Adaptation to climate change and conservation of biodiversity using green infrastructure

Running Title: Adaptation to climate change using green infrastructure

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ABSTRACT

In recent years, we have experienced mega-flood disasters in Japan due to climate change. In the last century, we have been building disaster prevention infrastructure (artificial levees and dams, referred to as “grey infrastructure”) to protect human lives and assets from floods, but these hard protective measures will not function against mega-floods. Moreover, in a drastically depopulating society such as that in Japan, farmland abandonment prevails, and it will be more difficult to maintain grey infrastructure with a limited tax income. In this study, we propose the introduction of green infrastructure as an adaptation strategy for climate change. If we can use abandoned farmlands as green infrastructure, they may function to reduce disaster risks and provide habitats for various organisms that are adapted to wetland environments. First, we present a conceptual framework for disaster prevention using a hybrid of green infrastructure and conventional grey infrastructure. In this combination, the fundamental green infrastructure, composed of forests and wetlands in the catchment (GI-1), and additional multilevel green infrastructures such as flood control basins that function when floodwater exceeds the planning level (GI-2) are introduced. We evaluated the flood attenuation function (GI-1) of the Kushiro Wetland using a hydrological model and developed a methodology for selecting suitable locations of GI-2, considering flood risk, biodiversity, and the distribution of abandoned farmlands, which represent social and economic costs. The results indicated that the Kushiro Wetland acts as a large natural reservoir that attenuates the hydrological peak discharge during floods, and suitable locations for introducing GI-2 are concentrated in floodplain areas developing in the downstream reaches of large rivers. Finally, we discussed the network structure of GI-1 as a hub and GI-2 as a dispersal site for conservation of the Red-crowned Crane, one of the symbolic species of Japan.

KEYWORDS

Green infrastructure, GETFLOWS, Flood risk management, Adaptation strategy, Red-crowned Crane

1 INTRODUCTION

The global average air temperature has been increasing over the long term; since the 1890s, it has risen at a rate of 0.72°C per 100 years (Ministry of the Environment et al., 2018). The IPCC (2013) showed that precipitation is different from air temperature, which shows an increasing trend across the Earth and has increased in North America and Europe at mid-latitudes in the Northern Hemisphere since the 1900s. In Japan, the fluctuation of yearly precipitation has increased since the 1970s, and the frequency of hourly heavy rains of 50 mm or more has increased (Ministry of the Environment et al., 2018). River regulation and urbanization over a century elevated flood risk. Thus, we have recently experienced many flood disasters associated with river regulation, land use change, and climate change.

In the last century, we have been building continuous artificial levees and large dams to protect human lives and assets from floods, but these hard protective measures will not function against extraordinary events such as mega-floods. Additionally, these structures alter flow, sediment, and large wood regimes (Lytle & Poff, 2004; Nakamura et al., 2017), which results in the loss of biodiversity of aquatic and riparian organisms. According to the WWF Living Planet Report 2014 Living Planet Index (LPI: a measure of the state of the world's biological diversity based on population trends of vertebrate species), the freshwater index has shown the greatest decline of any of the biome-based indices. The LPI for freshwater species showed an average decline of 76 % in the size of the monitored populations between 1970 and 2010 (WWF, 2014).

To prevent mega-flood disasters and loss of biodiversity in freshwater ecosystems, we should shift from conventional hard measures to more adaptive strategies using various functions that natural and/or semi-natural ecosystems provide. Moreover, hard measures require continuous maintenance costs to maintain their functions. Ecosystem-based disaster risk reduction (Eco-DRR) refers to “the suitable management, conservation and restoration of ecosystems to reduce disaster risk” (Renaud et al., 2013). Another similar idea is green infrastructure (GI), meaning “an interconnected network of waterways, wetlands, woodlands, wildlife habitats, and other natural areas that support native species, maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life for communities and people” (Benedict & McMahon, 2002). We chose to use GI in this paper because conservation of biodiversity is one of the important study themes.

For over a thousand years, the population of Japan continuously increased, although temporary or regional declines due to hunger, disease or war can be recognized. However, the population of Japan has begun to decrease since 2008 (Ministry of Internal Affairs and Communications, 2016). The drastic ageing and depopulation in Japanese society will likely have impacts on social security (such as medical services and care), pensions, tax revenues, and maintenance of existing infrastructures and will lead to farmland and forest abandonment. The Ministry of Agriculture, Forestry and Fisheries identified an increase in abandoned farmlands in Japan from 130,000 ha in the late 1980s to 400,000 ha in 2011 (Ministry of Agriculture, Forestry and Fisheries of Japan, 2011).

The current natural and social situation of Japan appears pessimistic, but it may provide other opportunities that we did not have in the past. If human withdrawal from flood areas becomes possible by implementing the best management of land use changes, these areas will become natural restoration areas supporting the conservation of endangered species that are adapted to colonize newly disturbed habitats. Additionally, these areas would play a disaster-prevention role as buffer zones, preventing the exposure of people and their assets to flood hazards. This approach represents a perceptual change from grey infrastructure to a hybrid of grey and green infrastructure.

The objectives of our study are to present a conceptual model of grey and green infrastructure from a disaster prevention point of view and to describe the effective combination of the two infrastructures as a hybrid. In the conceptual model, we define the fundamental green infrastructure (GI-1 in Fig. 1(c)), composed of forests and wetlands in the catchment, and additional multilevel green infrastructures (GI-2 in Fig. 1(c)) such as flood control basins that function when floodwater exceeds the maximal high water level determined by the artificial levees. Thus, as a case study of GI-1, we analysed the water retention ability of the natural wetland using a hydrological model of the Kushiro River basin. Green infrastructure is multifunctional (Lovell and Taylor, 2013; Demuzere et al., 2014), while grey infrastructure is built for single purpose. Thus, we developed a methodology for selecting suitable locations of GI-2, considering flood risk, biodiversity, and the distribution of abandoned farmlands, which represent economic costs to rent or purchase. Finally, we discuss the network structure of GI-1 as a hub and GI-2 as a dispersal site for conservation of the Red-crowned Crane, one of the symbolic flagship species of Japan.

The study was conducted in Hokkaido, the northern island of Japan, where the population has decreased more drastically than that of the main island of Honshu. The population of the eastern and northern parts of Hokkaido will decrease by approximately 40% from 2005 to 2035, and the population size is estimated to return to that of the early 1950s. With this rapid depopulation, abandoned farmland is increasing (Kobayashi & Nakamura, 2018). We would like to focus on wetland GI because wetlands are one of the types of endangered ecosystems that have been converted into agricultural and industrial areas (Finlayson & Spiers 1999). The wetlands that existed in Japan in the early twentieth century (approximately 2110 km^2) have been reduced to less than half (821 km^2) their area at that time, with more than 60 % of the wetlands having been lost during the last 100 years (Geospatial Information Authority of Japan, 2000). Fortunately, recent studies in Hokkaido revealed that abandoned farmlands in backwater marshes (mesic sites) may become wetlands and continue to provide suitable habitats for wetland/grassland vegetation (Morimoto et al., 2017), insects (Yamanaka et al., 2017), and birds (Hanioka et al., 2018). These abandoned farmlands are distributed along streams and rivers. If we restore these abandoned farmlands as wetland GI, it will exhibit the functions of flood protection and biodiversity conservation during climate change.

GI has mainly been discussed from an adaptation strategy perspective in cities and urban areas (e.g., Gill et al., 2007; Keeley et al., 2013; Netusil et al., 2014). However, we believe that GI can also function in rural and suburban areas where depopulation is prominent. Moreover, to protect cities, which are generally situated at downstream lower elevations, we should explore the preservation and restoration of forest GI at headwater basins and wetland GI along rivers from a catchment perspective. Additionally, disaster risk reduction by a hybrid of green and grey infrastructure has been examined for stormwater, flood, and coastal flooding (Keeley et al., 2013; Sutton-Grier et al., 2015; Zeller et al., 2016), but very few studies have quantitatively examined flood risk, biodiversity, and social-economic benefit by defining existing GI (e.g., forest and wetland in a catchment) and additional layered GI (e.g., flood control basin along a river).

