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Global wetlands: Potential distribution, wetland loss, and status

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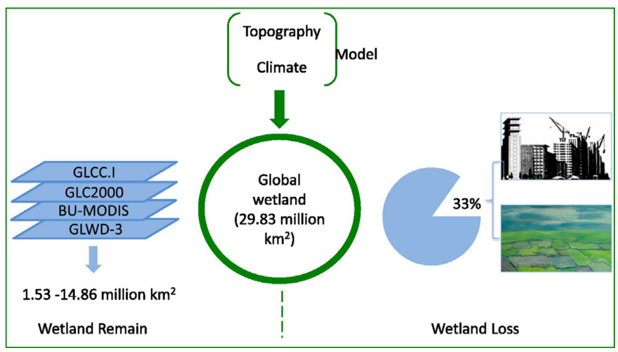
HIGHLIGHTS

- Global potential wetland distribution was simulated based on PTWI and RS samples.
- Global wetlands loss were at least 33% as of 2009, smaller estimation than before.
- The greatest wetland loss happened in Asia, but the most serious situation in Europe.
- There was a great inconsistency among the global wetland-related landcover products.

GRAPHICAL ABSTRACT



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ABSTRACT

Even though researchers have paid a great deal of attention to wetland loss and status, the actual extent of wetland loss on a global scale, especially the loss caused directly by human activities, and the actual extent of currently surviving wetlands remains uncertain. This paper simulated the potential distribution of global wetlands by employing a new Precipitation Topographic Wetness Index (PTWI) and global remote sensing training samples. The results show earth would have approximately 29.83 million km^2 of wetlands, if humans did not interfere with wetland ecosystems. By combining datasets related to global wetlands, we found that at least 33% of global wetlands had been lost as of 2009, including 4.58 million km^2 of non-water wetlands and 2.64 million km^2 of open water. The areal extent of wetland loss has been greatest in Asia, but Europe has experienced the most serious losses. Wetland-related datasets suffer from major inconsistencies, and estimates of the areal extent of the remaining global wetlands ranged from 1.53 to 14.86 million km^2. Therefore, although it is challenging, thematic mapping of global wetlands is necessary and urgently needed.

1. Introduction

Wetlands represent one of the world's most important types of ecosystems, and are also one of the most threatened. Wetlands play a critical role in climate change, biodiversity, hydrology, and human health (Ramsar Convention Bureau, 2001). In climate change, wetlands exert an effect on both global and local/regional climate by supplying the atmosphere with potential or near-potential evapotranspiration and by taking up carbon dioxide and emitting methane (Russi et al., 2013). From the aspect of biodiversity, although freshwater wetlands cover only 1% of the earth's surface, these wetlands provide a home to >40% of the world's species (Mitra et al., 2003). Hydrologically, wetlands replenish groundwater, regulate water movement, and purify water,

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providing these important parts of the hydrologic cycle (MEA, 2005). In support of human health, wetlands provide traditional medicines on which 80% of the world's population depends for primary health care (Mitra et al., 2003). Wetlands are internationally recognized as an indispensable resource for humans.

Wetland loss and degradation is an indisputable reality, and human activities are chiefly to blame as the main factors. Many researchers have frequently reported that 50% of the world's wetlands have been lost, although this is based on inadequate supporting evidence (Finlayson, 2012; Davidson, 2014). This figure originates from very limited data gathered solely from the U.S. and solely during the mid-20th century. Nevertheless, this loss rate has extrapolated to a global scale since 1990 (Davidson, 2014). Davidson (2014) reviewed 189 reports related to changes in wetlands and concluded that, over the long term, wetland conversion and loss has exceeded 50%, and is as much as 87% since the beginning of the 18th century. Davidson's research provides the first evaluation of published research studies related to wetland loss and changes on a global scale and has greatly enhanced our understanding of how wetlands have changed globally. However, Davidson (2014) recognizes the inconsistency of data on changes in wetland areas and scales in those published papers and reports renders the results somewhat uncertain.

The areal extent and spatial distribution of the world's remaining wetlands is another unresolved issue, which has many possible causes, including differences in the definitions of wetlands, the dynamics of hydrologic systems, and characteristics of seasonal vegetation (Loveland et al., 2000; Herold et al., 2008; Gong et al., 2012), sharp spectral characteristics (Gong et al., 2012), and limitations in satellite imagery acquisition. Dugan (1993) used the Ramsar definition of wetlands (nonmarine wetlands) and provided a global estimate of 5.6 million km^2. Matthews and Fung (1987) and Aselmann and Crutzen (1989) calculated the global extent of natural freshwater wetlands as 5.3 and 5.7 million km^2, respectively. Global assessments of wetland tend to concur that measures of wetlands have been extremely inconsistent (Nakaegawa, 2012). These estimates include the Global Land Cover Characteristics (GLCC·I and GLCC·S) completed for the International Geosphere-Biosphere Program (IGBP; Loveland et al., 2000), the Global Lake and Wetland Data Level 3 (GLWD-3; Lehner and Döll, 2004), the Global Land Cover 2000 (GLC2000; Bartholomé and Belward, 2005) and MOD12Q1 V004 Land Cover Data product developed by Boston University (BU-MODIS; Friedl et al., 2002), and GLOBCOVER2009 (Arino et al., 2012). The minimum estimate of the total global wetlands stands at 0.29 million km^2 (Friedl et al., 2002) while the maximum is 9.78 million km^2 (Lehner and Döll, 2004). The increasing awareness of the significant role wetlands play in the global climate system has led a proliferation of land surface models (LSM) designed to account for wetlands to their schemes. However, because those models adopt different approaches, extensive disagreements exist related to the extent of wetlands in both space and time. Among models, an almost fourfold difference exists between the lower and upper estimates of the areal extent of wetlands globally (8.6 to 269 million km^2; Wania et al., 2012). No commonly accepted figure is available for the areal extent of currently extant global wetlands.

