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Research article

Land use management recommendations for reducing the risk of downstream flooding based on a land use change analysis and the concept of ecosystem-based disaster risk reduction

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ABSTRACT

Sustainable management of ecosystems can provide various socio-ecological benefits, including disaster risk reduction. Through their regulating services and by providing natural protection, ecosystems can reduce physical exposure to common natural hazards. Ecosystems can also minimize disaster risk by reducing social and economic vulnerability and enhancing livelihood resilience. To showcase the importance and usefulness of ecosystem-based disaster risk reduction (Eco-DRR), this study (1) analyzed the land use change in a watershed in central Japan, (2) applied the concept of Eco-DRR, and made land use management recommendations regarding the watershed scale for reducing the risk of downstream flooding. The recommendations that emerged from the application, based on the land use change analysis, are: the use of hard infrastructure and vegetation to store and retain/detain stormwater and promote evapotranspiration is recommended for downstream, urban areas; the sustainable management of upland forest ecosystems and secondary forest-paddy land-human systems, and proactive land use planning in the lowland delta, where built land is concentrated, are key to the watershed-scale landscape planning and management to reduce downstream flooding risks.

1. Introduction

Globally, due to climate change, extreme weather-related events such as heavy rains and consequent flooding are expected to increase in frequency and intensity (Amendola et al., 2008; IPCC, 2012b; Royal Society, 2014; Lafrenière and Walbaum, 2017). Due to its location, topography, geology, weather, and other natural conditions, Japan is prone to various natural hazards such as typhoons, heavy rains, heavy snowfall, floods, landslides, earthquakes, tsunamis, and volcanic eruptions (Cabinet OfficeGovernment of Japan, 2020). Among the natural hazards, torrential rainfall events causing floods and landslides are becoming more intense and frequent in Japan (Cabinet OfficeGovernment of Japan, 2020). For example, the number of days with daily heavy rainfall of 200 mm or more has increased significantly during the statistical period since 1901 (JMA, 2007); the frequency of short-term heavy rainfall events with hourly precipitation of 50 mm or more has increased significantly during the statistical period since 1976 (JMA, 2020a). To protect human lives and assets, there is an urgent need to mitigate and develop resilience to natural disasters.

The response to natural disasters has been dominated by developing hard infrastructure such as embankments and sea walls (Jones et al., 2012). However, as previous disasters have demonstrated, no engineering solutions are completely fail-safe (Vallero and Letcher, 2012). For example, in the Taro district in Iwate Prefecture, the tsunami triggered by the Great East Japan Earthquake in 2011 breached and then destroyed what was Japan's most robust sea wall (Miyako City, 2015). Moreover, the maintenance and renewal cost of existing conventional infrastructure places a substantial burden on the local and national budget (MLIT, 2018).

Nature-based solutions to natural disasters can complement conventional engineering solutions (Depietri and McPhearson, 2017; Kabisch et al., 2017; Albert et al., 2019; Hobbie and Grimm, 2020). The concepts of nature-based solutions and ecosystem-based disaster risk reduction (Eco-DRR) have gained traction among landscape and urban planners, natural resource managers, and policy makers, as is evident in numerous international scientific and policy reports, and in the Sendai Framework for Disaster Risk Reduction 2015–2030 (PEDRR, 2010; UNFCCC, 2011; IPCC, 2014; EC, 2015; IUCN, 2020; PreventionWeb, 2020). These international reports recognize the importance of sustainable ecosystems and ecosystem-based approaches to disaster risk

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management.

The IPCC (2012a) defines disaster risk reduction (DRR) as "both a policy goal or objective, and the strategic and instrumental measures employed for: anticipating future disaster risk; reducing existing exposure, hazard, or vulnerability; and improving resilience." Eco-DRR includes approaches and actions that include the sustainable management, conservation, and restoration of ecosystems (nature) while simultaneously aiming for sustainable and resilient development (Estrella and Saalismaa, 2013). For example, sustainable forest management can protect communities, settlements, and infrastructure against natural hazards such as landslides and avalanches (Moos et al., 2018). While many ecosystem services rely on healthy and functioning ecosystems, Eco-DRR is particularly focused on disaster prevention and reduction (Furuta, 2017).

According to Estrella and Saalismaa (2013), there are two ways in which ecosystems can reduce disaster risk: first, by providing natural protection, and second, by enhancing livelihood resilience (Sudmeier-Rieux and Ash, 2009; Renaud et al., 2013a). Through their regulating services and by serving as natural protective barriers or buffers, ecosystems reduce physical exposure to common natural hazards, such as floods, landslides, storm surges, and wildfires (Sudmeier-Rieux and Ash, 2009; World Bank, 2010; Depietri and McPhearson, 2017).

