curves. For the two shapes of designed rainfall, we found that the first shape led to earlier peak discharge and the second shape led to higher but later peak discharge.

5. CONCLUSIONS

In this study, we found the following:

- (1) The Cell-based Distributed Rainfall Runoff Model performs very well for the representation of a historical flood event during hourly simulations.
- (2) The paleo-environmental conditions in 1843, 1902 and 1927 were reconstructed based on historical information and the 1976 land use map. Due to the urbanization of Kyoto city, the area of forest and rice field decreased and the building

sites A and B increased from 1843 to 1976.

- (3) Human activities such as land use change on increasing the building area and decreasing the forest area and rice field which could lead the peak discharge will become high and coming early, with the results of land use change response under historical recorded and designed rainfall events.
- (4) Due to urbanization, deforestation and decreasing of the rice field in the Kamo River basin has lead the increasing of discharge and the peak discharge coming early.
- (5) The shape of the rainfall is very important for the flood risk management and the land use change impact on the hydrological responses.

The results of this study could be used for guiding the future urban planning and supporting the important information for the reconstruction of the paleo-flood and the flood risk management.

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REFERENCES

- 1) Siriwardena et al.: The impact of land use change on catchment hydrology in large catchments: The Comet River, Central Queensland, Australia. *J. of Hydr.* 326, 199-214, 2006.
- 2) Mao and Cherkauer: Impacts of land-use change on hydrologic responses in the Great Lakes region. *J. of Hydr.* 374, 71-82, 2009.
- 3) Romanowicz and Osuch, M.: Assessment of land use and water management induced changes in flow regime of the Upper Narew. *Physics and Chemistry of the Earth*, doi: 10.1016/j.pce.2011.04.012, 2011.
- 4) Germer et al.: Implications of long-term land-use change for the hydrology and solute budgets of small catchments in Amazonia. *J. of Hydr.* 364, 349-363, 2009.
- 5) Breuer et al.: Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM). I: Model intercomparison with current land use. *Advances in Water Resources* 32, 129-146, 2009.
- 6) Viney et al.: Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) II: Ensemble combinations and predictions. *Advances in Water Resources* 32, 147-158, 2009.
- 7) Huisman et al.: Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM) III: Scenario analysis. *Advances in Water Resources* 32, 159-170, 2009.
- 8) Bormann et al.: Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) IV: Model sensitivity to data aggregation and spatial (re-)distribution. *Advances in Water Resources* 32, 171-192, 2009.
- 9) Wijesekara et al.: Assessing the impact of future land-use changes on hydrological processes in the Elbow River watershed in southern Alberta, Canada. *J. of Hydr.*, doi:10.1016/j.jhydrol.2011.04.018, 2011.
- 10) Ward et al.: Strong increases in flood frequency and discharge of the River Meuse over the late Holocene: impacts of long-term anthropogenic land use change and climate variability, *Hydr. Earth Syst. Sci.*, 12, 159-175, 2008.
- 11) Saengsrirachan et al.: Paleo-environments and tectonic setting of the Mesozoic Thung Yai Group in Peninsular Thailand, with a new record of *Parvamussium donaiense* Mansuy, 1914. *Gondwana Research* 19, 47-60, 2011.
- 12) EEA: Sustainable water use in Europe. Part 3: Extreme hydrological events: floods and droughts, Environ. issue report No. 21, EEA, Copenhagen, Denmark, http://reports.eea.europa.eu/Environmental_Issues_No_21/en, 2001.
- 13) WL: Onderzoek Watersnood Maas. Achtergrondrapport 1. Hydrologie, Deel A + B. Onderzoeksproject Watersnood Maas, Het Belgische stroomgebied. Waterloopkundig Laboratorium, Delft, The Netherlands, 1994.
- 14) Knol et al.: Historisch grondgebruik Nederland: een landelijke reconstructie van het grondgebruik rond 1900, Alterra report 573, Alterra, Wageningen, The Netherlands, http://library.wur.nl/wasp/bestanden/LUWPUBRD0032827_9_A502_001.pdf, 2004.
- 15) Dutoo: Onderzoeksproject Watersnood Maas. Het areaal onder bos in het Franse maasbekken van 1908 tot 1988, Universiteit Gent, Gent, Belgium, 1994.
- 16) Bunnik: Pollenanalytische Ergebnisse zur Vegetationsund Land-wirtschaftsgeschichte der J'ulicher L'obb'orde von der Bronzezeit bis in die fr'uhe Neuzeit, *Bonner Jahrb'ucher*, 195, pp.313-349, 1995.
- 17) Kojima, T. and Takara, K.: A grid-cell based distributed flood runoff model and its performance, Weather radar information and distributed hydrological modeling (Proceedings of HS03 held during IUG2003 at Sapporo, July 2003), *IAHS Publ. No. 282*, pp. 234-240, 2003.
- 18) Sayama, T., Takara, K., Tachikawa, Y.: Reliability evaluation of rainfall-sediment-runoff models, Erosion Prediction in Ungauged Basins: Integrating Methods and Techniques (Proceedings of symposium HS01 held during IUGG2003 at Sapporo, July 2003). *IAHS Publ. no. 279*, 131-141, 2003.
- 19) Apip et al.: Spatial lumping of a distributed rainfall sediment runoff model and effective lumping scale, *Hydrological Processes*, DOI: 10.1002/hyp.8300, 2011.
- 20) Luo et al.: Assessment of Japanese and Chinese Flood Control Policies, *Ann. of Disas. Prev. Res. Inst., Kyoto Univ.*, No.53B, 2010.
- 21) Luo et al.: Reconstruction of Paleo-Land use during the late Modern era in the Kamo River basin, Kyoto, Japan, *Int'l J. of Geographical Information Science*, in submitting, 2011.
- 22) Nhat et al.: A simple scaling characteristics of rainfall in time and space to derive intensity duration frequency relationships, *Ann. J. of Hydr. Eng. JSCE*, 51, 73-18, 2007.

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