2 CONCEPTUAL FRAMEWORK

Conventional grey infrastructure, such as dams and artificial levees, usually assure 100% disaster protection until the magnitude of the disaster reaches an upper limit determined by the prevention plan, though unexpected risks associated with structural flaws and human errors still exist. However, once the magnitude exceeds the upper limit, the grey infrastructure will completely lose its function; e.g., floodwater will spill into residential areas where artificial levees are breached. Thus, the safety-magnitude curve for grey infrastructure is a rectangular shape (Fig. 1(a)). In contrast, we expect the response of green infrastructure to show a gradually decreasing trend. In addition, the disaster prevention function of green infrastructure may be sustained longer than that of grey infrastructure (Onuma & Tsuge, 2018). However, the relationship between the green infrastructure response and disaster magnitude is not well studied and can vary depending on the kind of green infrastructure (Fig. 1(b)). The uncertainty of the function is high for green infrastructure.

In the past, we have discussed the advantages and disadvantages of grey and green infrastructure and compared them to choose which approach was better. Sometimes, such debates are not productive and promote polarization of opinions between grey and green approaches. Here, we discuss a combination of grey and green infrastructures with the aim of applying green infrastructure for disaster control in a society at high risk of various natural disasters, as is the case in Japan. We present a hybrid, combining two infrastructures in Fig. 1(c). In this conceptual diagram, GI-1 represents the fundamental green infrastructure composed of forests and wetlands in the catchment, while GI-2 is additional multilevel green infrastructures such as flood control basins that function when floodwater exceeds the maximal high water level determined by the artificial levees. In this diagram, an increase in the combined area of grey and green infrastructure guarantees safety, even at a very high magnitude of flooding.

How much should we expand or reduce the areas of grey or green infrastructure presented in Fig. 1(c)? We have to evaluate the effectiveness of hybrid infrastructure in terms of disaster prevention, biodiversity protection, and social and economic values to determine which combination is best in a given natural and social condition. If the area of grey infrastructure is expanded, high levels of disaster control may be achieved, but there may be losses in biodiversity and of the hometown landscape as well as increased maintenance costs.

Historically, we have been losing forest and wetland GI-1 through overharvesting of forest resources and land reclamation (Nakamura et al., 2017). As a result, we have had to compensate for the water retention ability that natural ecosystems provided in the past with grey infrastructure such as dams and artificial levees. The combination of grey and green infrastructure may change depending on land use. We may preserve or restore GIs using abandoned farmlands in rural areas. In contrast, it may be difficult to restore natural ecosystems in highly populated urban areas, and grey infrastructure therefore still plays an important role in disaster risk reduction with a limited introduction of GIs represented by gardens and city parks.

3 METHODS

First, we evaluated the water retention ability of Kushiro Wetland as an example of GI-1 (Fig. 1(c)). The rainfall-runoff model was built to simulate hydrographs in the Kushiro River (catchment area: 2,510 km^2: Fig. 2). Second, we introduced a methodology to find suitable locations for GI-2 (additional multilevel green infrastructures in Fig. 1(c)) on the entire island of Hokkaido (area: 83,454 km^2). These areas function as flood control basins when floodwater exceeds the heights of artificial levees. Finally, we introduced a project to restore wetlands and crane habitat in the artificial flood control basins in the Chitose River (catchment area: 1,244 km^2: Fig. 2).

Evaluation of the water retention ability of Kushiro Wetland (GI-1)

Three typhoons arrived in the Kushiro region in Hokkaido from August to September in 2016, accompanied by heavy rains. We evaluated the water retention function of wetlands during these floods using a hydrological model referred to as "GETFLOWS" (https://www.getc.co.jp/english/). GETFLOWS is a three-dimensional finite difference, multi-phase, multi-component fluid-flow simulator with a fully coupled surface and subsurface fluid flow (Fig. 3). GETFLOWS provides fast and robust numerical solutions to simulate all types of terrestrial fluid-flow systems, together with the distributed settings of precipitation, evapotranspiration, hydrogeology, land use, and water use (Mori et al., 2015).

The GETFLOWS model for the Kushiro River catchment was developed by the Kushiro Nature Restoration Committee (https://www.hkd.mlit.go.jp/ks/tisui/qgmend00000052vr-att/qgmend000000534w.pdf). We decided to use this model to evaluate the water retention function of the Kushiro Wetland (see Figs 3 and 4 for model structure and simulation procedure). The wetland areas are approximately 22,000 ha in total. First, we input spatially distributed (grid size of 250 m x 250 m in the catchment above the Kushiro Wetland and 100 m x 100 m within the Kushiro Wetland) precipitation data from July to December 2016, which covered three heavy rainfall events associated with typhoons (Fig. 4). Thiessen polygons were used to calculate areas in relation to 16 rain gauge stations (Fig. 5). We tuned climatic, geological, hydraulic, and land use model parameters to correctly simulate surface and groundwater levels from the observed data. Specifically, the hydraulic conductivity and the void ratio of geological layers are important to determine groundwater flows, while the roughness coefficient is a key variable of surface flow (Fig. 3). We parameterized these variables according to the guidelines made by the Kushiro Nature Restoration Committee (Tables S1 and S2). Second, approximately 55% of the Kushiro Wetland (approximately 12,200 ha), which is protected by artificial levees, was converted to residential lands in a simulation case by changing land use and respective roughness coefficients. Finally, the hydrological responses were calculated with GETFLOWS. We compared the timing and volume of peak discharge and the rising and descending limbs of hydrographs between the cases of present and 55% loss of wetlands.

Selection of suitable locations for flood control basins (GI-2) on the entire island of Hokkaido

We selected suitable locations for flood control basins by overlaying four thematic maps, showing the flood risk, species richness of wetland plants and wetland birds, and percentage of abandoned farmland. These maps were produced on a Japanese standard size grid, which is 30 arc seconds latitude x 45 arc seconds longitude (approximately 1 km x 1 km).

1) Flood risk

The flood hazard map was built by collecting flood inundation maps officially published by the MLIT and the Hokkaido prefectural government and then combining them to identify the inundation area and flood depth at a given point. Because flood control plans vary with the river segment and authority, the magnitude of the flooding and the resolution as well as the flood risk categories (e.g., water depths) of hazard maps differ among river segments. We obtained the flood hazard map where the recurrence interval was once per 150 years for the Ishikari River, the largest river in Hokkaido, and the greatest human population and assets are concentrated in this basin. The recurrence interval of the flood hazard maps for other rivers in Hokkaido was set to 1/100. Additionally, we standardized the resolution to 1 km x 1 km and assigned the expected maximum depth within a grid cell as the flood depth. Finally, we classified the flood hazard risk into five categories by the expected flood depths (1: 0-0.5 m, 2: 0.5-1.0 m, 3: 1.0-2.0 m, 4: 2.0-5.0 m, and 5: 5.0 m<).

2) Species richness of wetland plants and wetland birds

We selected characteristic plant species observed in wetlands and paddy fields based on phytosociological analyses (Miyawaki, 1988). Then, we extracted the observation year and the location of each of the species from the plant database created by the Environmental and Geological Research Department, Hokkaido Research Organization. Among these species, 42 that were present in more than 40 grid cells were used for model construction (Table S3). However, there was a potential drawback of geographic bias in the sampling locations and survey efforts of data collection (Reddy & Davalos, 2003; Schmeller et al., 2009). Thus, we developed occupancy models correcting for the spatially biased data sampling effort by considering the observation methods (imperfect detection) and the occupancy status of species separately in a hierarchical manner (Royle & Dorazio, 2008; Higa et al., 2015) (see Supporting information, Exp. S1). The partially observed occupancy states of the modelled species were assumed to be a function of land cover, elevation, and the topographic wetness index (TWI). Land cover data were derived from 1:50,000 digital vegetation maps based on the second to fifth vegetation surveys provided by the Natural Conservation Bureau, Ministry of the Environment (http://www.biodic.go.jp). We calculated the area of wetland, grassland, pasture, and paddy field within each 1 km x 1 km grid cell of the distribution dataset and the mean elevation from the digital elevation model provided by the Geospatial Information Authority of Japan (http://www.gsi.go.jp/kiban/index.html), and we calculated the TWI by using the System for Automated Geoscientific Analyses (SAGA) (http://www.saga-gis.org/en/index.html).