Numerous studies have documented the hazard mitigation functions of ecosystems such as forests, wetlands, floodplains, coastal ecosystems, and drylands (PEDRR, 2010; IPCC, 2012b; Renaud et al., 2013b; Doswald et al., 2014; Royal Society, 2014). Projects that leverage ecosystems for DRR are well known, and include, for example, planting mangroves to enhance coastal protection following the 2004 Indian Ocean tsunami (Renaud et al., 2013a), and the Dutch "Room for the River" Program, a nationwide program, to restore Dutch rivers' natural floodplains to improve their water retention capacity (Dutch Water Sector, 2019).

Ecosystems also reduce disaster risk by reducing social and economic vulnerability and by enhancing the livelihood resilience of hazard-exposed communities (Sudmeier-Rieux and Ash, 2009). Through provisioning services that strengthen local resilience against disasters, ecosystems can sustain human livelihoods (Estrella and Saalismaa, 2013; Renaud et al., 2013a). In addition, in post-disaster contexts, ecosystems and the resources they provide, form an essential part of local coping and recovery strategies, reducing vulnerability to hazards (Estrella and Saalismaa, 2013; Renaud et al., 2013a).

Therefore, the degradation of ecosystems leads to increased social-ecological vulnerability and reduced livelihood resilience (UNEP, 2009; Renaud et al., 2013a; Depietri, 2020). Degraded ecosystems can aggravate the impact of natural hazards, for instance, by altering the physical processes that affect the magnitude, frequency, or timing of hazards (Estrella and Saalismaa, 2013). For example, in many parts of the world, extensive deforestation has led to increased susceptibility to floods and landslides during heavy rainfall events and hurricanes (Peduzzi, 2010; Sudmeier-Rieux et al., 2011). The land use change, including deforestation, is one of the main causes of ecosystem degradation, affecting the impacts of natural hazards. For instance, the frequency of avalanches in the Italian Alps has been influenced by the land use changes in the region (Poratelli et al., 2020). Increase in broadleaf and mixed-tree forest area mitigates flood in China (Tembata et al., 2020). Changes in land use/cover, especially increased impervious surfaces represent hazardous increase in the velocity of water downhill in an urban watershed in São Paulo, Brazil (Young and Jorge Papini, 2020). Therefore, protecting and managing healthy ecosystems and conserving biodiversity contribute to DRR and the mitigation of hazard, vulnerability, and exposure (Renaud et al., 2013b; Royal Society, 2014; Furuta, 2017).

Healthy and well-managed ecosystems provide many beneficial services, including DRR. In river management, Eco-DRR has two important advantages over conventional engineering solutions, such as floodwalls and dykes. First, regardless of occurrence of a disaster event, Eco-DRR has multiple benefits for human well-being. Second, when ecosystems are healthy and well managed, Eco-DRR requires relatively low-cost construction and maintenance (UNFCCC, 2011; Estrella and Saalismaa, 2013; Onuma and Tsuge, 2018). Investment in Eco-DRR can also contribute to local community development by using local natural resources and personnel. Therefore, Eco-DRR is a cost-effective, no-regret investment (PEDRR, 2010; TEEB, 2010; Renaud et al., 2013a).

To showcase the importance and usefulness of Eco-DRR concept, this study applies it to a typical watershed in Japan and proposes watershed-scale, land use management recommendations for reducing the risk of downstream flooding. In this paper, we (1) analyze the changes in land use in a watershed in central Japan; (2) apply the concept of Eco-DRR based on the land use assessment; and (3) propose several recommendations to reduce downstream flood risks for land use management at the watershed scale. In a country where natural disasters are prevalent, we aim to show the usefulness of the concept using the actual watershed as a case study.

2. Materials and methods

2.1. Study area

The Ado River watershed in Shiga Prefecture is situated in the middle of Honshu, Japan's main island (Fig. 1). The watershed covers an area of approximately 300 km^2 (Shiga Prefecture, 2016). The Ado River originates in Tanba Highland, flows northward between the highland and Hira Mountain Range, and turns east in the Kuchiki district in Takashima city, eventually draining into Lake Biwa, Japan's largest lake.