The potential distribution of global wetlands is defined as the spatial distribution of wetlands that would exist if there were no human activities on earth. Knowing the potential distribution of global wetlands could facilitate our understanding wetland development, wetland changes, and decision-making for wetland restoration and protection. Because of the solid physical foundation on wetland formation, distributed hydrological models are used in simulations of the potential distribution of global wetlands. For example, Fan and Miguezmacho (2010); Fan et al. (2013) and Zhu and Gong (2014) simulated global wetlands with 1-km spatial resolution based on the relationship between water table depth and wetland distribution. Results suggest that this kind of method could capture the most prominent features of wetland distribution and extent (Fan and Miguezmacho, 2010; Zhu and Gong, 2014). However, this type of estimation still has limited usefulness, particularly at a large scale. One of the reasons for this is that distributed hydrological models have complex solutions that are time-consuming and that these numerical solutions have a degree of uncertainty (Zhu and Gong, 2014). The acquisition and the precision of the models' parameters also serves as another hindrance to making accurate wetland estimates; this is especially true for soil parameters such as hydraulic conductivity, soil permanent wilting point, soil porosity, and relative soil water content, which directly influence the accuracy of any simulation (Beven, 1990). The topographic wetness index (TWI) is an important model parameter and has been widely used in wetland simulation since it was first proposed in 1979 (Beven and Kirkby, 1979; Rodhe and Seibert, 1999; Infascelli et al., 2013; Murphy et al., 2007). Topography and precipitation serve as important model parameters, and data related to global topography and rainfall could be collected easily and at greater precision than in the past. However, the application of topographic indices still takes place on a small basin scale in many cases.

To address these issues, the objectives of this paper are: (1) to propose a new Precipitation Topographic Wetness Index (PTWI), and to simulate the potential distribution of global wetlands regardless of human activities; (2) to discuss the overall loss of global wetlands caused directly by human activities, and to estimate how much of the world's wetlands remain, based on the result of simulation and global wetland-related datasets.

2. Materials and methods

2.1. Wetland definitions

The earth's land surface can be divided into two categories: wetlands and upland. Creating a clear definition of wetlands has proven difficult, because wetlands by nature are the transitional area between terrestrial and aquatic systems. The Ramsar definition of wetlands has been accepted by many organizations, such as the International Union for the Conservation of Nature (IUCN, World Conservation Union) on a global scale (Navid, 2014). This definition is also adopted here to define wetlands. The term upland in this paper refers to all land cover types apart from wetlands.

2.2. Data sources

In the aim of our research, a global digital elevation model, GTOPO30, drainage basin boundary data along with climate data are used to simulate the potential distribution of global wetland. Global wetland-related datasets are used to evaluate the accuracy of simulation result and analyze global wetland loss and remaining. The specific datasets employed in our research are as follows:

(1) Topography and precipitation data were collected to calculate the topographic wetness indices. GTOPO30, developed by U.S. Geological Survey, has a 1-km resolution and covers the entire planet. Monthly average precipitation data from 1950 to 2000 with a 1-km resolution were downloaded from WorldClim. This data needed to be transformed into annually average precipitation in the calculation of topographic wetness indices.
(2) Drainage basin boundary provided by the HYDRO1K database is derived from the GOTO30. In consideration of the computational efficiency, the Level 1 drainage basin boundary was chosen as the basic unit for simulation of global wetland potential distribution.
(3) The global water table depth distribution data employed here came from a simulation result for global wetland with 1-km resolution (Fan and Miguezmacho, 2010; Fan et al., 2013) and is compared with our simulation result.
(4) Three global datasets, GLCC.I, GLC2000, and BU-MODIS, were all developed before the year 2000 and have a 1-km resolution;

these data were collected to establish a global wetland sample dataset.

(5) GlobCover2009 is a global dataset with a 500-m resolution provides the spatial extent of direct human activities. Five land-cover categories, including post-flooding and irrigated croplands (11), rain-fed croplands (14), cropland/vegetation mosaics (20), vegetation/cropland mosaics (30), and artificial surfaces and associated areas (190), were considered the results of direct human activities in the present study and were extracted from the GlobCover2009.

(6) Observed wetland datasets are national/regional wetland datasets having a high spatial resolution. They include a 240-m resolution dataset of China wetlands from 2008 (Niu et al., 2012), a 30-m resolution national land cover dataset known as NLCD2011 (Homer et al., 2015), the 100-m resolution Europe Corine land cover dataset CLC2012 (Soukup et al., 2016), and the 1-km resolution GLWD-3. These datasets were used to evaluate the performance of the topographic wetness indices and validate our simulation result.

In order to unify these datasets with different resolutions and coordinate systems, all the datasets were resampled to 1-km resolution and projected to World_Goode_Homolosine_Land.

2.3. Evaluating the precipitation topographic wetness index

While water is an important factor in the evolution of wetlands, topography and climate determine the spatial-temporal distribution of water thereby controlling the occurrence of wetlands. Merot et al. (2003) proposed a Climate-Topographic Index (CLTI) that combines the effective rainfall depth that is equal to the precipitation amount minus potential evapotranspiration with topographic wetness index to indicate the potential distribution of wetlands. A greater index indicates a stronger possibility that wetlands will develop. However, because of the maximum evaporating capacity of wetlands, the effective rainfall of the CLTI could be underestimated. Moreover, abundant precipitation always results in the occurrence of wetlands while greater evapotranspiration always results from the existence of wetland. It would be more reasonable to use a precipitation instead of effective rainfall amount to simulate the distribution of wetlands from its occurrence mechanism. Therefore, the CLTI (1) was here revised to develop a Precipitation Topographic Wetness Index (PTWI) using Eqs. (1) and (2):

$$\mathrm{CLTI} = \log(Vr/\mathrm{Tan}ß) \quad (1)$$

$$\mathrm{PTWI} = \log(Pr/\mathrm{Tan}ß) \quad (2)$$

where Vr refers to the drainage area multiplied by the mean annual effective rainfall depth; Pr refers to the drainage area multiplied by the mean annual precipitation (if mean annual precipitation = 0, then, Pr was set at 10^{-8}); and Tan$ß$ is the local topographic slope.

We evaluate the performance of PTWI based on its capability to predict the spatial distribution of wetlands. The map of PTWI firstly reclassified into binary maps (wetlands, non-wetlands) by the specific threshold value which was selected so that the simulated wetland percentage equaled the observed wetland percentage. Then the accuracy of the prediction was calculated using the direct spatial coincidence (SC; Eq. (3)); that is, the percentage of pixels that are correctly simulated compared with the total of the observed wetland pixels:

$$SC = A/B * 100\% \quad (3)$$

where A refers to the number of pixels which are correctly predicted as wetlands; B refers to the number of pixels which are predicted as wetlands. The value of SC ranges from 0 to 100 and a higher value indicates a better prediction.

The performance of PTWI has been validated in those regions, including China, the conterminous United States, and Europe, where high resolution wetland datasets were available. We also validated the index in Africa, where we used the GLWD-3 dataset, a database designed specifically for wetlands, as the observed wetland, because available wetland data in this region was very limited. Finally, ten basins in those regions were selected, representing a wide variety of climate and topographical features across the world (Table 1). These basins are distributed from tropical to boreal regions and from moist to dry climates. The present study adopted the climate zones of the Koeppen climate classification (Köppen and Geiger, 1930). The observed wetland area of these basins ranged from 9.8% to 58% of the total area, and the annual averaged precipitation was from 266 mm to 1394 mm.

