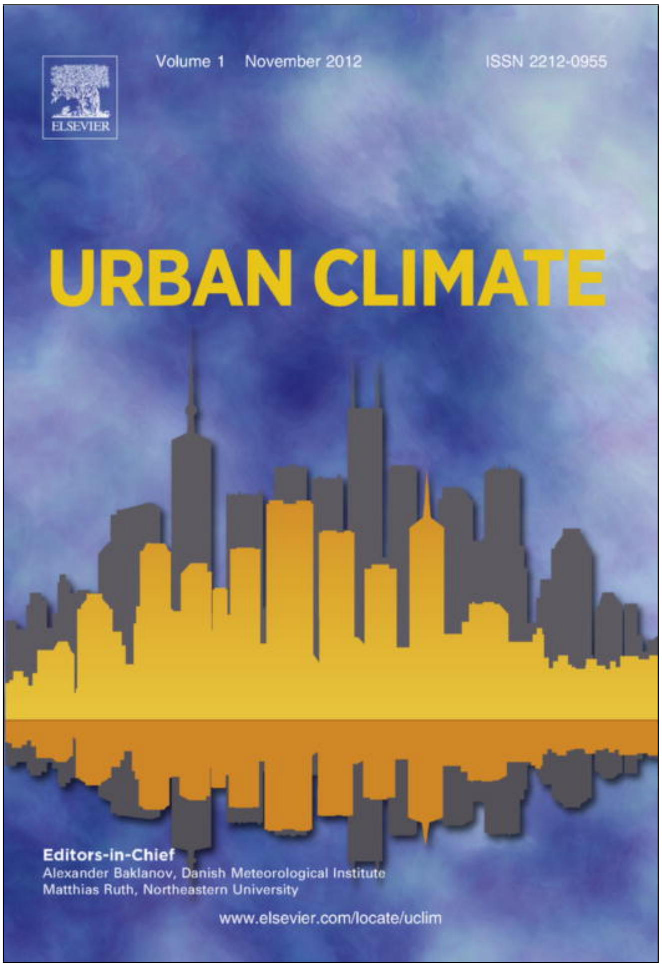
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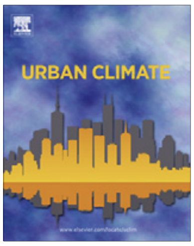

Ecological and hydrological responses to climate change in an urban-forested catchment, Nagara River basin, Japan

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ABSTRACT

Annual changes in temperature, precipitation, and stream flow in a forested watershed were investigated by statistical analysis of various time-series records. Climate change was apparent not only in increased temperature but also in altered precipitation patterns including a longer no-precipitation period, shorter precipitation duration, and changes in the cyclical interval of heavy rain. Such climate changes led to a shorter precipitation-runoff response, a decreased amount of effective precipitation, and an increase in sediment yields due to increased evapotranspiration and decreased soil moisture. Rapid urbanisation in some forested watersheds may cause larger peak flows and decreased low flows by significantly reducing soil infiltration capacities. In contrast, forests have minimal influence on landslides, debris flows, or floods caused by extreme natural events. The combined effects of vegetation cover and topography explained the differences in summer runoff and maximum daily specific discharges among experimental catchments and in the behaviour of the same catchments during individual storms. The results of this study demonstrate that forests in headwater watersheds in Japan generally help create favourable water flow conditions and reduce water-related disasters.

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1. Introduction

Base flow, an important component of stream water systems, is the flow contributed by groundwater discharge and other delayed sources such as snow melt into streams. Reay et al. (1992) cautioned that neglecting base flow (shallow groundwater discharge) as a nutrient source to streams could result in misinterpretation of data and mismanagement. Knowledge of base flow availability is important for numerous applications, including the development of water-management strategies, especially under drought conditions; the establishment of relationships between aquatic organisms and their environment; the estimation of small to medium water supplies; and the management of salinity, water quality, and algal blooms. Additionally, base flow maintains flow for navigation, water supply, hydroelectric power, and recreational uses in reservoirs (McMahon and Mein, 1986; Förch et al., 1996; Meiβner et al., 2007; Schröter et al., 2011). Stuckey (2006) noted that estimation of base flow contributions to streams is useful for watershed planners to determine water availability, water-use allocations, assimilative capacity of streams, and aquatic habitat needs. Base flow displays spatial and temporal variability influenced by climate, land use, soils, recharge frequency and amount, vegetation, topography, and geology (Stuckey, 2006; Delin et al., 2007). At the continental scale, Heath (1984) divided the United States into groundwater regions based on rock units; however, he did not address topography or climate. Vogel and Kroll (1992) statistically categorised regions and assessed many geomorphic variables but did not incorporate findings into definable landscape regions.

Several studies have related topographic parameters to base-flow statistics. Zecharias and Brntsaert (1988) examined the influence of several geomorphologic parameters on groundwater discharge in Appalachian watersheds in the US. Vogel and Kroll (1990, 1992) formulated a conceptual watershed model and developed regional regression equations for estimating low-flow statistics for 23 catchments in Massachusetts. These equations involve mainly topographic parameters. Nathan et al. (1996) conducted a regression analysis to create a base-flow index in terms of topographic and other properties for catchments in Victoria, Australia. The present study differs from those studies in that (a) it uses dimensionless topographic parameters and (b) seeks to identify an environmental indicator that expresses the key physical processes influencing base flow in a catchment. A number of European studies of base flow (Gustard, 1993; Gustard et al., 1989, 1992) utilised soil classes as explanatory variables of base flow. However, soil surveys were insufficient to establish such a procedure in Australia, where an approach using a set of geology and vegetation groups has been used instead. The use of the geology–vegetation groups to represent the bedrock and soils is based on the concept of an environmental indicator. The indigenous vegetation community of the catchment, in combination with geology, is serves as a surrogate for important physical characteristics influencing hydrological behaviour. The relationships among a base-flow index and geology–vegetation groups, three topographic indices, a climatic index, forest cover, and forest growth stage are examined, and the possibility of a scale effect with catchment size is also considered.