Because of the steep gradient of the surrounding mountains, the rivers in the Lake West region are characterized by being relatively short and steeply inclined (Shiga Prefecture, 2016). As a result, a great deal of sediment is transported from higher altitudes and a 6 km-long section of the Ado River downstream has become elevated, running higher than ground level (Shiga Prefecture, n.d.). In addition, due to active sediment deposition, the Ado River mouth has formed a delta where it enters Lake Biwa. The land around the rivers in the region comprises settlements, paddy fields, and other agricultural land (Shiga Prefecture, 2016). The climate of the region is characterized by heavy snowfall in winter, average annual air temperate of 14 °C, and average annual precipitation of 1900 mm (JMA, 2020b; MLIT, 2020a).

Forestry is the major industry upstream. In the past, timber was carried downstream by timber-raft. Downstream, bamboo was planted on embankments to prevent flooding (Shiga Prefecture, 2016). Bamboo has been harvested to make folding fans for over 300 years and, today, the region accounts for 90% of national folding fan production (MLIT, 2020a).

2.2. Data sources and preparation

The land use datasets at three time points (1997, 2006, and 2014) were retrieved in vector format from the National Land Information Division, National Spatial Planning and Regional Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT, 2020b). These land use data are based on National Land Numerical Information (MLIT, 2020b). The vector datasets were converted to a raster format at 100 m spatial resolution, using ArcGIS 10.4. Next, the watershed boundary was created from a digital elevation model and the boundary was used to "clip" land use within the watershed from the 1997, 2006, and 2014 land use datasets (Fig. 2).

Nine land use categories emerged for the three time points: paddy land, non-paddy farmland, forest land, barren land, densely built land, transportation land, other built land, water body, and golf course (MLIT, 2020b). "Densely built land" includes heavily populated residential and urban areas. "Other built land" includes athletic fields, airports, horse race tracks, baseball stadiums, school and harbor areas, and artificially constructed vacant lots. "Transportation land" includes roads, railways,

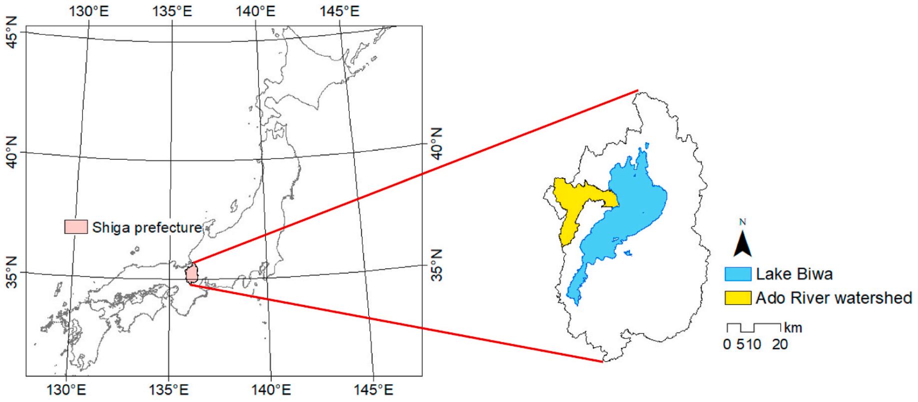

Fig. 1. Location of the Ado River watershed in Japan.