For the species richness of wetland birds, we used the estimated values for wetland bird species calculated by Higa et al. (2015), who performed almost the same analyses with the above occupancy model.

3) Abandoned farmlands

First, we superimposed the segmented grid data on the land utilization (National Land Numerical Information created by the National Land Information Division of the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT); spatial resolution: 100 m × 100 m) for 1976, 1987, 1997, 2006, and 2009. Among the grid cells that were classified as farmland, such as those of paddy fields or other agricultural land, before 2006 (i.e., 1976, 1987, 1997 and 2006), those areas that were instead classified as forest or wasteland in 2009 were defined as abandoned farmland. Second, among the above-defined abandoned farmlands, we extracted the grid cells that coincided with historical wetlands in topographic maps published in the 1920s and 1950s (Kaneko et al., 2008) as well as the grid cells that coincided with peat in the soil map (http://nrb-www.mlit.go.jp/kokjo/inspect/landclassification/download/index.html) as abandoned farmlands that used to be wetlands. The percentage of abandoned farmland that used to be wetlands was calculated for every grid of approximately 1 km × 1 km.

4) Selection of suitable locations for flood control basins

First, we extracted the areas with a higher flood risk where the predicted inundation depth was over 2 m, which were considered candidate areas for introducing flood control basins. Next, the flood risk map (inundation depth > 2 m) was superimposed with the species richness maps of wetland plants and birds to find areas where a high flood risk and biodiversity potential coincidentally appeared. In general, wetland endangered species require repeated flood disturbances in their life cycles. Thus, a high-flood-risk area functions as a water retention pond during a flood and conserves biodiversity under ordinary conditions. The predicted species richness values of wetland plants and birds were scored on 10 levels. The grid cells in the top quartile (plants + birds scores) were interpreted as areas with high biodiversity.

Finally, the above map was superimposed with the abandoned farmland map to find socially and economically acceptable areas where GI-2 can be introduced with a relatively low cost and without social opposition. The priority for GI-2 introduction was ranked according to three levels based on the area of abandoned farmland in a grid cell as follows: lower priority (0%), intermediate priority (0< and < 5%), and high priority (> 5%).

<u>Network of GIs for expanding the distribution of the Red-crowned Crane.</u>

The Red-crowned Crane (*Grus japonensis*) was distributed widely on the Hokkaido, Honshu and Kyushu islands of Japan in the beginning of the twentieth century. However, extensive farmland development of wetlands and overhunting caused a significant decline in the crane population to approximately 50 individuals (Masatomi H., personal communication). This population remained within a limited wetland area in eastern Hokkaido, occurring in the Kushiro Wetland in particular. Local residents in Kushiro initiated artificial feeding during the winter season, and the crane population rapidly recovered. As of 2014, the population had recovered to approximately 1,500 individuals. However, the breeding and nesting sites of the cranes are concentrated in the Kushiro Wetland, where the carrying capacity is limited. The genetic diversity of the current population is low because the number of cranes declined to close to the extinction level at one point and then recovered rapidly (bottleneck effect) (Miura et al., 2013; Masatomi & Masatomi, 2018). Thus, there is a risk of spreading infectious diseases among the population. Owing to this situation, Ministry of the Environment plans to expand their nesting and breeding sites outside of the Kushiro region.

In the Chitose River catchment, six large-scale flood control basins with areas of 150-280 ha were constructed to control extraordinary floods. These flood control basins have also created a wonderful wetland landscape where many swans, greater white-fronted geese, and bean geese gather in the early spring. We, together with the Ecosystem Conservation Society of Japan, proposed to restore one of the flood control basins to wetlands dominated by a reed (*Phragmites australis*) that is preferred by the crane for nesting (see geographical locations of Kushiro Wetland and Chitose River in Fig. 2.).

We would like to use the flood control basins as GI-2. Therefore, the appropriateness of their locations was examined by overlaying the locations of these basins with the GI-2 suitability map created through the above GIS analysis. Additionally, historical evidence assessed by Hisai (2009) was used to map the past crane distribution prior to land development. There are many written materials and other evidence indicating that the Red-crowned Crane used to inhabit floodplain wetlands in Hokkaido (Hisai, 2009).

Finally, in regard to management implications, we introduced current environmental activities organized by the municipality and farmers in local towns to illustrate how we can use GI to enhance social and economic benefits.

4 RESULTS

Water retention function provided by the Kushiro Wetland (GI-1)

The GETFLOWS model for the Kushiro River catchment simulated the fluctuation of water discharge at the Hirosato gauging station, downstream of and adjacent to the Kushiro Wetland from July to December 2016. The three dominant hydrological peaks created by heavy rains associated with typhoons were well simulated by the model (Fig. 6(a)). We calculated water discharge for the case in which approximately 55% of wetlands are converted into residential lands using this model. The hydrograph of the simulation case of partial loss of wetlands showed a higher peak discharge, sharper rising and descending limbs, a two-day-faster peak arrival, and a lower low-flow discharge than the those of present situation (Fig. 6(b) and Table 1). The peak discharges of simulation cases for the present and for partial loss of wetlands were 390 and 580 m^3/sec, respectively (Table 1).

Suitable locations for introducing flood control basins (GI-2)

Abandoned farmlands are mainly distributed over eastern and northern Hokkaido and are limited in central Hokkaido (Fig. 7). In contrast, the flood risk is high in central Hokkaido, especially along the Ishikari River, while it is low in eastern and northern Hokkaido. Furthermore, the downstream reaches and floodplains of large rivers such as the Ishikari, Teshio, and Tokachi Rivers are within high-flood-risk areas. The suitable locations for GI-2 were highly concentrated in the Ishikari River (Fig. 8).

The species richness of wetland plants is high in eastern, northern, and central Hokkaido, where floodplains and coastal wetlands are broadly distributed. In eastern and northern Hokkaido, where abandoned farmlands are concentrated, and central Hokkaido, where paddy fields dominate, floodplains show relatively high species diversity. The species richness of wetland/grassland bird species follows a similar pattern to that of wetland vegetation.

The results of overlay analyses showed that suitable locations for introducing GI-2 were concentrated in floodplain areas developing in the downstream reaches of large rivers, especially along the Ishikari River. The largest city, Sapporo, was developed in the alluvial fan and lowland areas of the Toyohira River, which is one of the tributaries of the Ishikari River. Additionally, there are suitable places for GI-2 along the Kushiro River. If GI-2s are built in the Kushiro River basin, they will function as flood retention basins together with GI-1 of the Kushiro Wetland, which greatly expands the safety zone against a large flood (see Fig. 1(c)).

New habitat for Red-crowned Crane provided by GI-2 along the Chitose River

We superimposed the locations of the six flood control basins being constructed along the Chitose River, which is one of the tributaries of the Ishikari River. Although the locations were selected through an agreement process involving residents, municipal authorities, and river managers of the MLIT, they were constructed on or close to relatively suitable areas according to our evaluation presented in Fig. 8.

Based on the research of Hisai (2009), there is much evidence suggesting the presence of cranes in the lowlands of the Chitose River. Her research was conducted based on various historical written materials, paintings, pictures, and place names given by Japanese or indigenous Ainu people. Thus, there were many cranes in the lowlands of the Chitose River and Ishikari River basins.

In 2012, a pair of Red-crowned Cranes appeared in the Maizuru flood control basin, which is one of the six basins in the Chitose River (Fig. 9). Since then, one or two pairs of cranes have appeared in the flood control basin and neighbouring farmlands every year and have remained for approximately three months. Unfortunately, they have not yet nested and bred in this area.

5 DISCUSSION

During climate change, green infrastructure combined with grey infrastructure will expand the safety zone (Fig. 1(c)). We will discuss the multi-functions (flood control, biodiversity, recreation, and environmental education) of individual wetland GIs, the network structure at the catchment and regional scales, and the ripple effect on the local economy and social activities.