2.4. Global wetland sample dataset

Theoretically, a region with a relatively large PTWI will have a greater chance for wetland development. Among all the wetland categories, water will have the highest PTWI value, followed by non-water wetlands (nw-wetland) and upland in turn. Therefore, we divided wetlands into two types: water and nw-wetland and collected the corresponding training and validation samples, respectively.

(1) Training sample dataset
To determine the thresholds of PTWI that could distinguish these three types, a global wetland training sample dataset was developed. This dataset was based on three global land cover products for which data collection periods were all before 2000 (Table 2); in addition, high spatial resolution images of Google Earth and related papers and hierarchical sample methods were used (Gong et al., 2012; Zhao et al., 2014; Zheng et al., 2015).

Water samples: these were selected from the water categories of GLCC·I, GLC2000, and BU-MODIS datasets, respectively (Table 2), considering these datasets had a relatively close agreement on water, based on Nakaegawa (2012). The intersection analysis was conducted to randomly produce 6000 water samples using the Hawths Tools (http://www.spatialecology.com/htools/download.php) in ArcGIS 9.3 software. Here, 1024 additional samples were added to keep these samples more evenly distributed in each basin.

Nw-wetland samples: the global validation dataset, which was built in 2014 based on manual interpretation of Landsat Thematic Mapper and Enhanced TM Plus images with the quality control correctness level reached 90% at Level 1 class, was used and 1417 nw-wetland samples were extracted (Zhao et al., 2014). Moreover, 330 additional samples of nw-wetland were supplemented from some global land cover datasets (Table 2), in which regularly flooded tree cover and herbaceous cover categories in GLC2000 dataset were considered as nw-wetland.

Table 1
The climate zones, precipitation amount, area percentage of wetland (%) of ten verified basins in Africa (3 basins) China (2), Europe (3), and North America (2).

Regions	Basin ID	Climate zones	Precipitation (mm)	Wetland percentage (%)
China	CH1	Dwb; BSk	266	21
	CH2	Cfa	1394	26
United States	US1	Dfb	780	58
	US2	BSk;Dfb;Cfa	406	9.8
Europe	EU1	Dfb;Dfc	664	20
	EU2	Dfc	971	26
	EU3	Dfc	438	27
Africa	AF1	AW	1067	17
	AF2	BWk;BSh;AW	631	37
	AF3	BSh	430	12

AW, tropical dry climate; BSh, low-latitude semiarid climate; BSk, cold semiarid climate; BWk, cold desert climate; Cfa: humid subtropical climate; Dfb, warm-summer humid continental climate; Dfc, subarctic climate; Dwb, humid continental climate.

Table 2
Datasets used to develop global wetland samples.

	Training sample			Validation sample		
	GLCC·I	BU-MODIS	GLC2000	China wetland	NLCD	CLC
Date collection period	1992–1993	2000–2001	1999–2000	2008	2011	2012
Resolution	1-km	1-km	1-km	240-m	30-m	100-m
Number of land cover types	17	17	22	14	16	48
Nw-wetland	Permanent wetland	Permanent wetland	Tree Cover, regularly flooded, fresh water/saline water; Regularly flooded shrub and/or herbaceous cover	Inland marshes/swamp; tide zone/shallow beach; estuarine delta; other wetlands	Woody wetlands; Herbaceous wetlands	Wetland
Water	Water	Water	Water bodies	Rivers; lakes; reservoirs/ponds; artificial channel; seawater fish farm/salt flats; estuarine water; lagoons	Open water	Water bodies

Note: Nw-wetland indicates the non-water wetlands.

Upland samples: The water and nw-wetland categories of GLCC, GLC200, and BU-MODIS datasets were combined, and the union area was erased from the global continents. Then, 10,752 upland samples were randomly produced in the remaining area of the global continents using the Hawths Tools.

(2) Validation sample datasets
A validation sample dataset was established to validate the accuracy of the simulated wetlands. Because no widely accepted global wetland dataset exists, the validation was performed only in the regions that have high resolution wetland data available as defined in Section 2.3 above. We randomly produced 1000 upland samples, 500 water samples and 500 nw-wetland samples in each region, respectively, by using the Hawths Tools.

2.5. Simulation of the potential distribution of global wetland

The different values of PTWI were tested repeatedly to simulate the spatial distribution of wetlands. Considering the computational efficiency of the global wetland simulation, we took drainage basin of Level 1 on a global scale as the basic unit of simulation. The thresholds were determined based on training samples to avoid subjectivity. First, GLWD-3 was reclassified into water (lake, river and reservoir) and nw-wetland (other wetland categories). We calculated the statistical distribution of the PTWI value for each type of GLWD-3 and obtained the modes of PTWI value for GLWD-3 water and nw-wetland. Next, each basin was divided into three categories: water, nw-wetland, and upland, by setting the modes of PTWI for GLWD-3 water and nw-wetland as thresholds temporarily. Second, the classified results were evaluated using the global wetland training sample dataset based on the overall accuracy assessment, user's accuracy and producer's accuracy (Stehman, 1997). Third, the D-value which was equal to user's accuracy minus producer's accuracy was calculated. If the D-value was >5%, then the thresholds were adjusted until it was <5%. The tradeoff between the user's and producer's accuracies can represent improved classification results. Finally, based on the determined thresholds of PTWI, we simulated the potential distribution of wetlands globally.

3. Results and discussion

3.1. The evaluation of PTWI

Although it has been verified that topographic wetness indices are efficient in distinguishing wetlands and upland (Rodhe and Seibert, 1999; Infascelli et al., 2013; Murphy et al., 2007; Merot et al., 2003), a need still exists to evaluate the capability of the newly proposed index, PTWI, in predicting the location of wetlands. In order to assess the performance of the PTWI, the predicted and observed wetland distribution maps have been compared and the direct spatial coincidence for CLTI (SC-CLTI) and PTWI (SC-PTWI) in each basin was calculated. The comparison of the predicted wetland with the observed wetland (Fig. 1) shows that, although the details of wetland simulation were not satisfied because of the current coarse resolution and poor quality of the DEM (Merot et al., 2003; Grabs et al., 2009), both indices, PTWI and CLTI, can well predict the general spatial pattern and the areal extent of wetland. In the meantime, we found that SC-PTWI was larger than SC-CLTI in nearly all the test basins; this was especially true in EU2 SC-PTWI where the accuracy of prediction had improved by 9% (Table 3). Although the CLTI was proposed and tested in Europe, the performance of the PTWI in Europe was better than the CLTI. The performances of these two indices were not satisfactory in Africa such as in basins AF2 and AF3. This may have been caused by the observed wetland data (GLWD), which was compiled from maps mostly generated prior to 1996; in addition, in some arid or semiarid regions this dataset has overestimated the areal extent of some wetlands (Lehner and Döll, 2004). Nevertheless, one can conclude that predictions of PTWI were in better agreement with the observed wetland than that of CLTI, and PTWI can be employed to predict the spatial distribution of wetlands on a global scale.