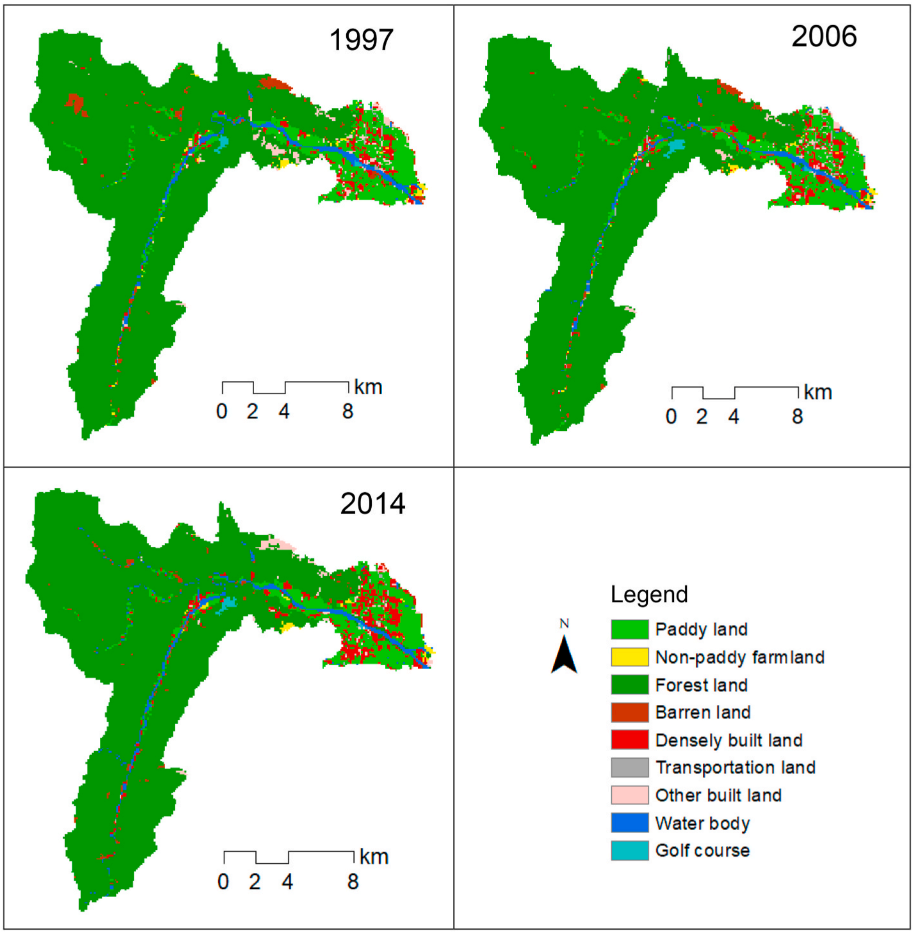

Fig. 2. Land use maps of the Ado River watershed for 1997, 2006, and 2014.

and rail yards.

2.3. Land use change analysis

Land use change can be characterized and measured according to a variety of landscape structure indices (Fan and Shibata, 2015; Bu et al., 2016; Huang et al., 2016; Zhang et al., 2017; Kumar et al., 2018). Landscape structure consists of landscape composition and configuration (McGarigal and Marks, 1995; McGarigal et al., 2012). Landscape composition refers to features associated with the variety and abundance of patch types within the landscape without reference to spatial attributes, while landscape configuration refers to the spatial character and arrangement, position, or orientation of patches within a class or landscape (McGarigal, 2015).

A variety of landscape metrics can be used to represent landscape composition and configuration (Leitão et al., 2006; McGarigal, 2015). For this study, a compendious analysis of landscape structure change in the watershed was conducted using four representative landscape metrics: patch cohesion index (COHESION), contagion (CONTAG), percentage land use type in a landscape (PLAND), and Simpson's diversity index (SIDI). Landscape composition is represented by PLAND and SIDI, and landscape configuration is represented by COHESION and CONTAG.

Landscape metrics were calculated using FRAGSTATS version 4.2 (McGarigal and Marks, 1995; McGarigal et al., 2012). In FRAGSTATS terms, SIDI and CONTAG are "landscape" metrics and COHESION and PLAND are "class" metrics (McGarigal, 2015). Landscape-level metrics are computed over the entire land mosaic, for all land use types within a defined area (landscape). Class-level metrics, in contrast, are computed for specific land use types across all patches belonging to that land use type within a specified area. The landscape metrics used in the analysis and their interpretation are summarized in Table 1.

In this study, PLAND was the percentage area occupied by each land use type in the watershed, and was calculated for all land use types. COHESION was chosen to specifically measure physical connectivity. COHESION increases with percentage increase in focal land use type and as focal land use patches become more clumped or aggregated in their distribution, more physical connection is created. COHESION was calculated for the following three land use types: forest land, paddy land, and densely built land. These land uses are of particular interest to landscape planners and natural resource managers because of their both positive and negative ecosystem services. In the context of Eco-DRR, forests and paddy fields are known to have various regulating services, such as the prevention of soil erosion and water retention for disaster reduction. Forests and paddy fields also provide important provisioning services, including timber, fuel, and rice. Connectivity is an important indicator of an ecosystem's ability to sustainably provide ecosystem services. Conversely, densely built land produces a large volume of stormwater, which is a major source of water pollution and cause of flooding. Connectivity of densely built land is a negative indicator of how much stormwater is produced. Therefore, class-level metrics for these three land use types were calculated.

SIDI represented the diversity (number and evenness) of land use types in the watershed. SIDI represents the probability that any two cells selected at random will be different land use (patch) types (McGarigal, 2015), and it approaches 1 as the number of different land use types increases and the proportional distribution of area between land use types becomes more equitable. SIDI was chosen over Shannon's diversity index because it is less sensitive to the presence of rare land use (patch) types and has a more intuitive method of interpretation (McGarigal, 2015). CONTAG measured the extent to which patches were spatially aggregated in the watershed (Lee et al., 2009; Bu et al., 2016; Huang et al., 2016). Conway and Lathrop (2005) used this metric to quantify forest fragmentation.