Natural ecosystems acting as GI-1 should be kept in a healthy condition

The results of the GETFLOWS model simulation clearly demonstrated that the Kushiro Wetland acts as a large natural reservoir that attenuates the hydrological peak discharge during floods. The reduction and delay of flood peaks conferred by wetlands were estimated by the simulations. Thus, if we lose these natural ecosystems, we will have to depend more on grey infrastructure (dams and artificial levees). However, these grey infrastructures have high maintenance costs and may not be economically feasible in a depopulating society such as Japan and other countries.

There are many threats to the persistence of a healthy Kushiro Wetland. One of the serious threats is sediment delivery from the upper basins. Forest harvesting and agricultural development in headwater basins and middle elevational areas produce fine sediment. This sediment is then transported by rivers and streams and eventually accumulates in the Kushiro Wetland, which is situated at the bottom of the catchment (Nakamura et al., 2004). The sediment and associated nutrients alter the original edaphic conditions of the wetland soil, which promotes succession from reed and sedge communities to alder and willow forests across the Kushiro Wetland (Nakamura et al., 2002). The forests in headwater basins initially act as GI-1 at a catchment scale, but overharvesting of forest resources may cause soil erosion and thus loss of GI function. Sedimentation and successive forestation of wetlands also reduce the water-holding capacity of the original spongy peat soil. Furthermore, forest expansion in wetlands threatens the population persistence of endangered species such as the Red-crowned Crane because this species requires reed communities for nesting and breeding.

This situation is shown to result in a decrease in the areal extent of GI-1, as shown in Fig. 1(c). To prevent further reduction in the area of GI-1, restoration of deteriorated ecosystems is necessary. Fortunately, the Kushiro Restoration project was launched in 2003, which involves reforestation in headwater basins, construction of riparian buffers to prevent sediment and nutrient transfer from agricultural lands, and restoration of rivers and wetland floodplains (Nakamura et al., 2014). We believe that these natural restoration activities contribute to the restoration of the multifunctionality of wetland GI. Currently, these restoration sites are used for the recreation and environmental education of local citizens and tourists (http://hef.jp/kushiro/).

Abandoned farmlands can be restored to act as GI-2

The reason that abandoned farmlands are concentrated in eastern and northern Hokkaido is because of a high depopulation rate in these regions. The population of eastern and northern Hokkaido is predicted to decrease by approximately 40% in the coming 30 years, and Kobayashi and Nakamura (2018) found that depopulation has been one of the significant drivers increasing abandoned farmland in Hokkaido since 1997.

Several studies have focused on succession after farmland abandonment in Hokkaido. Regarding vegetation, the original back marsh community dominated by *P. australis* tends to recover after the abandonment of pastures (Morimoto et al., 2017). Additionally, abandoned farmland can serve as an alternative habitat for wetland ground beetles (Yamanaka et al., 2017) and wetland and grassland birds (Hanioka et al., 2018). Thus, if we can use abandoned farmlands as GI-2, there is a high possibility that these areas may function as wetland ecosystems, which we have lost through land conversion for agriculture.

If farmlands in the downstream reaches of the large rivers are abandoned, these areas are of high priority for utilization as GI-2 because large cities (Sapporo and Obihiro city) with large populations and assets develop in downstream reaches. However, GI-2 situated in the middle reaches and tributaries is also important because these infrastructures retard the concentration of floodwater into the mainstream and thereby keep the floodwater level low in the downstream reaches.

Network of GI-1 and GI-2 promises persistence of the crane population and will contribute to sustainable development of local towns

One of the important characteristics of GI is an interconnected network of green spaces (Maes et al., 2015). The six flood control basins (GI-2) in the Chitose River are located at or close to suitable sites according to our analyses based on flood risk, biodiversity, and land use. Thus, flood control basins act as ecological networks. In fact, a study that compared the abundance of different organisms (fish, aquatic insects, birds, and aquatic plants) among various water bodies (natural ponds, artificial channels, etc.) revealed that their abundance was highest in flood control basins. Additionally, the composition in basins differs from that in other water bodies because basins present a dynamic environment similar to the floodplains and mudflats that we have lost, which are essential habitats for plants and animals dependent on flood disturbance (Ishiyama, in preparation). Many species inhabiting disturbance-prone areas are currently nominated as endangered species (Nakamura et al., 2017).

Another network for the conservation of the Red-crowned Crane on a large scale can be built employing the Kushiro Wetland as a hub wetland (GI-1) and flood control basins as satellite wetlands (GI-2). As indicated previously, there is a risk of spreading infectious diseases because of the low genetic diversity of the cranes, and Ministry of the Environment would like to expand the cranes' distribution outside of the Kushiro Wetland and reduce the risk of disease outbreaks.

Since the arrival of the cranes to the flood control basins in the Chitose River, some of the local farmers have begun to grow their crops without using pesticides or to grow them organically. Moreover, the local office of the MLIT experimentally built several soil mounds to provide nesting and breeding sites for cranes with the help of local people. The town distributes newsletters introducing these activities and has created several environmental education programmes. Children enjoy catching fishes and invertebrates in the flood control basins as well as the chance to observe various bird species, including cranes (http://hokkaido.env.go.jp/post_55.html). Currently, these activities are supported by farmers, local citizens and consumers in large cities, such as Sapporo, and the organic crops produced by these farmers may therefore be purchased by conscientious consumers at higher prices.

6 CONCLUSIONS

Functions of forests and wetlands have long been recognized and analysed quantitatively; thus, the idea of green infrastructure is not new. However, we lost GIs because of the historical overuse of natural resources and intensive land use development. To compensate for the loss of GI functions, many grey infrastructures have been built. However, the construction and maintenance costs of grey infrastructure are enormous, and they have various negative impacts on biodiversity and ecosystem services. Thus, the strategy of dependence on grey infrastructure may not be acceptable, specifically in a depopulating society such as Japan. Moreover, climate change adds another constraint on the use of grey infrastructure because an extraordinary event caused by global warming may frequently exceed the planning level of the grey infrastructure, which results in a great deal of damage to human lives and properties. Unfortunately, we could not perform a model analysis assessing the hydrological effects of implementing the flood control basins (GI-2). The spatially explicit hydrological analysis considering the location and size of the flood control basin is definitely an important theme for future GI studies.

A novel strategy using grey and gree as a hybrid contributes to resolving the above problems. Among the sustainable development goals (SDGs) in the United Nations call to action, GI can contribute to the achievement of goals No. 6 (clean water and sanitation), No. 13 (climate action), No. 14 (life below water), and No. 15 (life on land). In this framework, GI contributes to maintaining a healthy biosphere, and thereby a healthy economy and society can be maintained. A good example is the widespread effects of GI on environmentally harmonized agriculture and environmental education in the case study of the Maizuru flood control basin.

The effective combination of grey and green infrastructure, as shown in Fig. 1(c), is essential to build economically and environmentally friendly and socially acceptable land use plans. To use GIs for adaptation to climate change and biodiversity conservation, we should evaluate various functions and costs of a hybrid infrastructure more quantitatively and propose a best mixture considering the needs and future prospects of local and regional communities.

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8 FIGURE CAPTIONS

Fig. 1 Conceptual framework of grey (a), green (b), and hybrid infrastructures (c). Shaded and white areas denote the safety zones created by grey and green infrastructure, respectively. The area denoted by GI-1 is the fundamental green infrastructure, while GI-2 is an additional multilevel green infrastructure. Figures (a) and (b) are modified from Onuma and Tsuge (2018).

Fig. 2 Locations of study rivers and catchments.

Fig. 3 Structure of the GETFLOWS simulation model (redrawn from original sources provided by Kushiro Nature Restoration Committee).

Fig. 4 Study flows for evaluating the attenuation of flood peaks by the Kushiro Wetland (GI-1).

Fig. 5 Thiessen polygons to calculate areas in relation to rain gauge stations. The circles indicate the locations of gauge stations (redrawn from original sources provided by Kushiro Nature Restoration Committee).

Fig. 6 Attenuation of flood peaks by the Kushiro Wetland. The fit of the simulation results to the observational hydrograph (a) and comparison of the simulation results with and without wetland GI (b).