3.2. The potential distribution of global wetland

Using the new index, PTWI, and the thresholds determined by the global wetland samples that have been established based on the global training dataset, we developed a potential distribution map of global wetlands with a 1-km spatial resolution (Fig. 2, except for Antarctica and glaciated Greenland because no wetlands are distributed in these regions). This map includes inland and some coastal wetlands, such as mangrove swamps, and it excludes marine wetlands such as reefs and sea grass. According to this map, the total global wetland area was approximately 29.83 million km^2, including water of 11.41 million km^2 and nw-wetland of 18.42 million km^2. Among them, Asia had the largest wetland area, with about 9.72 million km^2 followed by South America and North America with 7.95 million km^2 and 5.65 million km^2, respectively. The total wetland area in these three continents included about 78% of the world's total area. Oceania had the smallest wetland area with 1.56 million km^2, or about 5% of the global wetland area.

Accuracy validation was performed in China, the conterminous United States and Europe. The overall accuracy of the simulation was 64%, 69% and 69% with Kappa coefficients of 0.4, 0.5 and 0.5, respectively. Because all the topographic wetness indices depend on the resolution and quality of the DEM from which they were derived, improved input data would affect the performance of a PTWI for wetland simulation. In addition, the validation samples were derived from latest wetland-related datasets, where wetland loss caused by human activities was included, while wetland loss was not considered in the simulation of potential wetland distribution. This discrepancy can undoubtedly have effects on the accuracy of wetland simulation.

3.3. Comparison of simulation results to global wetland-related datasets

Three satellite-based global land-cover products, GLCC.I, BU-MODIS, and GLC2000, containing wetland categories and a simulation of global

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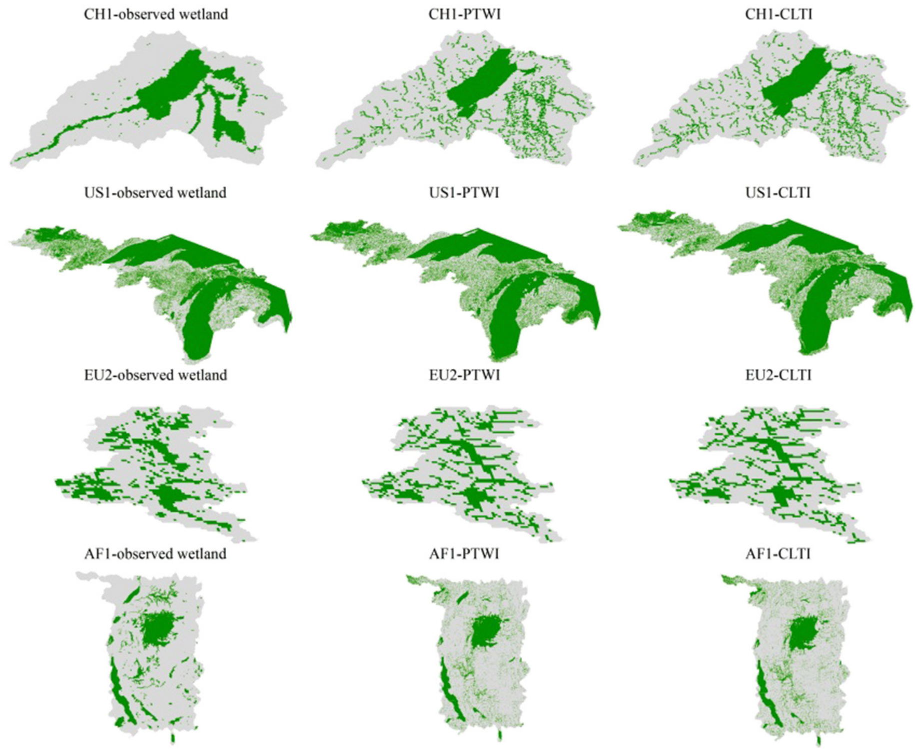

Fig. 1. The comparison between predicted and observed wetlands Note: test basins in China (CH), the United States (US), Europe (EU), and Africa (AF); PTWI, Precipitation Topographic Wetness Index; CLTI, Climate-Topographic Index.

wetlands based on a distributed hydrological model by Fan and Miguezmacho (2010); Fan et al. (2013) were selected for comparison with our simulation. Overall, the results (Fig. 3) show 1) that these five datasets have similar pattern of spatial wetland distribution and 2) that global wetlands were mainly distributed in the tropics (10°S–10°N) and the middle-high latitudes of the northern hemisphere (40°N–60°N). They also showed that the two wetland simulations produced visibly larger figures than the three satellite-based global datasets. This probably occurred because the latter mostly indicated the actual status of global wetlands, and the simulations indicated the potential distribution of global wetlands. Moreover, the methods used in global satellite-based land-cover datasets have been directed towards identifying vegetation (Gumbricht, 2012). The classification methods and systems they used were not also suitable for wetland identification. As a result, they may cause an underestimation of wetland area (Loveland et al., 2000). Only some types of wetland, such as permanent wetlands, were considered by these global land-cover methods (GLCC.I and BU-MODIS), and the areas of forest wetland (regularly flooded forest) in the tropics and high-latitude areas could have been underestimated because of the limitations of multi-spectral remote sensing approaches (Hess et al., 2015).

Table 3
The evaluation of the Precipitation Topographic Wetness Index among different basins.

Regions	Basin ID	SC-CLTI (%)	SC-PTWI (%)
China	CH1	61	62
	CH2	43	46
United States	US1	79	80
	US2	60	60
Europe	EU1	50	51
	EU2	50	59
	EU3	46	46
Africa	AF1	60	65
	AF2	37	38
	AF3	33	35

PTWI, Precipitation Topographic Index; CLTI, Climate-Topographic Index.