Table 1
Landscape metrics used in the study (McGarigal and Marks 1995; McGarigal 2015).

Level	Landscape metric	Description (unit)	Range
Class	Percentage of landscape (PLAND)	Percentage of the landscape in the corresponding patch type (%)	$0 <$ PLAND$<=100$
	Patch cohesion index (COHESION)	Physical connectedness of the corresponding patch type (%) COHESION equals 1 minus the sum of patch perimeter divided by the sum of patch perimeter times the square root of patch area for the focal land use patches, divided by 1 minus 1 over the square root of the total number of cells in the watershed, multiplied by 100 (to convert to a percentage).	$0 =<$ COHESION < 100
Landscape	Simpson's diversity index (SIDI)	Diversity (number and evenness) of the land use types in the landscape (unitless) SIDI equals 1 minus the sum, across all patch types, of the proportional abundance of each patch type squared.	$0 =<$ SIDI < 1
	Contagion (CONTAG)	Tendency of land use types to be aggregated (%) CONTAG is the probability that two randomly chosen adjacent cells belong to the same land use type.	$0 <$ CONTAG$<=100$

2.4. The relationship between the land use change analysis and the land use management recommendations

Based on the analysis of land use change in the Ado River watershed (sections 3 and 4), land use management recommendations (section 6) were proposed to reduce the risk of downstream flooding. The recommendations were developed by applying the concepts of Eco-DRR and green infrastructure (Kato, 2012; Government of South Australia, 2018; US EPA, 2020) to the watershed (cf. Dutch Water Sector, 2019), taking the results of land use change analysis into consideration. By reviewing the relevant literature in the Introduction, Eco-DRR criteria were distilled (Table 2). Table 3 shows how the land use planning and management recommendations match to the developed criteria.

3. Results

3.1. Class-level analysis

At the class level, changes to PLAND over the three time points are shown in Table 4. The percentage the landscape (PLAND) comprised of paddy land, non-paddy farmland, and barren land gradually decreased over time. PLAND for forest land and golf courses increased between 1997 and 2006, but decreased between 2006 and 2014. PLAND for transportation increased between 1997 and 2006, but decreased by approximately the same percentage between 2006 and 2014. PLAND occupied by densely built land increased over time, with a greater increase between 2006 and 2014. PLAND for other built land decreased between 1997 and 2006, but increased between 2006 and 2014.

A visual examination of land use maps for 1997, 2006, and 2014 (Fig. 2) revealed (1) the conversion of barren land to forest land in the western mountainous area of the watershed between 1997 and 2006; (2) the conversion of barren land to other built land in the northern edge of the watershed between 2006 and 2014; (3) the gradual conversion of paddy land and other built land to densely built land in the delta at the river mouth; and (4) the conversion of other built land south of the river and near the start of the delta to forest (1997–2006) and densely built land (2006–2014).

Regarding COHESION for the selected three land use classes, forest land change was negligible and remained close to 100% (see Table 1 for the interpreted COHESION value). COHESION for paddy land increased slightly between 1997 and 2006, but decreased between 2006 and 2014, while COHESION for densely built land decreased between 1997 and 2006, but increased sharply between 2006 and 2014 (Fig. 3).

Table 2
Eco-DRR criteria.

Description		Code
Prevent and anticipate future disasters		I
Sustainably manage, conserve, and restore ecosystems	Reduce existing exposure, hazard, or vulnerability	II
	Improve resilience	III
Aim for sustainable and resilient development		IV

References: Sudmeier-Rieux and Ash (2009); IPCC, 2012a; Estrella and Saalismaa (2013); Renaud et al. (2013a); Furuta (2017).

Table 3
Applicability of land use management recommendations to Eco-DRR criteria.

Land use planning and management recommendations	I	II	III	IV
1: Use GI (e.g., water tanks and green spaces) to facilitate stormwater storage and evapotranspiration in downstream lowlands, especially on densely built and other built lands. Strategically and proactively plan GI that are multifunctional.	+	++	++	+
2: Sustainably manage upstream forest ecosystems.	++	++	++	++
3: Conserve and sustainably manage paddy land and protect rice farmers' livelihoods.	+	++	++	++
4: Maintain rural vernacular satoyama landscape.	+	+	++	++
5: Develop more strict land use policies and guidelines to restrict future development on floodplains and relocate existing buildings to higher grounds.	++	++	+	++
6: Integrate traditional and local knowledge into land use management.	++	++	+	++

Note: The more plus (+) signs, the more applicable each land use management recommendation is to each criteria (see Table 2 for the matching code).

Table 4
Area statistics of different land use types at three time points.