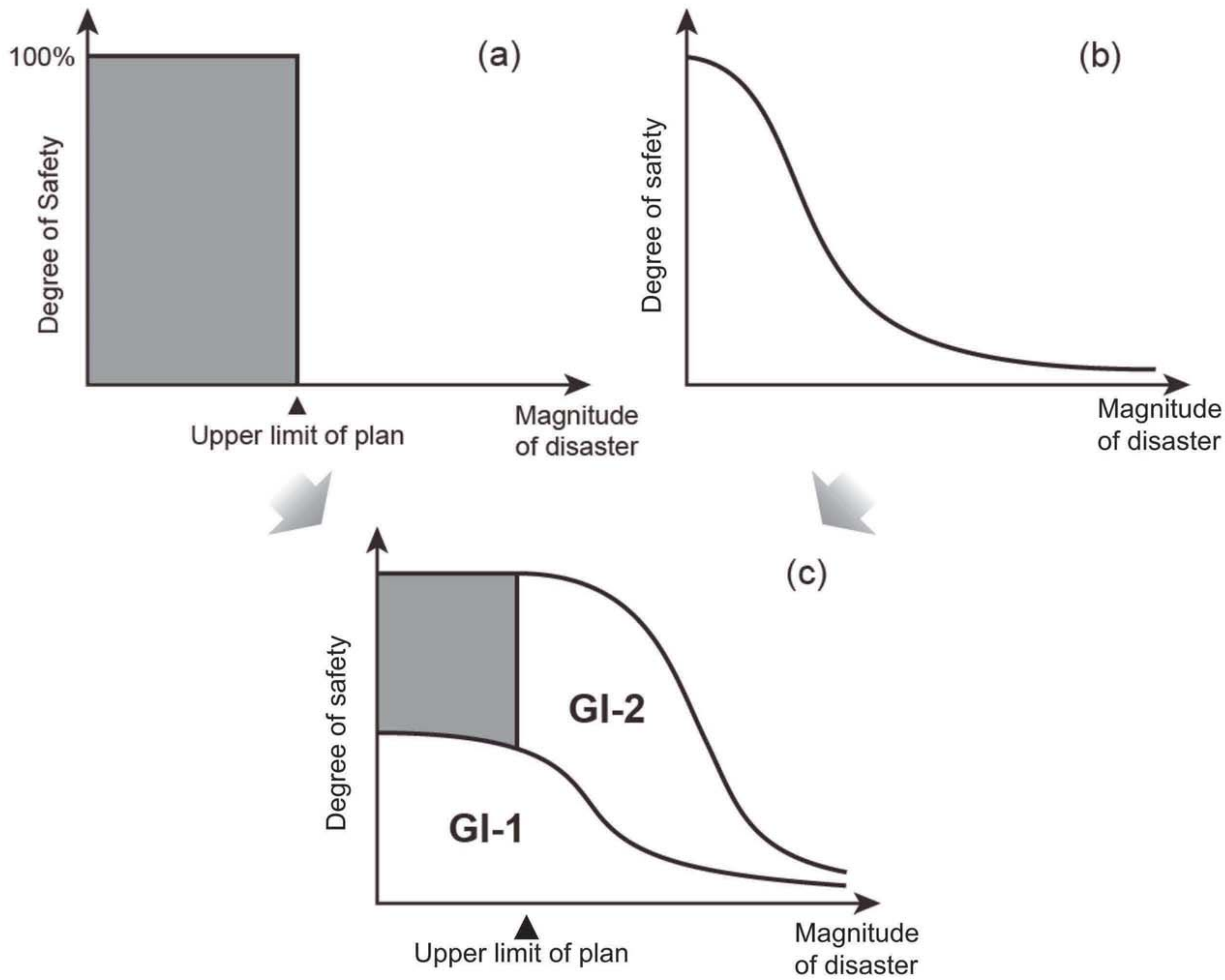
Fig. 7 Results of the four evaluated maps regarding abandoned farmlands, flood risk, and the species diversity of wetland birds and plants in Hokkaido.

Fig. 8 Suitable locations for flood control basins. The light green, blue and red grids indicate low, medium and high priorities, respectively.

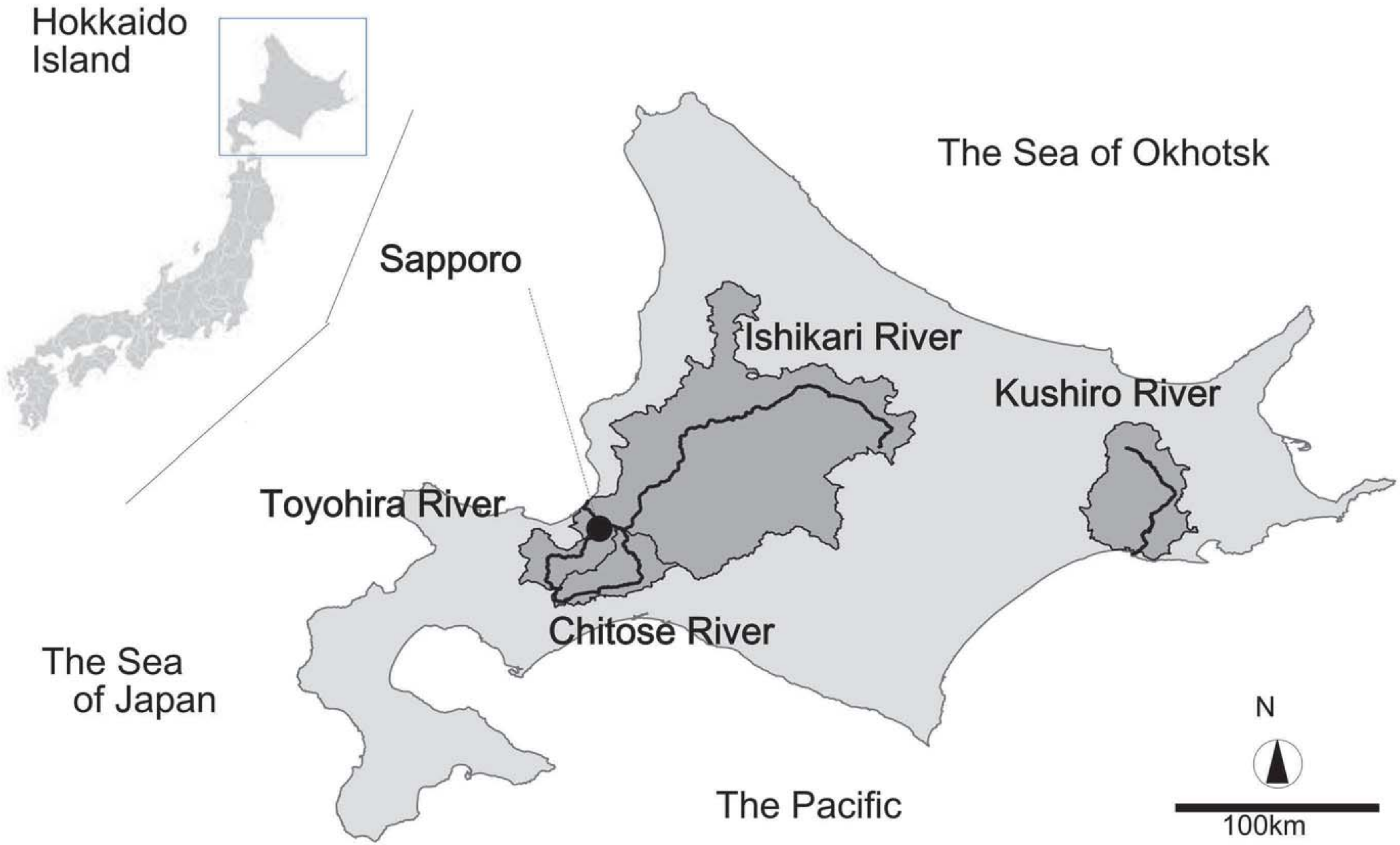
Fig. 9 Pair of Red-crowned Crane that arrived in the Maizuru flood control basin in August 2012. The image in the upper-right corner is an aerial photo of the entire basin (image provided by the MLIT).