Reviews of basin studies (Beschta et al., 2000; MacDonald and Hoffman, 1995; MacDonald et al., 1997; Plamondon, 1993, 2002; Sandgård et al., 1991) have indicated that logging may increase peak flows enough to affect stream morphology. MacDonald et al. (1997) reviewed the effects of forest harvesting on peak flows and concluded that, regardless of whether the peak was caused by rainfall or snowmelt, (1) changes in the magnitude of peak flows tend to decline with increasing annual precipitation; (2) the percent change is usually less important in the dormant season than in the growing season; (3) about 10–15% of a basin area has to be cleared for a change in peak flows to be detectable; and (4) the percent change generally shows a decrease with peak flow with an increasing return period. However, results vary widely due to uncontrollable factors such as topography, soil characteristics, and forest species harvested and as a function of other elements such as harvested area, road location, ski trails, magnitude of peak flow, and method of data analysis. For example, small summer peak flows were increased by an average of 419% after clear cutting 20% of a basin area in Pennsylvania (Dietterick and Lynch, 1989), whereas several other studies indicated no significant changes in peak flows following clear cuts of up to 100% of the basin area (Harr et al., 1979, 1982; Harris, 1973; Miller, 1984; Nakano, 1967).

Forest operations are among the most significant land-use changes in terms of hydrological effects (Calder, 1992; Mölders and Rühaak, 2002; Mölders and Kramm, 2007). In Chile, hydrological effects have occurred from the afforestation of uncovered lands, the type of harvesting techniques (large-scale clear cuttings), and the intense interventions that occur at the end of the growing cycle in short rotations (22–24 years in Monterey pine and 10–12 years in eucalyptus plantations) in environments characterised by abundant and intense rainfalls in winter and dry summers. In these driest months, water availability reductions associated with large-scale plantation developments have generated concern among the general public and among interest and environmental groups. This cover type is in its full growing period when interception and transpiration rates are at their highest potential. Problems have been reported in drinking and irrigation water supply catchments and where groundwater table depletions are affecting water availability in farms and rural settlements. In dry areas, replacing the existing vegetation with plantation forest may raise evapotranspiration to the point where it balances with or exceeds rainfall (e.g., Bathurst et al., 1998). Although some studies examining the relationships between forests and water resources have been conducted (Huber and Oyarzún, 1990, 1992; Huber and López, 1993; Huber and Martínez, 1995; Förch et al., 1996; Huber and Iroumé, 2001; Iroumé and Huber, 2002), information about the effects of forest practices on summer water production is lacking.

Additionally, although various aspects of interaction between forests and water have been investigated for more than 75 years (Bates and Henry, 1928; Hibbert, 1965; Hewlett and Helvey, 1970; Lull and Reinhart, 1972; Hornbeck, 1973; Anderson et al., 1976; Bosch and Hewlett, 1982; Hewlett, 1982; Brunijzeel, 1990; Whitehead and Robinson, 1993; Brooks et al., 1997), the roles of forests in regulating stream flows and in mitigating soil- and water-related disasters have often been misunderstood or misinterpreted by many people, including the general public, conservation groups, politicians, and even academics. There is a need for a systematic review including a synthesis of available studies and data regarding the influences of forests on water flows from headwater watersheds, such as the Baltimore Ecosystem Study of the Long Term Ecological Research Network, which examines a metropolitan area as an ecological system.

Recently, in mountainous forested regions throughout Japan, changes in stream flow have been reported, including reductions in base-flow that cause some streams to become dry, as well as more rapid rises in water level during rainstorms. Artificial influences such as forestry exploitation and

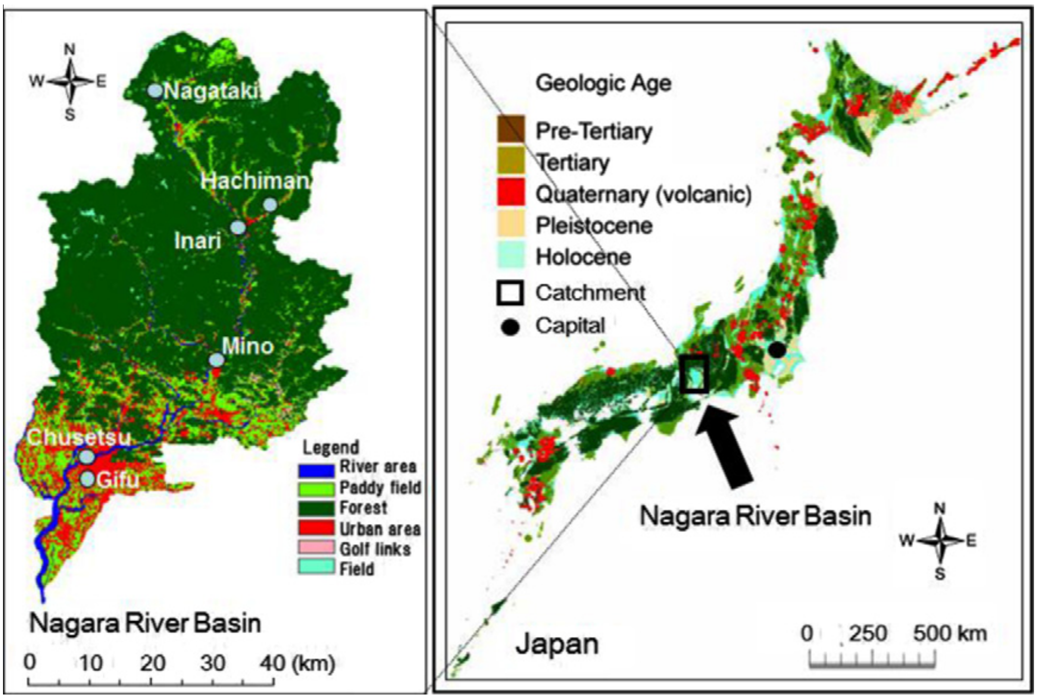

Fig. 1. Location map showing the Ministry of Land, Infrastructure and Transport (MLIT) monitoring network in the Nagara River basin. Data are from the MLIT and Digital National Information (DNI).

forestry management including cutting are thought to have contributed to these changes (Mouri and Oki, 2010; Mouri et al., 2010, 2011a,b, 2012). The present study considered that a wide range of outflow change has occurred in forested mountain streams in Japan, with climate change being a strong influencing factor. Such changes and their relationship to climate factors were examined by analysis of weather and hydrological data for the forested Nagara River basin. Flow characteristics in the Nagara River were also obtained from a questionnaire given to catchment residents. Time-series analyses of these data were conducted, considering the influence of climate change on the forested catchment and changes in its stream flow.