Land use class	1997	2006	2014
	PLAND	PLAND	PLAND
Paddy land	10.12	9.59	9.01
Non-paddy farmland	0.62	0.51	0.43
Forest land	79.88	80.98	80.63
Barren land	2.05	1.58	1.02
Densely built land	2.59	3.02	4.43
Transportation land	0.19	0.76	0.17
Other built land	1.86	1.04	1.29
Water body	2.45	2.17	2.72
Golf course	0.26	0.35	0.29

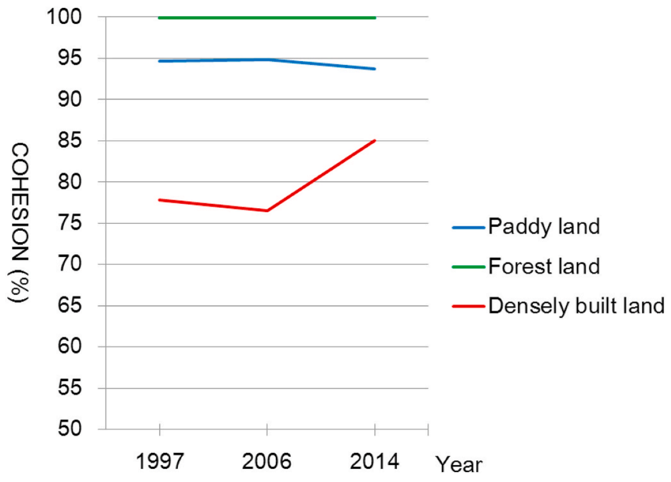

Fig. 3. Changes in COHESION over the three time points.

3.2. Landscape-level analysis

At the landscape level, land use change over the three time points was almost undistinguishable in the selected metrics (Table 5). SIDI was largest in 1997 and smallest in 2006, although this difference was very small. Meanwhile, CONTAG was smallest in 1997 and largest in 2006. The change trends in SIDI and CONTAG indicate that land use was least diverse and most spatially aggregated in 2006.

Table 5
Changes in landscape-level metrics.

Landscape metric	1997	2006	2014
SIDI	0.35	0.33	0.34
CONTAG	72.82	73.64	73.5

3.3. Landscape composition analysis

The number or variety of land use classes remained the same over time. Since SIDI showed only very small change, the proportional abundance of each land use type remained almost unchanged in the watershed. Taking PLAND and SIDI together, the change, however small, was more evident in the change of PLAND.

3.4. Landscape configuration analysis

CONTAG increased between 1997 and 2006 and, during the same time period, COHESION for densely built land decreased slightly. The overall landscape mosaic in the watershed became spatially more aggregated between 1997 and 2006 (Table 5). The increase in COHESION for densely built land between 2006 and 2014 showed the most significant change (Fig. 3).

4. Discussion

4.1. Class-level analysis

Analysis of PLAND indicates some fundamental, though gradual and small, change in land use in the watershed over the three time points. The area of paddy field and non-paddy field agricultural land gradually decreased over time. In 1997, paddy fields and non-paddy farmland comprised 10.7% of the watershed; by 2014, this had decreased to 9.4%. This decline was likely due to the abandonment of fields as farmers aged with no successors to continue the practice (Qiu et al., 2014). This is a common problem in Japan's rapidly aging society (MAFF, 2007). The decline in the percentage of land under agriculture is likely due conversion to residential and urban use, because the population in Shiga Prefecture increased until 2013 (Shiga Prefecture, 2018, Table 4). The increase in forest land between 1997 and 2006 was probably due to the conversion to forest of barren land in the western watershed and built land south of the river near the delta (see Fig. 2).

Over time, PLAND increased overall on built land, including densely built, other built, and transportation land. This increase was sharper between 2006 and 2014 due to the large increase in densely built land that occurred mostly in the river delta. This increase can be explained by Shiga Prefecture's population growth, despite Japan as a whole experiencing population decrease since 2008 (SBJ, 2017; Shiga Prefecture, 2018).

The COHESION value, or physical connectedness, of forest remained close to 100% over time, implying that forest areas remained connected despite PLAND changes over time. However, the ecosystem quality of forest land cannot be inferred from these two metrics. The decline in the physical connectedness of paddy fields between 2006 and 2014 may be due to the conversion of land to residential use or to land abandonment. The large increase in COHESION for densely built land during the same time period indicates the increase and expansion of urban areas, the encroachment and fragmentation of paddy fields, and the conversion of agricultural areas and barren land to residential and urban areas.