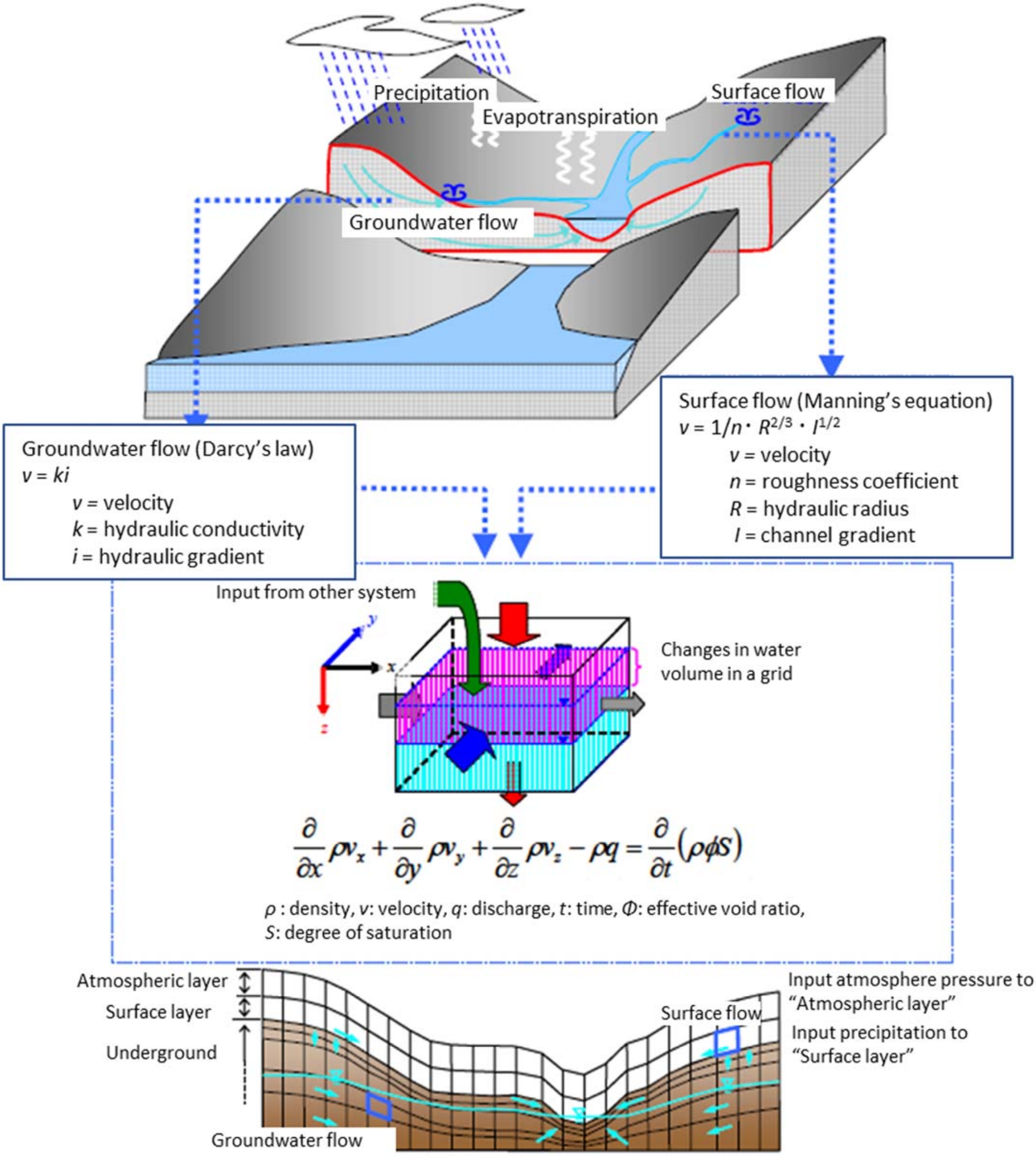
Table 1 Results of GETFLOWS simulation

Simulation case	Peak discharge	Date of peak discharge	Lowest discharge
	(m^3/sec)	(July 1-Dec. 31,2016)	(m^3/sec)
Current situation	390	Aug. 23	57
(with 22,000 ha wetlands)			
Partial loss of wetlands	580	Aug. 21	44
(with 9800 ha wetlands)			



100%
(a)
Degree of Safety
Upper limit of plan
Magnitude of disaster
(b)
Degree of safety
Magnitude of disaster
(c)
Degree of safety
GI-2
GI-1
Upper limit of plan
Magnitude of disaster


Hokkaido
Island
The Sea of Okhotsk
Sapporo
Ishikari River
Kushiro River
Toyohira River
Chitose River
The Sea
of Japan
N
The Pacific
100km



Precipitation
Evapotranspiration
Surface flow
Groundwater flow
Groundwater flow (Darcy's law)
v = ki
v = velocity
k = hydraulic conductivity
i = hydraulic gradient
Surface flow (Manning's equation)
v = 1/n · R^2/3 · I^1/2
v = velocity
n = roughness coefficient
R = hydraulic radius
I = channel gradient
Input from other system
Changes in water volume in a grid
$$\frac{\partial}{\partial x}\rho v_x + \frac{\partial}{\partial y}\rho v_y + \frac{\partial}{\partial z}\rho v_z - \rho q = \frac{\partial}{\partial t}(\rho \phi S)$$
ρ : density, v: velocity, q: discharge, t: time, Φ: effective void ratio,
S: degree of saturation
Atmospheric layer
Surface layer
Underground
Input atmosphere pressure to "Atmospheric layer"
Surface flow
Input precipitation to "Surface layer"
Groundwater flow

STEP 1 Preparation of precipitation data for GETFLOWS simulation

Analysis area: The entire Kushiro River catchment (grid size is 250 m x 250 m)
Objective: Select rain gauge stations distributing over the entire catchment.
Use Thiessen polygons to calculate representative areas in relationship to each of gauge stations (see Figure 5).