2. Study site description

Fig. 1 shows the study area in central Japan and its situation within Japan's geologic setting. The Nagara River basin covers 1985 km^2. Land-use data were determined from satellite images by the Landsat/Thematic Mapper (TM). As shown in Fig. 1, the upper part of the Nagara River basin is mostly covered by forest (75.3%). The figure also shows the observation points of the hydrological and atmospheric data used in this paper. From upper to lower parts of the stream, observations were made in the Nagataki, Hachiman, Mino, and Gifu areas, where meteorological observatories measure temperature and precipitation. Additionally, river level is measured by the Ministry of Land, Infrastructure and Transport at Inari, and flow velocity is measured at Chusetsu.

3. Long-term atmospheric and hydrological characteristics

The 6 observation points described above have collected data continuously for more than 25 years. Although many observatories and weather survey points operated by the Ministry of Land, Infrastructure, and Transport (MLIT) are installed in the Nagara River basin, this study focused on the observational data collected at the 6 locations.

3.1. Upward tendency of temperature

For the 25 years from 1979 to 2003, Fig. 2 shows the daily maximum, minimum, and average temperatures at the Hachiman observation point in the upper region of the Nagara River. Changes in temperature were observed over the study period, with a clear upward tendency in all three temperature measures. The rates of increase were 1.6 °C/25 years for daily maximum temperature, 1.4 °C/25 years for daily minimum temperature, and 1.8 °C/25 years for daily average temperature. Fig. 3 shows the

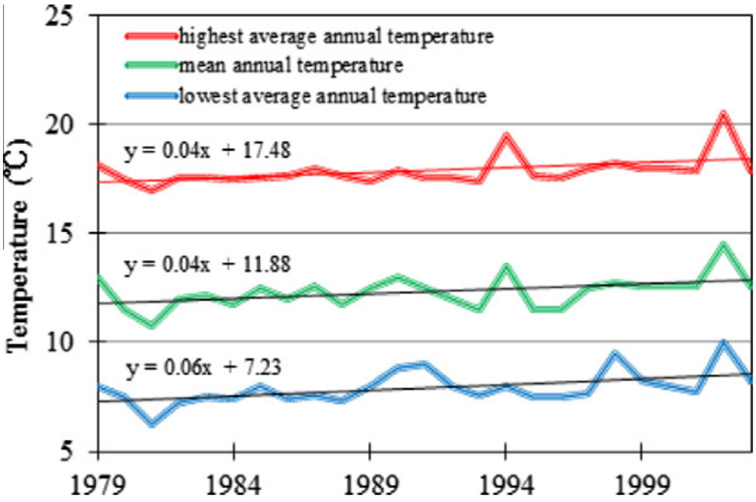

Fig. 2. Lowest, highest, and average daily temperatures at Hachiman from the late 1970s to the 2000s. Data are from the Ministry of Land, Infrastructure and Transport (MLIT) and the Automated Meteorological Data Acquisition System (AMEDAS) of the Japan Meteorological Agency.

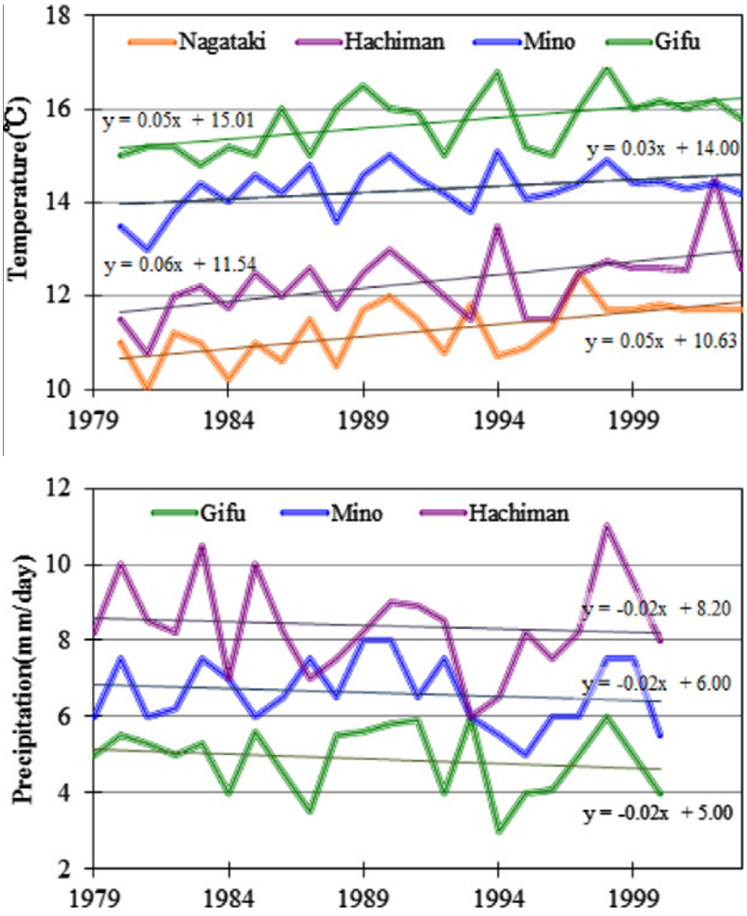

Fig. 3. Long-term changes in annual temperature and precipitation in the Nagara River basin. Data are from the Ministry of Land, Infrastructure and Transport (MLIT) and the Automated Meteorological Data Acquisition System (AMEDAS) of the Japan Meteorological Agency.

changes in daily average temperature and precipitation at lower to upper stream stations in the Nagara River basin. A clear upward tendency in temperature is apparent at all locations. The average rate of temperature increase for all locations was considered to be high at 1.1 °C/25 years. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), a 1.4–5.8 °C rise in temperature is expected in the 100 years after 1990. Compared with this predicted value, the temperature increase in the Nagara River basin over just 25 years is very large. The results indicate the importance of initiating a forest preservation policy based on the examination of climate change and its relationship to forest change, as well as to the circumstantial evidence found in this study and from field observation or numerical model analysis.