4.2. Landscape-level analysis

Although the difference was very small, SIDI and CONTAG exhibited consistent change. SIDI for 1997 was the largest of the three time points and CONTAG was smallest. Conversely, in 2006, SIDI was smallest and CONTAG was largest. Since the number of land use types (classes) remained the same over the three time points, this consistent trend indicates that (1) land use types were most evenly distributed and least spatially aggregated in 1997, and (2) land use types were least evenly distributed and most spatially aggregated in 2006. In short, in 2006, there were more large clumps of land use and these large aggregations tended to be of certain land use types, such as forest, as shown in Tables 4 and 5

5. Summary of land use change analysis

Analysis of the changes in land use in the Ado River watershed over three time points, using four landscape metrics and land use maps, reveals that (1) densely built land increased along the river and in the delta due to the conversion of other built land and of paddy land in the delta; (2) densely built land expanded in clusters in the delta between 2006 and 2014; and (3) land use patches became more spatially aggregated between 1997 and 2006, and the proportional abundance of forest patches, in particular, increased during the same time period.

6. Landscape planning and management recommendations

First, in downstream lowland areas, green infrastructure (GI) development to facilitate stormwater storage and evapotranspiration through artificial storage and green spaces is recommended. Currently, most densely built land is concentrated in the river mouth delta (Fig. 2) where there is a large flat land and a likely high-water table. In addition, a 6 km stretch of the river downstream is embanked to form an elevated river. Therefore, when engineered solutions to prevent flooding, such as river embankment, fail, the flooding of large lowland areas ensues.

Stormwater infiltration facilities, such as rain gardens and bioswales (Fitzgerald and Laufer, 2017), can be constructed in densely built areas in the delta. However, the likely existence of a high water table and poor drainage (Geospatial Information Authority of Japan, 2011) hinder the infiltration effectiveness of these facilities for the reduction of downstream flooding. Stormwater storage and evapotranspiration, however, are recommended for densely built and other built land downstream. Hard infrastructure, such as water tanks, rain barrels, and underground stormwater storage spaces, can be constructed in the built areas of the delta. In addition, the creation of green spaces, including vegetated GI facilities, to promote increased evapotranspiration is an effective strategy not only in the reduction of downstream flooding but also in the reduction of ambient air temperature, mitigating the urban heat island effect (Lehmann, 2014; Gunawardena et al., 2017). Creating green spaces on densely built and other built land also provides species habitat. These small “pockets of nature” in urban areas play an important role in sustaining local biodiversity by providing shelter and acting as stepping stones for movement and dispersal (Ichinose, 2010; Kato, 2011). If these scattered green spaces are strategically and proactively planned to connect to each other and/or to existing corridors, such as rivers and ridgelines, their social, economic, and ecological benefits can be reinforced (Kato, 2011).

Second, since a high percentage of land upstream is forested (see Fig. 2), an effective strategy to prevent flooding in the lowland delta is the sustainable management of healthy forest ecosystems. The maintenance of these ecosystems is required upstream, where vast and contiguous areas of land are forested (Table 4; Fig. 3). Since well-functioning forests hold and slowly release water, thus delaying the peak of the first flush, sustainable management of upstream forest areas is critically important for downstream flood management. Not only do forests retain water, allowing for its infiltration, evapotranspiration, and slow release, they also provide other important ecosystem services, such as the provision of timber, the prevention of soil erosion, and carbon storage. Therefore, the sustainable management of upland forests becomes a no-regret strategy for reducing the risk of downstream flooding in the watershed.

Third, conservation and sustainable management of paddy land is recommended for reducing the risk of downstream flooding. Wet rice cultivation is an integral component of Japanese agriculture. In the Ado River watershed, most paddy fields are located downstream, and are concentrated in the delta, with some paddy fields scattered along the river upstream (Fig. 2). The recent land use trend, however, has seen the conversion of paddy land to densely built land in the delta with continuous decrease in PLAND for paddy land over time (Table 4) and decrease in COHESION value between 2006 and 2014 (Fig. 3). Since paddy land plays an important role in holding and regulating water, its development and transformation reduces water holding capacity, leading to increased risk of flooding. Like forests, paddy fields provide other important ecosystem services, such as recharging groundwater, provisioning rice, providing habitat for insects, amphibians, and fish, and regulating water temperature (Natuhara, 2013). Therefore, sustainable management of paddy land and the protection of farmers’ livelihoods are important no-regret strategies for reducing downstream flooding risk.