Fan's result was mostly similar to those of the present work, both in area and in spatial distribution. They differ only within 10°S–30°S and 40°N–50°N, where Fan's result was smaller. The following factors may have caused these differences. First, Fan's simulation was closely related to the ground water table. However, at many sites the water table observations were affected by pumping (Fan et al., 2013). For example in the high plains of the U.S. and in Argentina where pumping has caused significant declines in the water table, this pumping can cause an underestimation of wetland. Our result was influenced by the spatial resolution of the DEM used here. GTOPO30 was derived from several raster and vector sources of topographic information, and only has a relatively moderate horizontal resolution. However, the degree of this kind of effect is difficult to quantify especially on larger scales because the situation may be distinct in different regions. Second, the coarse spatial resolution in Fan's model can contribute to the underestimation of wetland areas such as prairie potholes; many smaller wetlands and isolated potholes were missed (Fan et al., 2013). In our simulation, because the majority training samples in these areas were water samples and the topography is quite flat, these regions tend to be simulated as water. Therefore, our result may have led to an overestimation of water in this area. Similar natural condition exists in Argentina, where a large difference was observed between the two methods. Third, Fan's simulation depends on the accuracy of recharge estimates. The recharge estimations used in Fan's simulation were probably biased and too high in the arid and internal-drainage basins; this would have led to a shallow simulated water table in the arid valley floors (Fan and Miguezmacho, 2010).

3.4. How much wetland the world has lost as a result of direct human activities

Agriculture and urbanization, two main human activities, directly cause wetland loss (Gong et al., 2012; Niu et al., 2012). Areas that are both placed in the wetland category in the global wetland potential distribution map and are also directly affected by human activities were extracted from GlobCover2009 and were counted as wetland loss due

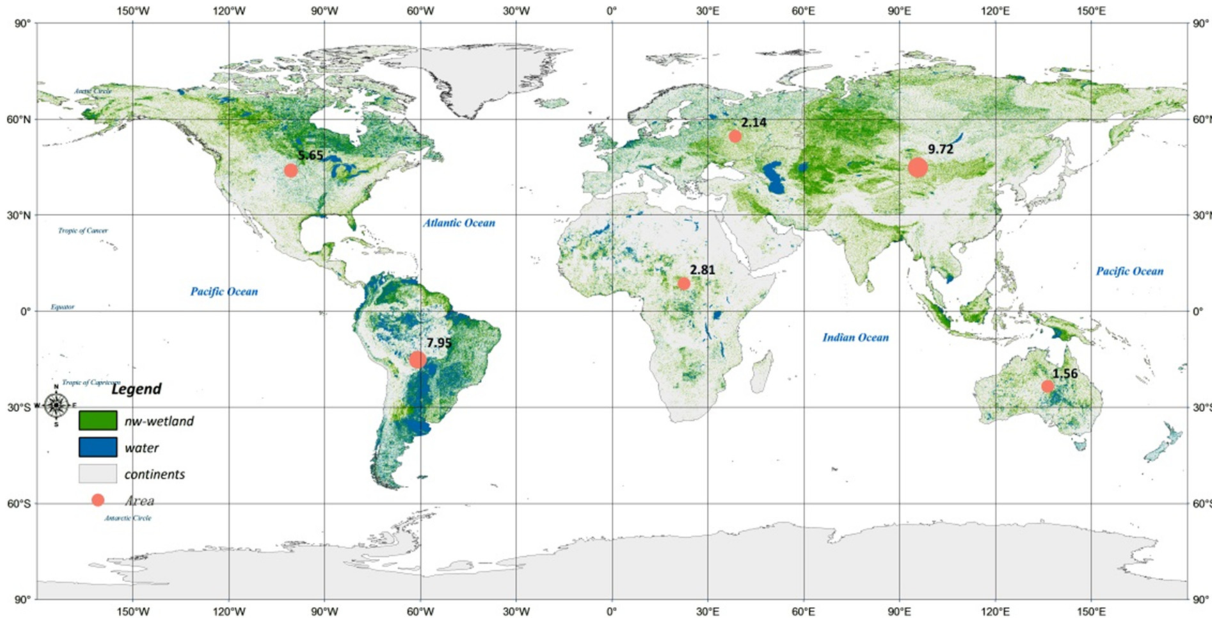

Fig. 2. Potential distribution of global wetlands (unit of area: million km^2).

to human activity. Overlapping those two data layers shows that, as of 2009, the world had lost 33% of its wetland in area, including 4.58 million km^2 of nw-wetland and 2.64 million km^2 of water. Although wetland loss takes place all over the world, the wetland loss situation that was indicated by the ratio of wetland loss (equal to the lost area/potential area) varied greatly among continents (Fig. 4). The largest wetland loss has occurred in Asia with about 2.65 million km^2 and the least happened in Oceania with about 0.18 million km^2. However, the most serious situation was observed in Europe, which has lost 45% of its wetland. This is followed by South America and Asia with approximately 32% and 27% of wetland lost, respectively. This global wetland loss situation shows a similar trend with population density of 2009 among continents according to the Food and Agriculture Organization Corporate Statistical database (Fig. 4), which confirmed that the disappearance of wetlands was principally attributable to human activities. The vast populations, which are always accompanied by high levels of demand for food and housing and then result in the acceleration of the development of agriculture and urbanization, was one of the most important factors that contributed to the severe wetland loss observed worldwide.

Davidson (2014) argued that the long-term global loss of wetland could be 54–57%, which is larger than the estimate made here. The difference could come from any of the following: (1) some types of wetland, such as intermittently flooded wetland (wet meadows, flooded forested areas in the Amazon and Congo) were not well included in Davidson's research (Davidson, 2014), which can lead to a smaller base of global wetland areas. (2) Davidson's research was based on published papers and reports which are few in number and affected by geographical bias in the numbers of published reports among different regions and at different spatial scales (Davidson, 2014). For example, the shortage of published reports for changes in total wetland area in Africa, the neotropics, and Oceania would inevitably affect the total figure of wetland loss worldwide (Davidson, 2014). (3) The accuracy of GlobCover2009 products could also have an impact on the assessment of wetland loss. For example, urbanized surfaces and associated areas (urban area < 50%) are not contained in the GlobCover2009 dataset (Arino et al., 2012), which may have caused an underestimation of global wetland losses.