3.2. Change in rain patterns

The lower panel of Fig. 3 shows annual changes in average daily precipitation. Values vary largely from year to year, and no clear tendency is evident, unlike for temperature. More detailed examination was conducted considering the characteristics of rainfall events. An example of changes in rainfall characteristics at Hachiman is shown in Fig. 4 and discussed below. The upper panel presents the maximum hourly precipitation (mm/h), represented as the daily average of maximum hourly precipitation for each year. Other precipitation characteristics such as number of precipitation events and precipitation amount per event are also shown, as yearly averages.

Although these values appear to decrease slightly, yearly variation is large, and no clear tendency can be identified. A no-rain period is defined as the period in which no precipitation occurs for 24 h or more. A rainy period between two no-rain periods is treated as one rain event. The annual averages of

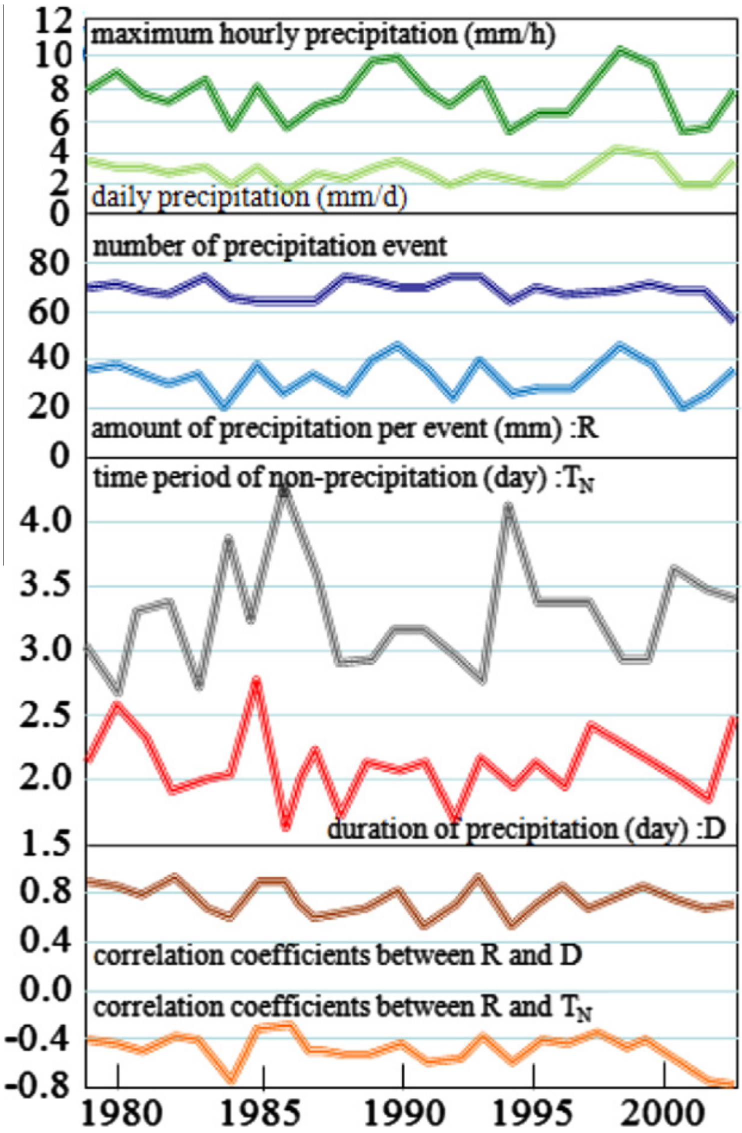

Fig. 4. Long-term change in precipitation characteristics at Hachiman. Data are from the Ministry of Land, Infrastructure and Transport (MLIT) and the Automated Meteorological Data Acquisition System (AMEDAS) of the Japan Meteorological Agency.

total rain events and total precipitation per event were calculated, and changes in these features were evaluated, as were the average durations of no-rain periods and rain events. The annual number of rain events tended to decrease, whereas the duration of no-rain periods became longer. In other words, in this 25-year period, it appears that, as a general trend, no-rain periods became more protracted and rain events became shorter.

On the other hand, many single events had large precipitation and long duration. The correlation coefficient of total precipitation per event and rain duration was found to be a high positive value. However, as shown in the bottom panel of Fig. 3, this correlation coefficient indicates a decreasing trend, changing from a strong to a weak correlation over the 25 study years. This suggests longer duration of periods of light rain or short periods of concentrated heavy rain. In most years, precipitation amount per rain event is thought to have decreased or precipitation has been delayed by prolonged no-rain periods.

The bottom panel of Fig. 4 also shows the relationship between total precipitation per event and the duration of no-rain periods, which changes from weakly negative to strongly negative over the study period. This either indicates an increase in episodes of light rain following period of no rain or suggests that heavy rains are occurring in rapid succession without no-rain periods in between. Tendencies similar to those described for Hachiman were found at the other observation points.