STEP 2 Groundwater and surface flow simulation at the entire catchment scale

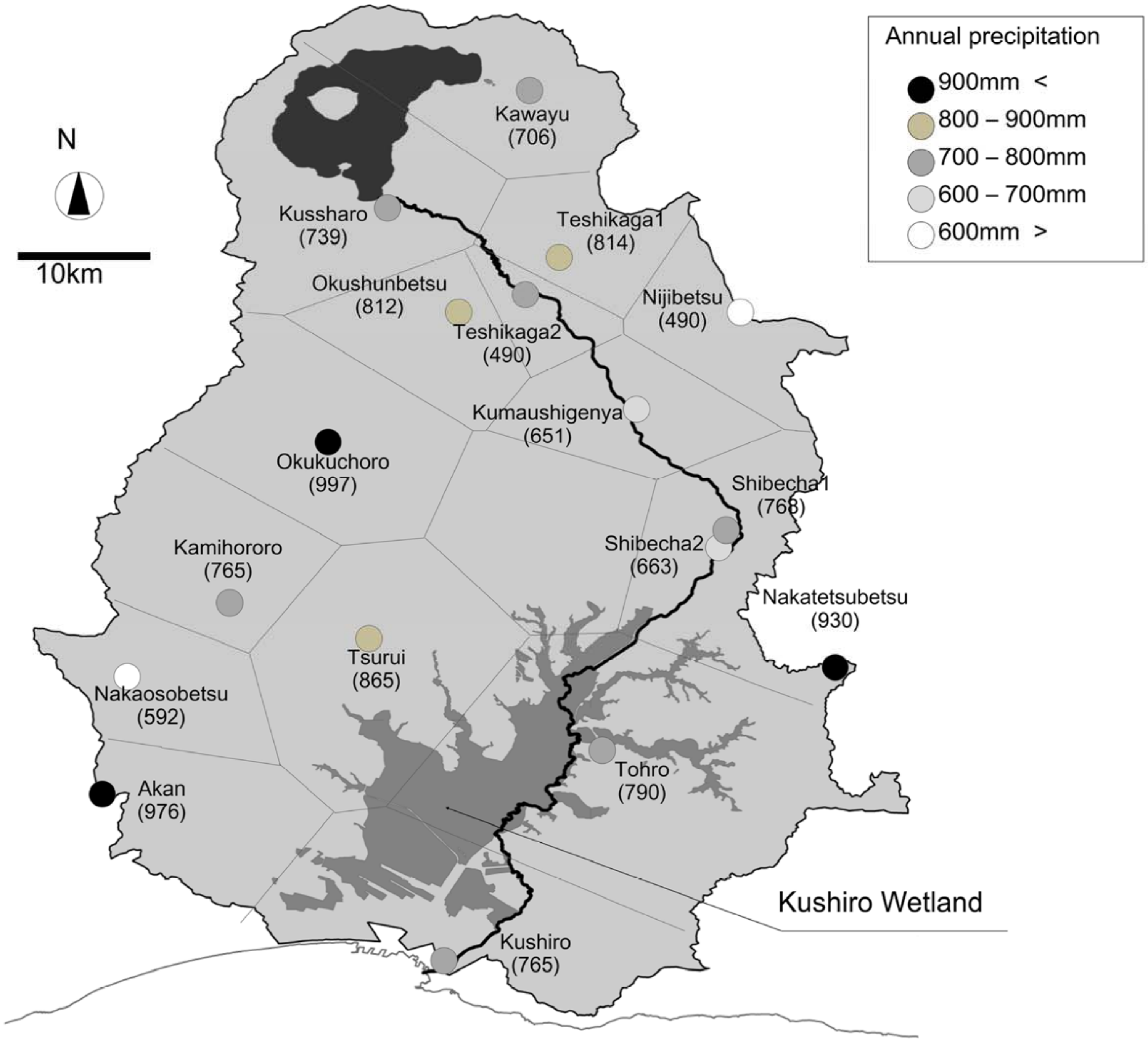
Analysis area: The entire Kushiro River catchment (grid size is 250 m x 250 m)
Objective: Simulate groundwater and surface flows at the entire catchment scale.
Simulate groundwater and surface flow fluxes entering into Kushiro Wetland.
Simulate water budget in the Kushiro Wetland.
Examine boundary conditions to conduct groundwater simulation in the Kushiro Wetland.
Model validation of water discharge at Hirosato gauging station (outlet of Kushiro Wetland) from 1/1/2015 to 31/12/2016.
Tune climatic, geological, hydraulic, and land-use model parameters to correctly simulate surface and groundwater levels from the observed data (see Tables S1 and S2).

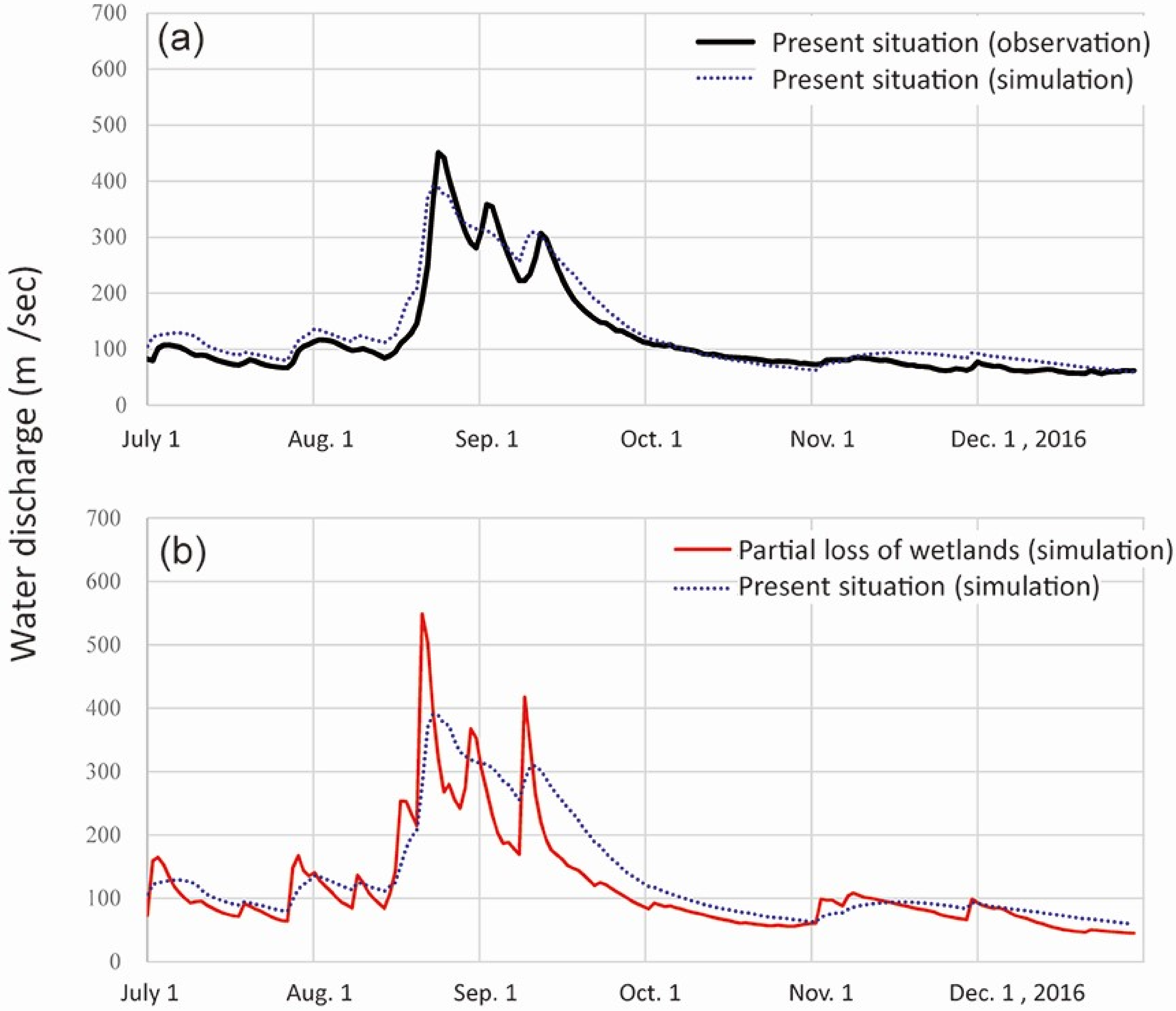
STEP 3 Groundwater and surface flow simulation at the Kushiro Wetland area

Analysis area: The Kushiro Wetland area (grid size is 100 m x 100 m)
Objective: Simulate groundwater and surface flows at Kushiro Wetland (see Figure 6(a)).