The 8% figure noted here for wetland loss in North America is surprising because it is much lower than the 56% reported by Davidson (Table 4) and the 50% put forward by Shaw and Fredine (1956) for the United States alone. However, the papers and reports upon which Davidson's conclusion was based were principally concerned wetlands in the United States and some specific parts of Canada, while omitting those of Central America (Davidson, 2014). Whether these regional scale papers and reports represent the whole continent is debatable. A series of reports on the status and trends of wetlands in the conterminous United States from the 1780s to 2009 show approximately 50% of the wetlands in the conterminous United States have been lost. Among the vanished wetlands, 50–60% was lost to rural and urban development and agriculture (Dahl, 1990, 2000, 2005, 2011; Dahl and Johnson, 1991). Consequently, it can be concluded that 25–30% of wetlands has been lost because of rural and urban development as well as agriculture in the conterminous United States, which is roughly equal

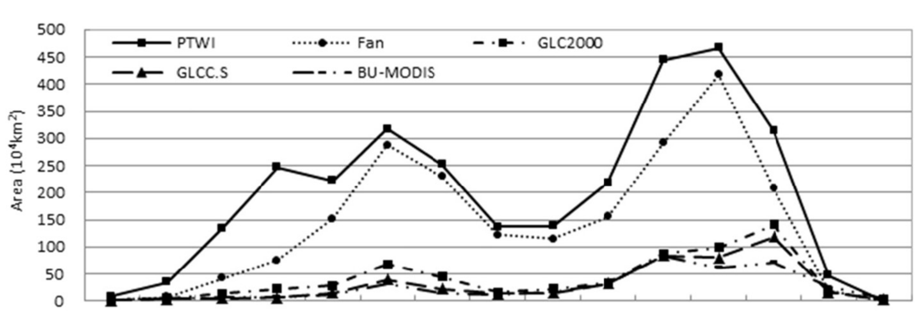

Fig. 3. Latitudinal distribution of global wetland among various global datasets Precipitation Topographic Wetness Index; Fan, Fan and Miguezmacho (2010); GLC2000, the Global Land Cover 2000; CLCC.S, Global Land Cover Characteristics; BU-MODIS, MOD12Q1 V004 Land Cover Data from Boston University.

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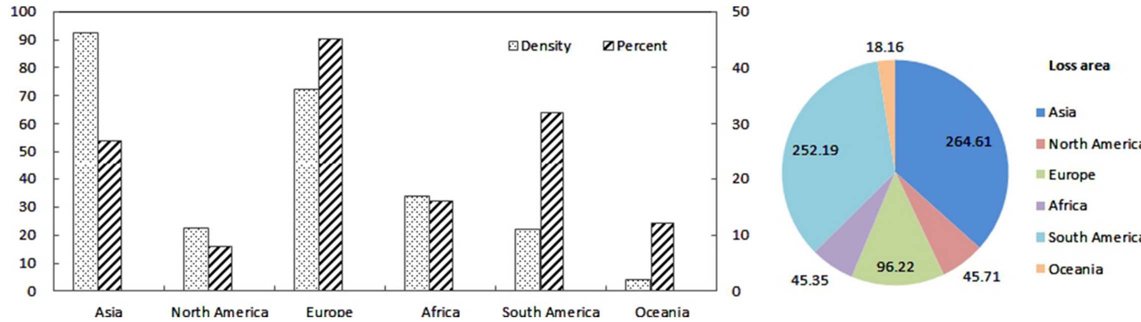

Fig. 4. The percentage of wetland loss and population density among different continents (unit of area: 10^4 km^2).

to the current estimate of 24% for wetland loss in this area. However, the small wetland loss ratio in Canada of 2% causes the low overall wetland loss ratio for North America that was observed in the present paper.

Eurasia is home to 40% of the world's wetlands, while the loss area represents for 50% of the total loss area of global wetlands. Among all areas globally, Europe shows the most serious situation with respect to wetland loss both in the current work and in Davidson's research (Table 4). Of all the continents, Asia has the largest overall area of wetland loss. According to the current estimation, nearly 29% of China's wetlands have been lost due to direct human activity, which is close to the figure cited in a previous study by Niu et al. (2012); that paper stated 33% of China's wetlands had been lost between 1978 and 2008.

Compared with the ratio of wetland loss caused by agriculture, provided by the OECD (1996), the largest difference was observed among areas such as South America and Africa where the estimate made in the current work is notably larger. However, in other areas, such as North America and Asia, the current estimate is similar to that previous estimate (Table 4). It is not possible to support or refute the value given by the OECD in Africa or South America using existing information because the limited number of papers, reports, and inventories available for these two areas leave a dearth of a reliable data on wetland areas and this then leads to uncertainty in assessing wetland loss. However, small-scale studies of these regions have shown alarming ratios of wetland loss. For instance, Taylor et al. (1995) found that the Tugela Basin and the Mfolozi catchment in South Africa lost approximated 90% and 58% of their wetlands, respectively. In South America, Colombia's Cauca River Valley lost 88% of its mapped wetlands between the 1950s and 1980 (Moser et al., 1996). Moreover, according to a 1999 global wetland inventory (Finlayson et al., 1999), wetlands in Africa and South America in tropical and sub-tropical zones have been seeing increasing ratios of loss since the 1950s, alongside their rapid economic development. In this way, the ratio of wetland loss on these two continents may be greater than indicated by the OECD.

3.5. How much wetland remains worldwide?

Theoretically, the area of simulated wetlands minus the wetland loss occupied by human activities, which is 22.61 million km^2, should be equal to the remaining wetland area. However, natural wetland degradation and the transformation of wetlands to grasslands or woodlands, which can be classified into nw-wetland categories in the Globcover2009 dataset, were not included in global wetland loss (Arino et al., 2012). This inevitably causes an underestimation of global wetland loss and overestimated the amount of global wetland remaining. In this way, the figure of 22.61 million km^2 for remaining wetlands may be exaggerated.

Remote sensing can be a useful tool for large-scale mapping of wetlands. However, extensive discrepancies exist among the various satellite-based global wetland-related land-cover datasets (Jung et al., 2006; Giri et al., 2005). Nakaegawa (2012) found that the inconsistency among six 1-km resolution global wetland-related land-cover datasets (GLCC.S, GLCC.I, GLC2000, BU-MOIDS, GLCNMO, and GLWD-3) was >70%. This situation leads to variation in figures for global wetland area, which ranges from 0.29 to 9.78 million km^2 (Friedl et al., 2002; Lehner and Döll, 2004). In this way, none of these global wetland-related datasets alone can reflect the real situation of the world's remaining wetlands.