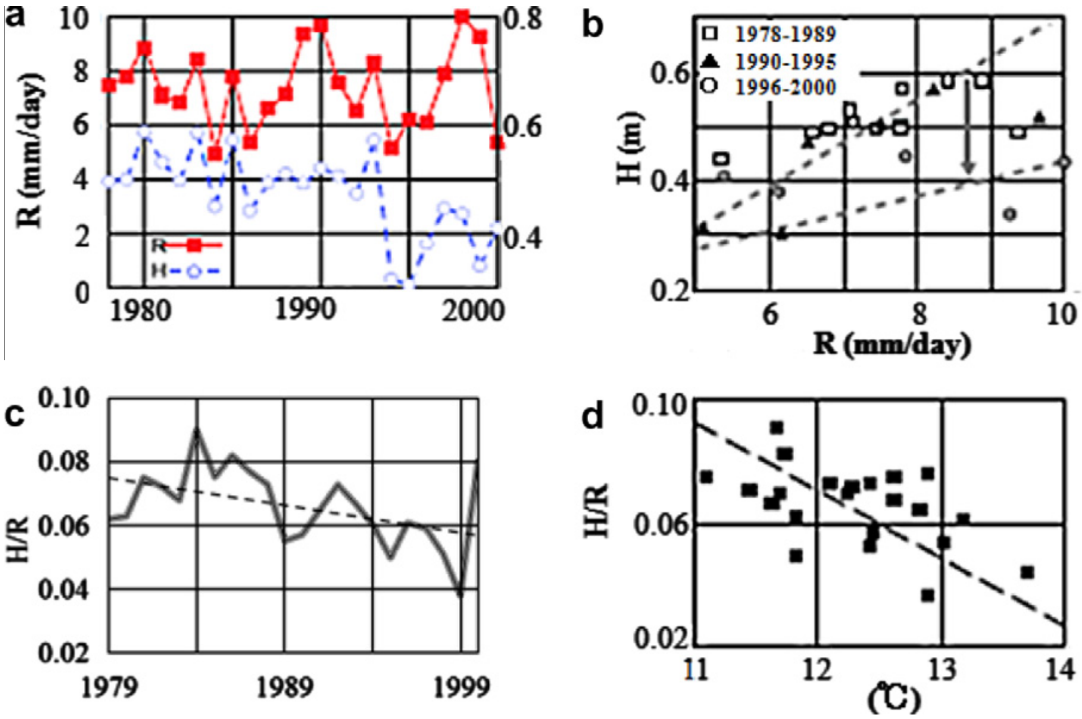

Fig. 5. Relationships among precipitation, river level, and temperature in the upper part of the Nagara River. (a) Time series of average daily precipitation measured at Hachiman (R: red squares, unit = mm/day) and average river level (H: white circles, unit = m) measured at Hachiman. (b) Relationship between precipitation (*R*) and river level (*H*) at Hachiman. (c) Time series of river water level per unit of precipitation. (d) Relationship between river water level per unit precipitation and annual average temperature.

Although no significant change tendency was shown in yearly precipitation, substantial change appears to be occurring in the pattern of rain events, which is considered one feature of climate change.

This indicates that the temperature–precipitation relationship in the mountainous area decreased significantly because of the impact of increased evapotranspiration in forested areas. The characteristics of rainfall events have also changed, particularly for small-scale rain events (Mouri et al., 2011a); i.e., cases of precipitation <100 mm/event were correlated with a tendency of decreased river flow.

4. Long-term rainfall runoff characteristics

The temperature increases and changes in rainfall patterns noted above are expected to have a large influence on outflow. This section examines changes in flow characteristics in the upstream parts of the Nagara River around the city of Gifu. In this part of the Nagara River valley, forest represents 90% or more of the land cover.

4.1. Change in effective precipitation

Fig. 5a shows the annual average water level of the Nagara River at the Inari station along with daily precipitation at Hachiman. Variations can be seen in both graphs over the study period, with annual average water levels becoming high in years with much precipitation, as expected. However, upon careful examination, the relative correspondence of precipitation and river level becomes less clear for the most recent decade. Fig. 5b shows the relationship between precipitation and river level in three time periods. The slope of the regression line demonstrates a good correspondence between precipitation and river levels, until the 1980s. After 1980, the slope of the regression line indicated a weak correlation. This tendency can also be seen in Fig. 5c, which shows the change in river level (*H*) per unit of precipitation (*R*); the decreasing trend can be interpreted as a reduction in effective

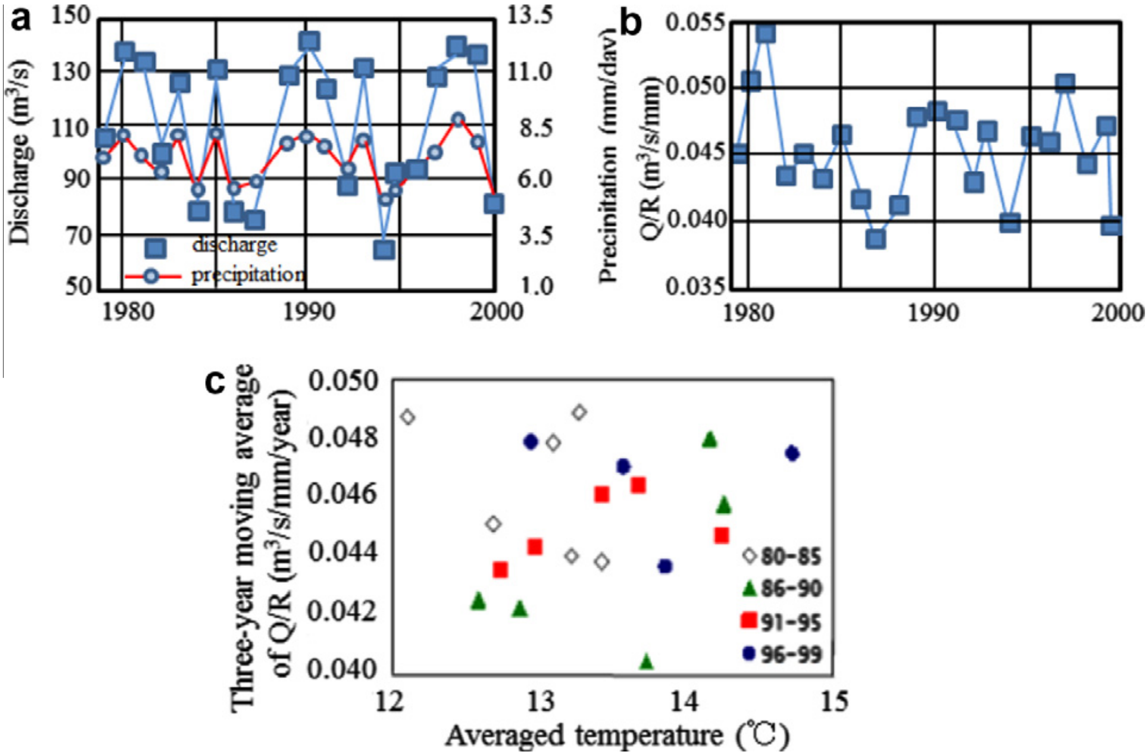

Fig. 6. Relationships among precipitation, river discharge, and temperature for all stations in the Nagara River basin. (a) Time series of precipitation and river water level. (b) Time series of river water level per unit precipitation. (c) Relationship between river discharge and annual mean temperature.