Fourth, similar to the importance of sustainable upstream forest management, maintaining rural Japanese *satoyama* landscapes—composed of mosaics of paddy and non-paddy farm land and forest land intermixed with settlements at the foot of mountains—is key to the provision of water regulating services and other social, economic, and ecological benefits (Morimoto, 2011; Kamiyama et al., 2016; Takeuchi et al., 2016). However, although not directly evident in the land use change analysis, previous studies show that this rural vernacular *satoyama* landscape is in danger of extinction in many parts of Japan (Fukamachi, 2017; Jiao et al., 2019). The management of traditional Japanese rural landscapes has become increasingly difficult as local populations rapidly decline and age.

Fifth, more strict land use policies and guidelines are recommended to reduce buildings’ exposure to floods. The land use change analysis showed that not only did densely built land continuously increase its proportional area in the watershed, but also it greatly increased its physical connectivity between 2006 and 2014 (Table 4; Fig. 3). Newer housing developments or “new towns” occur near the river in the lowlands, while older settlements are located on higher ground. The development of “new towns” on downstream floodplains increases exposure to flooding. Also, connectivity of densely built land tends to produce a large volume of stormwater, worsening the flood risk and water quality. To reduce exposure to flood hazards, it may be necessary to restrict future development on floodplains and relocate existing developments to higher ground. Developing policies and enacting legislations to restrict development on the floodplains and enforce relocation of existing buildings and assets is often controversial. However, to reduce exposure to floods, such regulatory zoning and land use policies may be necessary and should be given serious consideration in watershed planning. Considering Japan’s ongoing population decline, this recommendation is a viable and realistic one as well.

Finally, use of traditional and local knowledge must be integrated into land use management to aim for sustainable and resilient development. This knowledge consists of sustainable management of local natural resources based on traditional engineered solutions. Such solutions include the use of primary and secondary forests to prevent flooding, wind and sand erosion, and the use of rice paddies as a form of flood control dam. One traditional engineered solution example is the use of *kasumi-tei* (embankments) to reduce flood risk. In use since the 16th Century, *kasumi-tei* are discontinuous embankments, where the downstream embankment is extended to the land side of the upstream embankment to create an overlap upstream of the opening (MLIT, 2007). *Kasumi-tei* have two advantages. First, drainage from the embankment can be easily achieved under normal conditions. Second, water that has overflowed into the embankment upstream can be immediately returned to the river from the embankment opening, thereby preventing the damage from spreading (MLIT, 2007). *Kasumi-tei* are one example of using traditional knowledge to reduce river flooding.

7. Conclusions

The following summary of land use management recommendations for reducing the risk of downstream flooding at the watershed scale is based on the land use change analysis of the Ado River watershed in central Japan, applying the concepts of Eco-DRR and GI (Table 3). Stormwater storage and evapotranspiration are suggested for densely built and other built land downstream. Hard infrastructure to store rainwater and stormwater can be constructed in the built areas of the delta. In addition, green spaces including vegetated GI facilities can be developed to promote increased evapotranspiration for the reduction of downstream flooding, mitigate the urban heat island, and provide species' habitats.

Sustainable maintenance and management of upstream forests and downstream paddy fields are crucial for reducing the risk of downstream flooding in the watershed. Because forest and paddy ecosystems provide crucial ecosystem services (e.g., the provision of timber and rice, species' habitats, and the regulation of water temperature) other than flood control, sustainable management of these ecosystems becomes a no-regret strategy for reducing downstream flooding risk. The same argument applies to the rural vernacular *satoyama* landscape. To reduce exposure to floods, developing land use policies to restrict future development on floodplains and relocating existing buildings to higher grounds should be seriously considered in watershed planning. Traditional engineered solutions such as *kasumi-tei* should also be used to reduce river flooding. The use of regulating ecosystem services (e.g., primary and secondary forests to prevent flooding, wind, and sand erosion, and rice paddies as a form of flood control dam) is considered part of traditional, local knowledge, which must be integrated into land use management.

In this paper, we discussed the importance of watershed-scale landscape planning and management by using the concept of Eco-DRR and GI. To prevent and reduce downstream river floods, relying too much on conventional engineering solutions such as embankments and dams alone is risky because of increasing climate change impacts and limited budgets for infrastructure maintenance and renewal. Complementing these engineering solutions with GI facilities and the sustainable management of upland forests and rice paddies, harnessing their flood regulation services, and using traditional knowledge to reduce downstream flood risks are the preferred DRR strategies in holistic watershed-based management.

Credit author statement

Sadahisa Kato: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing- Review and Editing. Wanhui Huang: Methodology, Investigation, Visualization, Writing-Review.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This research was supported by the Research Institute for Humanity and Nature (RIHN: a constituent member of NIHU) Project No. 14200103.

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