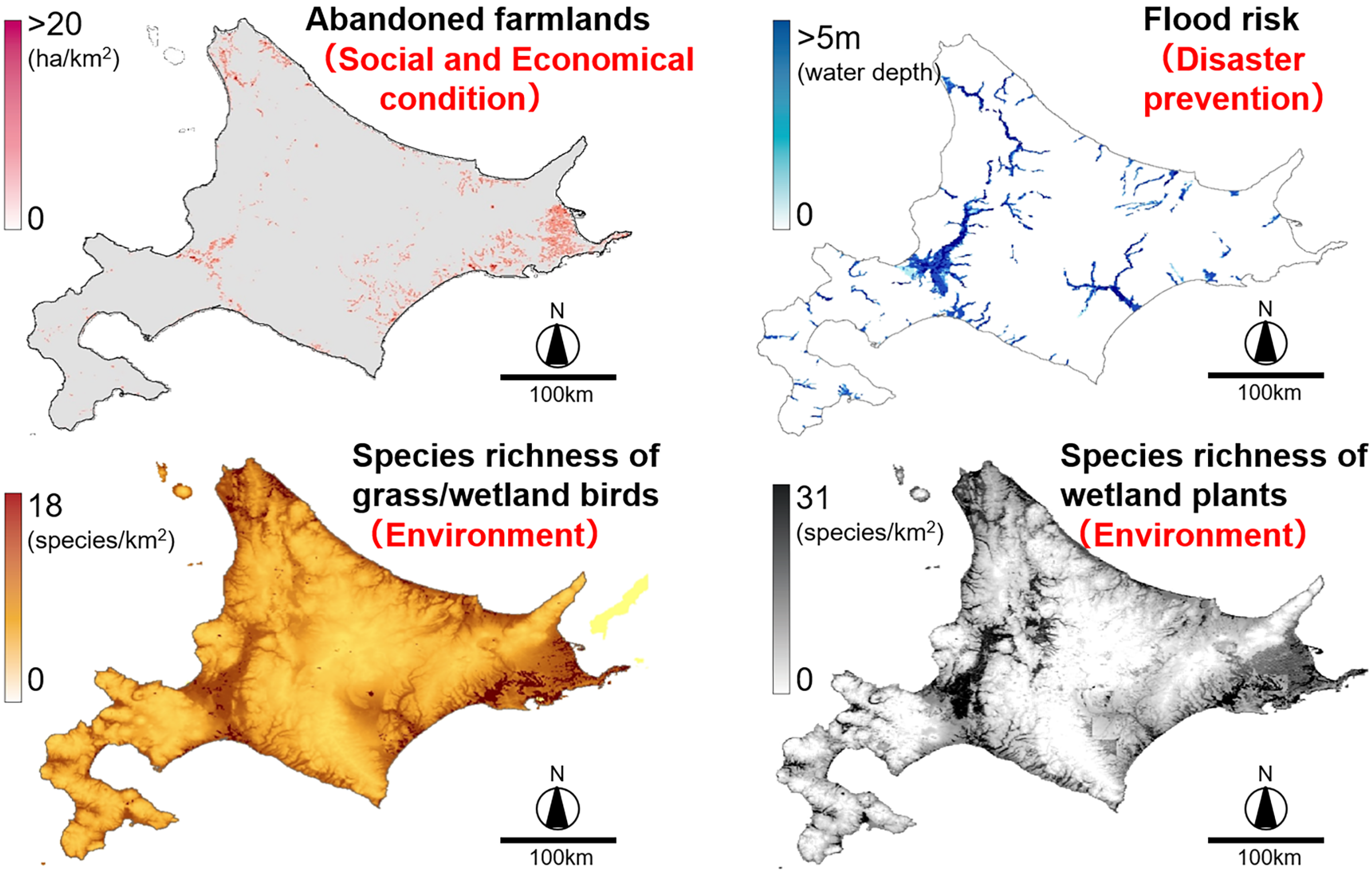
STEP 4 Simulate groundwater and surface flow simulation with land use coversion

Analysis area: The Kushiro Wetland area (grid size is 100 m x 100 m)
Objective: Simulate groundwater and surface flows at Kushiro Wetland by converting approximately 12,200 ha wetlands to residential lands (see Figure 6(b)).

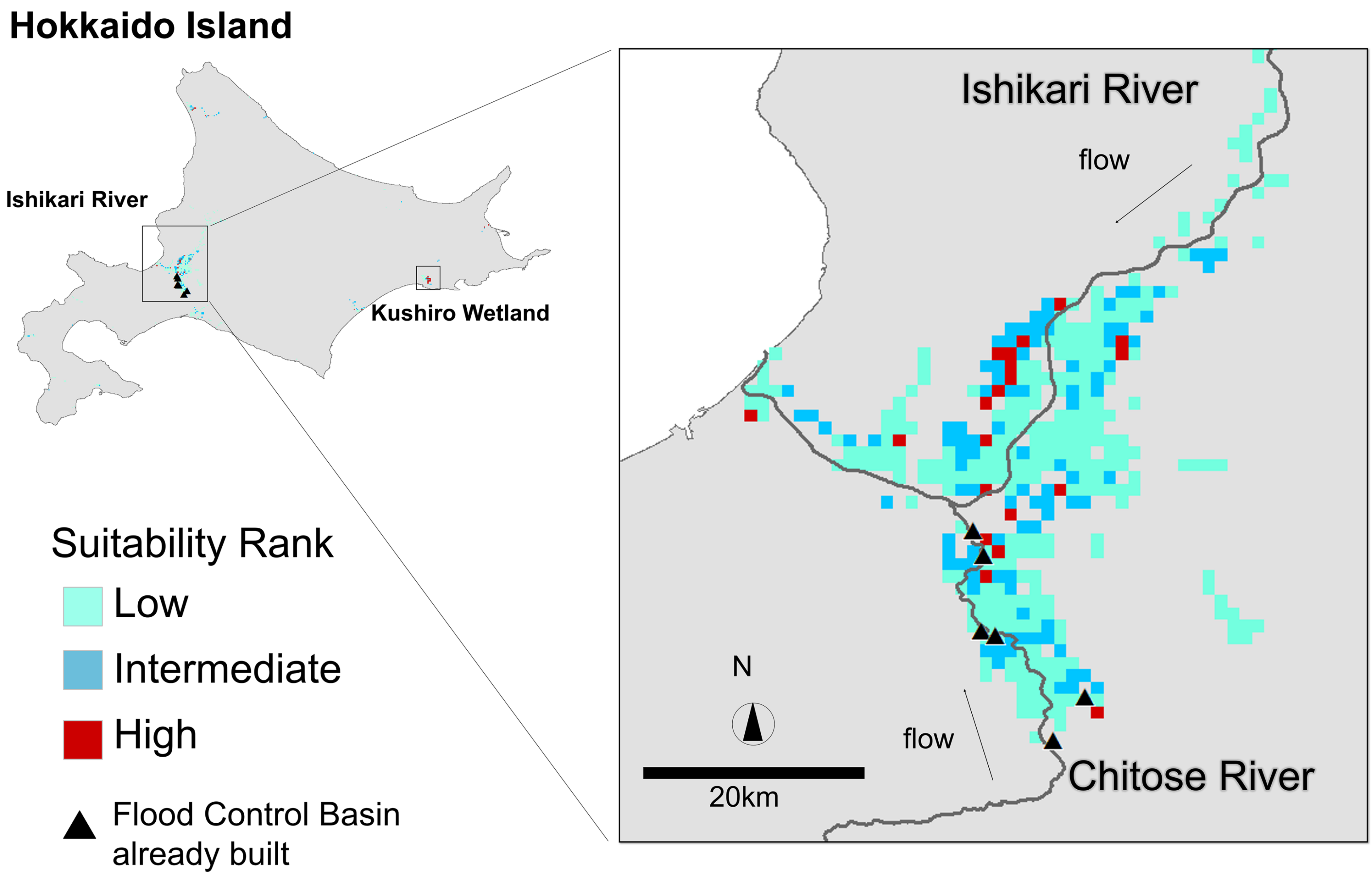

Annual precipitation
900mm <
800 – 900mm
700 – 800mm
600 – 700mm
600mm >
N
10km
Kawayu
(706)
Kussharo
(739)
Teshikaga1
(814)
Okushunbetsu
(812)
Teshikaga2
(490)
Nijibetsu
(490)
Kumaushigenya
(651)
Okukuchoro
(997)
Shibecha1
(768)
Shibecha2
(663)
Kamihororo
(765)
Nakatetsubetsu
(930)
Tsurui
(865)
Nakaosobetsu
(592)
Tohro
(790)
Akan
(976)
Kushiro Wetland
Kushiro
(765)



(a)
Present situation (observation)
Present situation (simulation)
(b)
Partial loss of wetlands (simulation)
Present situation (simulation)
Water discharge (m /sec)
0
100
200
300
400
500
600
700
July 1
Aug. 1
Sep. 1
Oct. 1
Nov. 1
Dec. 1 , 2016



Abandoned farmlands
（Social and Economical condition）
>20
(ha/km²)
0
N
100km
Flood risk
（Disaster prevention）
>5m
(water depth)
0
N
100km
Species richness of grass/wetland birds
（Environment）
18
(species/km²)
0
N
100km
Species richness of wetland plants
（Environment）
31
(species/km²)
0
N
100km



Hokkaido Island
Ishikari River
Kushiro Wetland
Ishikari River
flow
flow
Chitose River
N
20km
Suitability Rank
Low
Intermediate
High
Flood Control Basin already built