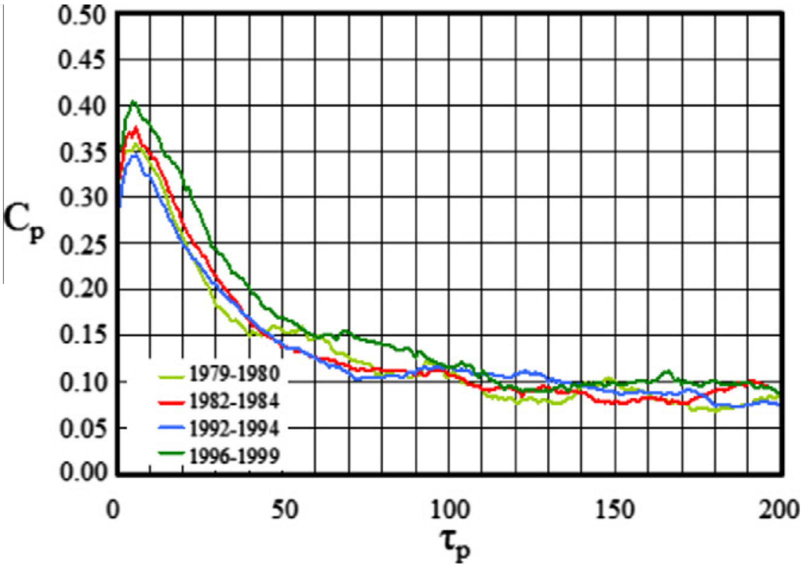

Fig. 7. Crossing correlogram of precipitation and river water levels in the upper part of the Nagara River. Data are from the Ministry of Land, Infrastructure and Transport (MLIT) and the Automated Meteorological Data Acquisition System (AMEDAS) of the Japan Meteorological Agency.

precipitation. Additionally, Fig. 5d plots the relationship between annual average temperature and H/R. The results in 5(d) are attributable to a decrease in effective precipitation with rising temperature; from this, we can infer that falling river levels have been caused by water loss accompanying the rise in temperature.

Fig. 6 presents the results of the same examinations for the Nagara River basin as a whole. The values in this figure were calculated using the annual average temperatures at the four observations points shown in Fig. 1 and the average annual flow rate and precipitation at each point.

Because the water level in Fig. 5 is also used in Fig. 6, the utility of comparing the figures is limited. However, in Fig. 6, which represents the entire Nagara River basin, there is no clear downward tendency in effective precipitation accompanying the rise in annual average temperature. This might be attributable to land-cover effects, such as the heating effect of an urban region, which would influence the temperature and wind velocities and their effects on total annual precipitation and flow rates. The part of the catchment, which is largely occupied by forest, showed decreased precipitation with the rise in temperature. In other parts of the catchment, where other land uses exist in addition to forest, other factors of the overall community may influence the effective precipitation, even if the water balance is readily and directly influenced by temperature rise. Thus, next we focus on the upper region of the Nagara River to consider possible changes in flow characteristics accompanying climate change.

4.2. Change in rainfall runoff response

Fig. 7 shows the crossing correlogram of precipitation at Hachiman and river levels at Inari in various time periods. cP in a figure – and τP – respectively – peak height (correlation coefficient) of a time series response behind – time (h). Although we cannot draw long-term conclusions from this result, the figure suggests that τP has been becoming shorter in recent years and also that long lags in outflow reflect longer no-rain periods.

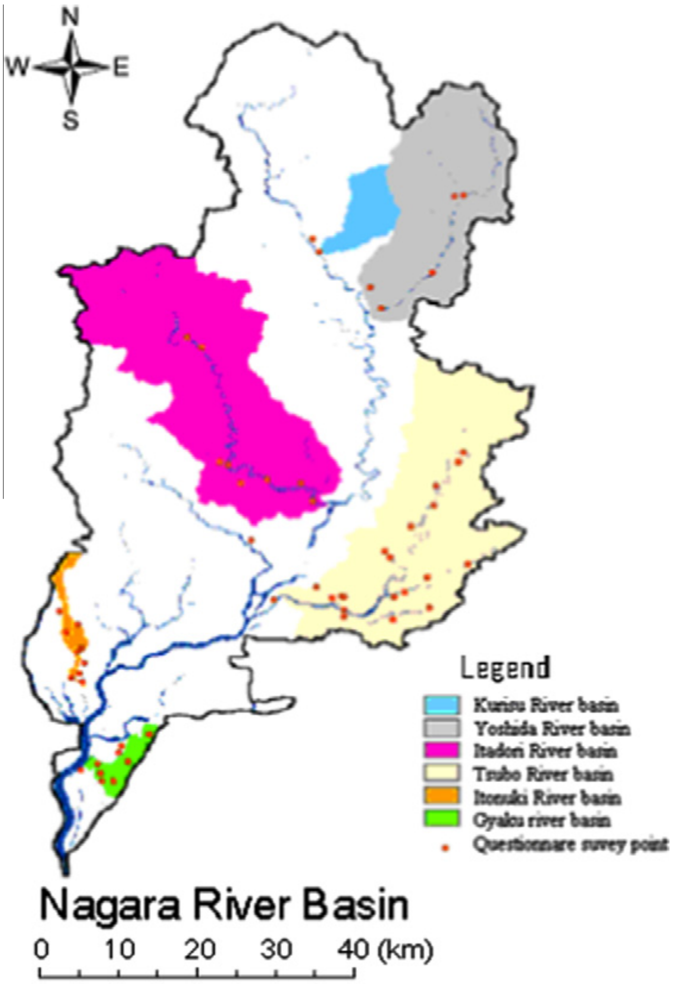

Fig. 8. Locations of the sub-catchments studied in the Nagara River basin. Red dots mark the elementary and junior high schools where the questionnaires were distributed.