To understand the possible coverage of remaining global wetlands, the consistency of estimates of the remaining wetlands globally was calculated by synergizing four global wetland-related datasets, GLCC.I, GLC2000, BU-MODIS, and GLWD-3, for which satellite imagery exist dating back to circa 2000. The consistency was defined as the conformity of the same category among various datasets and was calculated pixel by pixel. If a pixel shows identical categories among the four datasets simultaneously, the consistency is 100%; if three datasets indicate the same category in the pixel, the consistency is 75%, and so on. The results show that the possible areal extent of global wetlands could range from 1.53 to 14.86 million km^2 (Table 5). In addition, the inconsistency of the spatial distribution of wetlands among those various satellite-based global land-cover products is prominent. These four datasets simultaneously identified an area as wetland for <8% of the total area.

At the same time, the estimation of global wetlands was between 5.9 and 9.7 million km^2, according to a 1999 global wetland inventory report (Finlayson et al., 1999). In contrast, a study by Tuanmu and Jetz (2014) reported 1.12 million km^2 were covered by regularly flooded vegetation globally and 3.19 million km^2 was water. In that report, the four global land cover products (DISCover, GLC2000, BU-MODIS, and GlobCover2005) were integrated using a generalized classification scheme and an accuracy-based integration approach. Prigent et al. (2007) provided another important study of global inundation based on satellite data for global wetlands, in which global inundated area ranged from 2.12 to 5.86 million km^2.

At present, providing an accurate and acceptable figure related to the areal extent of wetlands on a global scale is very difficult based on currently available information. However, those previous efforts could help outline the sketch of a global wetland map. Given the important role of wetlands in biodiversity and ecosystem modeling, global wetland thematic mapping is urgently needed and necessary.

Table 4
A comparison of wetland loss ratio of continents among various studies and reports.

Continent	Current work	OECD (1996)	Davidson (2014)
Period	Until 2009	Until 1985	Long-term average
World	33%	50%	54–57%
Asia	27%	27%	45%
Africa	16%	2%	4%
Europe	45%	56–65%	56%
North America	8%		56%
South America	32%	6%	–
Oceania	18%	–	44%

4. Summary and conclusions

A new topographic wetness index, PTWI, was proposed here based on CLTI. The evaluation result of these two indices in wetland prediction shows that the PTWI was in better agreement with the observed

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Table 5
The possible coverage of remaining wetland (unit of area: million km^2).

Type	Consistency	Area
Nw-wetland	25%	11.85
	50%	1.50
	75%	0.14
	100%	0.01
	Total	13.05
Water	25%	3.01
	50%	1.16
	75%	0.73
	100%	1.52
	Total	6.42

Note: Nw-wetland indicates non-water wetlands.

wetland and was better able to predict the general spatial pattern and extent of wetlands at global scale. The potential distribution of global wetlands was simulated based this new index and indicates approximately a total of 29.83 million km^2 of wetlands exist worldwide, including 11.41 million km^2 of water and 18.42×10^6 km^2 of nw-wetland. These wetlands were mainly distributed in Asia, North America, and South America. The accuracy validation was reviewed in China, the conterminous United States and Europe. The overall accuracy and kappa coefficient were 69% and 0.5, respectively.

A comparison against global wetland-related datasets indicated that our simulation result could capture the most prominent features of global wetland distribution and that wetlands were mainly distributed in the tropics and the middle-high latitude of the northern hemisphere. The comparison against Fan's result suggests that these two simulation results are similar both in spatial distribution and areal extent which are larger than wetland-related datasets because human influences are not considered. Some discrepancies were observed in South America (10°S–30°S) and North America (40°N–50°N). These might have occurred because limited observations of ground water were available and because of the difficulty of identifying wetland samples in those areas.

Unlike the previous estimates of global wetland loss, the global wetland loss estimated here could be 33%, which could be an underestimation because natural factors were not taken into consideration. However, analysis shows that, on most continents, this estimation process can indicate the wetland loss that is directly a result of human activity. Europe, Asia, and South America exhibited the most wetland loss. Among them, Europe showed the greatest percentage of wetland loss, 45%, and Asia showed the largest wetland loss by area, about 2.65 million km^2.

Integrating the existing global wetland-related products and reviewing previous studies showed that providing an accurate and acceptable figure related to the areal extent of global remaining wetlands based on current available datasets is difficult. The areal extent of global wetlands could range from 1.53 to 14.86 million km^2. And the inconsistence of the spatial distribution of wetlands among various satellite-based global land-cover products (GLCC.I, GLC2000, BU-MODIS, and GLWD-3) is prominent. In consideration of the importance of wetlands in ecosystem modeling and in relation to climate change, global wetland thematic mapping is urgently needed and necessary.

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References

Arino, O., Ramos Perez, J.J., Kalogirou, V., et al., 2012. Global Land Cover Map for 2009 (GlobCover 2009).
Aselmann, I., Crutzen, P.J., 1989. Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. J. Atmos. Chem. 8, 307–358.
Bartholomé, E., Belward, A.S., 2005. GLC2000: a new approach to global land cover mapping from earth observation data. Int. J. Remote Sens. 26, 1959–1977.
Beven, K., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. Hydrolog. Sci. J. 24, 43–69.
Beven, K.J., 1990. A discussion of distributed hydrological modelling. In: Beven, K.J. (Ed.), Distributed Hydrological Modelling. Springer, Berlin, pp. 255–278.
Dahl, T.E., 1990. Wetlands Losses in the United States, 1780's to 1980's. Report to the Congress, National Wetlands Inventory, St. Petersburg, FL (USA).
Dahl, T.E., Johnson, C.E., 1991. Status and Trends of Wetlands in the Conterminous United States, Mid-1970's to Mid-1980's. 28. US Department of the Interior, Fish and Wildlife Service, Washington, DC.
Dahl, T.E., 2000. Status and Trends of Wetlands in the Conterminous United States 1986 to 1997. US Department of the Interior, Fish and Wildlif Service, Washington, DC.
Dahl, T.E., 2005. Status and Trends of Wetlands in the Conterminous United States 1998 to 2004. US Department of the Interior, Fish and Wildlif Service, Washington, DC.
Dahl, T.E., 2011. Status and Trends of Wetlands in the Conterminous United States 2004 to 2009. US Department of the Interior, US Fish and Wildlife Service, Fisheries and Habitat Conservation.
Davidson, N.C., 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar. Freshw. Res. 65, 936–941.
Dugan, P., 1993. Wetland in Danger: A World Conservation Atlas. Oxford University, London, Oxford.
Fan, Y., Li, H., Miguezmacho, G., 2013. Global patterns of groundwater table depth. Science 339, 940–943.
Fan, Y., Miguezmacho, G., 2010. A simple hydrologic framework for simulating wetlands in climate and earth system models. Clim. Dynam. 37, 253–278.
Finlayson, C.M., 2012. Forty years of wetland conservation and wise use. Aquat. Conserv. Mar. Freshw. Ecosyst. 22, 139–143.
Finlayson, C.M., Davidson, N.C., Spiers, A.G., et al., 1999. Global wetland inventory — current status and future priorities. Mar. Freshw. Res. 50, 717–727.
Friedl, M.A., McIver, D.K., Hodges, J.C., et al., 2002. Global land cover mapping from MODIS: algorithms and early results. Remote Sens. Environ. 83, 287–302.
Giri, C., Zhu, Z., Reed, B., 2005. A comparative analysis of the Global Land Cover 2000 and MODIS land cover data sets. Remote Sens. Environ. 94, 123–132.
Gong, P., Wang, J., Yu, L., et al., 2012. Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data. Int. J. Remote Sens. 34, 2607–2654.
Grabs, T., Seibert, J., Bishop, K., et al., 2009. Modeling spatial patterns of saturated areas: a comparison of the topographic wetness index and a dynamic distributed model. J. Hydrol. 373, 15–23.
Gumbricht, T., 2012. Mapping global tropical wetlands from earth observing satellite imagery. Center for International Forestry Research (CIFOR). Indonesia, Bogor.
Herold, M., Mayaux, P., Woodcock, C.E., et al., 2008. Some challenges in global land cover mapping: an assessment of agreement and accuracy in existing 1 km datasets. Remote Sens. Environ. 112, 2538–2556.
Hess, L.L., Melack, J.M., Affonso, A.G., et al., 2015. Wetlands of the lowland Amazon basin: extent, vegetative cover, and dual-season inundated area as mapped with JERS-1 synthetic aperture radar. Wetlands 35, 745–756.
Homer, C.G., Dewitz, J.A., Yang, L., et al., 2015. Completion of the 2011 National Land Cover Database for the conterminous United States-representing a decade of land cover change information. Photogramm. Eng. Remote. Sens. 81, 345–354.
Infascelli, R., Faugno, S., Pindozzi, S., et al., 2013. Testing different topographic indexes to predict wetlands distribution. Procedia Environ. Sci. 19, 733–746.
Jung, M., Henkel, K., Herold, M., et al., 2006. Exploiting synergies of global land cover products for carbon cycle modeling. Remote Sens. Environ. 101, 534–553.
Köppen, W., Geiger, R., 1930. Handbuch der klimatologie. Gebrüder Borntraeger Berlin, Germany.
Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. J. Hydrol. 296, 1–22.
Loveland, T., Reed, B., Brown, J., et al., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. Int. J. Remote Sens. 21, 1303–1330.
Matthews, E., Fung, I., 1987. Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. Glob. Biogeochem. Cycles 1, 61–86.
Millennium Ecosystem Assessment, M.E.A, 2005. Ecosystems and Human Well Being: Wetlands and Water Synthesis. Washington, DC, USA, Water Resources Institute.
Merot, P., Squividant, H., Aurousseau, P., et al., 2003. Testing a climato-topographic index for predicting wetlands distribution along an European climate gradient. Ecol. Model. 163, 51–71.
Mitra, S., Wassmann, R., Vlek, P., 2003. Global inventory of wetlands and their role in the carbon cycle. Discus. Pap. 18771.
Moser, M., Prentice, C., Frazier, S., 1996. A global overview of wetland loss and degradation. Technical Session B of the 6th Ramsar COP. Brisbane, Wetlands International.
Murphy, P.N., Ogilvie, J., Connor, K., et al., 2007. Mapping wetlands: a comparison of two different approaches for New Brunswick, Canada. Wetlands 27, 846–854.
Nakaegawa, T., 2012. Comparison of water-related land cover types in six 1-km global land cover datasets. J. Hydrometeorol. 13, 649–664.
Navid, D., 2014. International law of migratory species: the Ramsar convention. Dokl. Earth Sci. 455, 296–298.
Niu, Z.G., Zhang, H.Y., Wang, X.W., et al., 2012. Mapping wetland changes in China between 1978 and 2008. Chin. Sci. Bull. 57, 2813–2823.
OECD, 1996. Development Assistance Committee Organisation for Economic Co-Operation and Development. Guidelines for aid agencies for improved conservation and sustainable use of tropical and sub-tropical wetlands.
Prigent, C., Papa, F., Aires, F., et al., 2007. Global inundation dynamics inferred from multiple satellite observation, 1993-2000. J. Geophys. Res. Atmos. 112, 1103–1118.

Ramsar Convention Bureau, 2001. Wetlands values and functions. Ramsar Convention Bureau. Gland, Switzerland.
Rodhe, A., Seibert, J., 1999. Wetland occurrence in relation to topography: a test of topographic indices as moisture indicators. Agric. For. Meteorol. 98, 325–340.
Russi, D., Brink, P.T., Badura, T., et al., 2013. The Economics of Ecosystems and Biodiversity for Water and Wetlands. IEEP, London and Brussels.
Shaw, S.P., Fredine, C.G., 1956. Wetlands of the United States: Their Extent and their Value to Waterfowl and Other Wildlife.
Soukup, T., Büttner, G., Feranec, J., et al., 2016. CORINE Land Cover 2012 (CLC2012). European Landscape Dynamics. CRC Press, pp. 93–99.
Stehman, S.V., 1997. Selecting and interpreting measures of thematic classification accuracy. Remote Sens. Environ. 62, 77–89.
Taylor, A.R.D., Howard, G.W., Begg, G.W., 1995. Developing wetland inventories in southern Africa: a review. Plant Ecol. 118, 57–79.
Tuanmu, M.N., Jetz, W., 2014. A global 1-km consensus land-cover product for biodiversity and ecosystem modelling. Glob. Ecol. Biogeogr. 23, 1031–1045.
Wania, R., Melton, J.R., Hodson, E.L., et al., 2012. Present state of global wetland extent and wetland methane modelling: methodology of a model intercomparison project (WETCHIMP). Geosci. Model Dev. Discuss. 5, 4071–4136.
Zhao, Y., Gong, P., Yu, L., et al., 2014. Towards a common validation sample set for global land-cover mapping. Int. J. Remote Sens. 35, 4795–4814.
Zheng, Y.M., Niu, Z.G., Gong, P., et al., 2015. A database of global wetland validation samples for wetland mapping. Chin. Sci. Bull. 60, 428–434.
Zhu, P., Gong, P., 2014. Suitability mapping of global wetland areas and validation with remotely sensed data. Sci. China Earth Sci. 57, 2283–2292.