Table 1
Questionnaire distribution to local residents.

Selected Sub-catchment	Date of survey	Sub-catchment area [km^2]	Land use [%]			Number of schools	Effective answers			
			F	C	U		Students	Parents	Total	Ratio[%]
Kurisu	Dec. 2003	167	87.7	10.9	1.4	2	107	95	202	57.7
Yoshida	Oct. 2001	187	90.9	5.5	2.0	5	526	398	924	68.7
Itadori	Dec. 2003	314	93.1	3.1	1.2	9	677	547	1,224	79.1
Tsubo	Dec. 2003	292	66.8	21.1	7.0	18	1,821	1,232	3,053	63.6
Itonuki	Dec. 2003	21	19.4	40.8	39.5	10	2,057	1,646	3,703	71.5
Gyaku	Dec. 2003	20	0.0	44.2	54.6	9	1,904	1,372	3,276	66.6
Total		(1985)	75.3	18.2	6.5	53	7,092	5,290	12,382	68.2

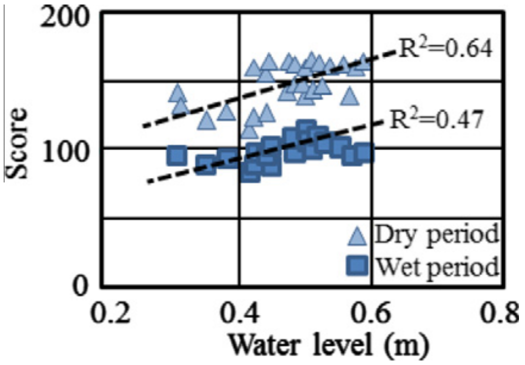

Fig. 9. Correlation between observed annual average water level and the relative scores for dry- and wet-period water levels obtained from the questionnaires.

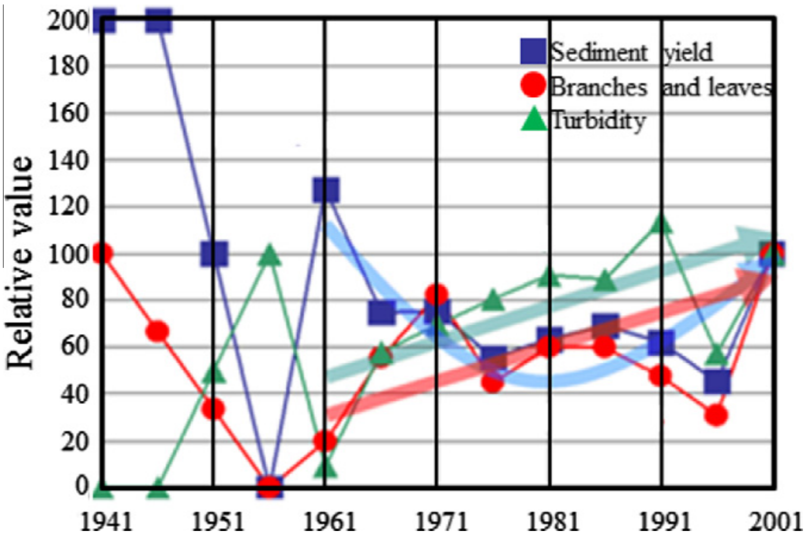

Fig. 10. Annual changes in environmental factors in the forested watershed, estimated using data obtained from the questionnaires.

4.3. Change in sediment discharge

Rises in temperature accompanying climate change and changes in rain patterns can be expected to affect not only moisture dynamics but also sediment dynamics. However, data with which to understand long-term change in sediment discharge in the Nagara River are scarce, and the river does not have a dam where sediment can collect. Therefore, changes in sediment dynamics were inferred from characteristics reported in questionnaires distributed to local residents in various sub-catchments. Fig. 8 shows the sub-catchments and the locations of elementary and junior high schools where questionnaires were distributed to children and their adult guardians. Table 1 lists the number of surveys distributed and the response rates. Respondents were asked to consider various aspects of the river and to compare past conditions with those at present. Questions concerned turbidity, the river as a habitat for living things, the timings of various water levels, sediment deposition, and rainfall. The responses were converted to relative time-series data and plotted as data points. In total, about 12,382 surveys were distributed, and the response rate was very high (70%). Because serial change in the environmental state was presumed based on respondents' subjective impressions or memories, the accuracy of the survey could be problematic. It would be desirable to scientifically acquire data for each corresponding environmental state and to compare these data to the questionnaire item responses to ensure accuracy (Fig. 10).

Fig. 9 shows the correlations between the observed water level during fine weather and questionnaire results from Inari for clear and rainy weather, respectively. The two types of data show good

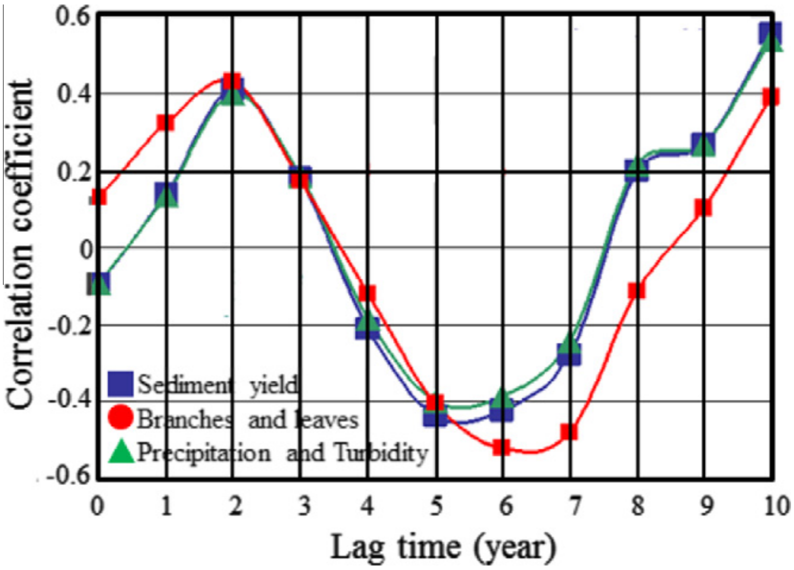

Fig. 11. Crossing correlogram of annual average precipitation, the amount of sediment and sand deposition, and the time of recovery from turbidity.

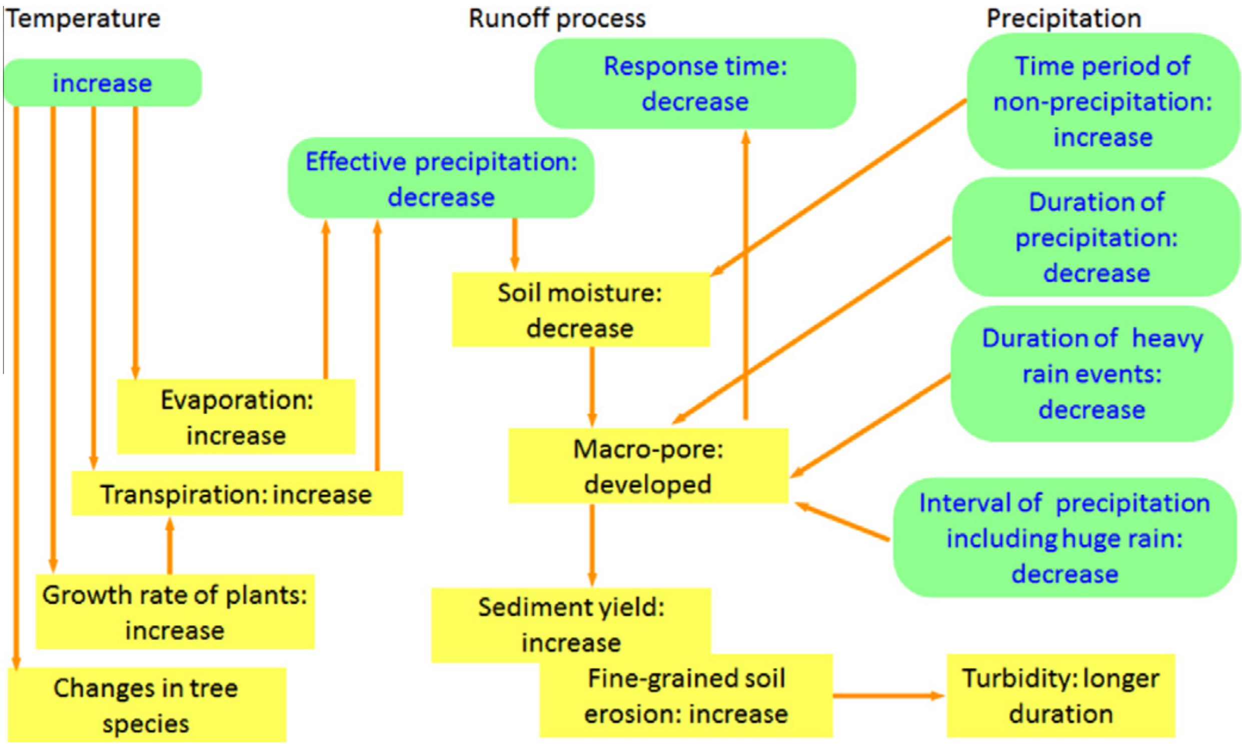

Fig. 12. Summary of climate changes and the effects on runoff processes in the forest environment.

correlation, and the observations help to validate the chronological order of the hydrology estimated from the questionnaire results.

Fig. 10 confirms the validity of presuming hydrological time-series data from the questionnaire results. The figure shows the converted questionnaire data for the Yoshida sub-catchment, including Hachiman and near the observation point in Inari. The relative data from the questionnaire show a dramatic change in the amount of sediment deposition in the stream bed around the 1950s, as well as a change in the turbidity recovery time following a flood. After this period, both sediment deposition and turbidity tend to rise. Although the reliability of these data might be weak because few respondents could answer questions for the early time periods, the results were accepted and the data were used to create a correlogram with annual average precipitation at Hachiman, as shown in Fig. 11. A clear peak was found with a 2-year lag, indicating a change in the state of sediment discharge with a 2-year delay from a change in precipitation.

5. Conclusions

Considering the combined results described above, the rise in annual average temperature, as shown in Fig. 12, will lead to a decrease in the amount of water, a tendency that was most notable for the study period in the heavily forested upper watershed. In conjunction, effective precipitation will decrease, and longer no-rain periods will result in drier soil conditions in forest soils. At the same time, the amount of outflow sediment during rain events will increase, causing increased stream bed deposition, simultaneous surge formation and macro-pore formation, and soil erosion with the outflow of fine-grained sandy soil. In this situation, turbidity recovery will be lengthened. With shorter rainfall duration, there will also be an increase in short-term concentrated rainfall, and the intervals between heavy rainfalls will become shorter. These changes will result in increased direct runoff and an earlier appearance of intermediate flow components, ultimately shortening the rain outflow response. The mechanisms of the relationship between climate change and changes in forested catchments must be further examined and considered when developing plans to conserve forests and water resources. Many water resource management issues require an understanding of how hydrological, climate, and land-use contexts will influence the distribution of daily base flows, large events, and long-term change in the flow duration curve. Resources and tools for use in such analyses include local observations and numerical modelling of not only the effects of climate change but also the effects of land use (Carlson, 2007; Dow and DeWalle, 2000; Mouri et al., 2011a,b). Our findings underline the need to thoroughly analyse possible changes in flood behaviour when designing flood structures or managing flood risk. These findings provide a sound foundation for applications in hydrological catchment modelling. The method used in this study can reveal the effects of environmental improvement policies applied individually or simultaneously as multiple measures, which can compound improvement effects. The method can also be used for evaluations from the perspectives of various users, which can help multiple interest groups reach suitable agreements and decisions. Through the method introduced here, the implementation of best management practices should become more possible. Uncertainty, particularly regarding ecological changes, is represented by probabilistic linkages. Further modelling efforts are underway to define the interactions among catchment management, ecosystems, disaster prevention, and economic values in the form of conditional probabilities. The results will be discussed in a future report.

Acknowledgments

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