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Satellite imagery evidence for a multiannual water level decline in Hulun Lake, China, with suggestions to future policy making responses

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Abstract

Lakes are ecosystems characterised by a substantial vulnerability to climate change. Their geomorphological features mean that they are particularly exposed to extreme events, which are known to put a significant pressure on fauna, flora and human populations. An example of the impacts of climate change on lakes can be taken from Hulun Lake, China, whose water levels have changed over time due to the combined impact of climate extremes and anthropogenic activities. There is a limited amount of literature on Hulun Lake and a perceived need to monitor, document and disseminate information on how water level changes influence such ecosystems. This paper attempts to address the current information needs by reporting on a study, which lists the pressures and stressors Hulan Lake is exposed to and considers the role of policy-making in addressing them. The methods used in this paper and the results obtained may serve the purpose of encouraging similar studies elsewhere.

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Zusammenfassung

Seen sind Ökosysteme, die durch den Klimawandel erheblich gefährdet sind. Aufgrund ihrer geomorphologischen Eigenschaften stellen extreme Ereignisse besondere Risiken für sie dar; Risiken, die auch die Fauna, Flora und Bevölkerung stark unter Druck setzen. Ein Beispiel für die Auswirkungen des Klimawandels auf Seen ist der Hulun-See in China, dessen Wasserspiegel sich aufgrund der kombinierten Auswirkungen von Klimaextremen und anthropogenen Aktivitäten im Laufe der Zeit verändert hat. Es gibt nur wenig Literatur über den Hulun-See und es wird daher als notwendig angesehen, darüber zu informieren, wie sich Wasserstandsänderungen auf solche Ökosysteme auswirken. In diesem Beitrag wird versucht, den aktuellen Informationsbedarf zu decken, indem über eine Studie berichtet wird, in der die Belastungen und Stressfaktoren aufgelistet werden, denen der Hulan Lake ausgesetzt ist. Gleichzeitig wird die Rolle der Politik bei der Bewältigung dieser Probleme diskutiert. Die in diesem Beitrag verwendeten Methoden und die erzielten Ergebnisse können dazu dienen, ähnliche Studien an anderer Stelle zu fördern.

Keywords Hulun Lake, climate extremes, anthropogenic disturbance, climate policy

1. Introduction

Lakes or lake regions in different geographical areas can display different responses to external forcings. Therefore, an understanding of how lakes respond is essential for the management of their water resources and related ecosystem services (*Bracht-Flyr* et al. 2013). The water level is a commonly used proxy to indicate the change of lakes (*Zohary* 2011; *Han* et al. 2016). Lake water levels are dependent on the balance between inflow (i.e., precipitation, river inflow, discharge from communities and industries, and seepage) and outflow (i.e., evaporation, groundwater percolation, withdrawals, and river outflow) (*Duan* and *Bastiannssen* 2013). For most lakes, it is not feasible to compute water level fluctuations from all these flows and their associated uncertainties. Thus, direct measurements of water level as an integrative response variable are necessary.

Traditionally, water levels in lakes are measured based on data from in-situ gauging stations installed near or within the lakes. However, many lakes are never gauged, and even in places where gauging stations exist, measured data are not always freely available to other institutions and the public, especially in China (*Li* et al. 2017). Currently, advanced remote sensing techniques are widely used to monitor water levels in lakes in remote areas where the gauging conditions are full of challenges. Landsat data is often used to establish the depth of water, a water balance model is employed, or the water surface area changes are analyzed (*Sun* 2010). ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) (*Wang* 2012a) is used to measure the elevation of a lake surface, and JASON-1 altimetric is the only satellite providing radar and laser altimetry data to analyze the water level variations of lakes (*Chu* 2005). However, these kinds of remote sensing data have a relatively low spatial resolution, compared to the average size of a GLAS (Geoscience Laser Altimeter System) footprint, which is 70 m. ICESat (Ice, Cloud, and land Elevation Satellite)/GLAS signals, with small spatial resolution and high precision measurements, are available for both large lakes and small, narrow lakes (*Li* 2011a, *Duan* and *Bastiannssen* 2013), and are extensively applied in lake water level research (*Zhang* et al. 2011, *Wang* et al. 2013, *Priyeshu* 2013; *Li* et al. 2017). Cross-validation of lake levels between ICESat and in-situ measurements in January from 2003 to 2009 of Bosten Lake (*Ye* et al. 2017) and in May from 2006 to October 2009 (*Li* 2011a) of Jason Lake were made, and the results are that maximum water levels differ by no more than 5 cm with correlation coefficient r as high as 0.990 and 0.996, respectively. A similar cross-validation was also made in Lake Qinghai using ICESat derived elevation data and in situ measurements of water level at Xiashe station, which yielded a correlation coefficient r as high as 0.93 (*Chu* et al. 2014). The above analysis indicates that data derived from ICESat can accurately measure small changes in water level.

Other researchers have found that lakes are very sensitive to climatic changes, both historically and recently (*Sene* et al. 2001; *Jonathan* et al. 2015). The pressure lakes are subject to, reiterate the need to develop their resilience towards sustainability (*Souza* et al. 2017). Among the different climatic factors, temperature, precipitation, and evaporation exert the most significant influence on lake water levels (*Yan* and *Zheng* 2015). But despite its importance, there are few studies (e.g. *Huang* and *Chen* 2012), which considered the influence of climate extremes in lakes. Thus, this paper lists the main issues that Hulun Lake is exposed to and considers the role of future policy-making in addressing the stressors of the water body and the wetlands around Hulun Lake. It was however not the aim of this paper to investigate the influence of climate extremes in lakes on an empirical basis, but the inclusion of this important aspect in the considerations must be made in policy-making.

2. Hulan Lake: a case study on water resources management

As other countries, China has many lakes. Hulun Lake is one of the ten largest Chinese lakes, as shown in *Table 1* (*Zhang* et al. 2013). In total, their area is more than 20,000 km^2. These lakes are critical for China, owing to the social, ecological, and environmental benefits they provide to the country's 1.3 billion residents (*Zhang* et al. 2013). While water levels rise and fall, changes in the natural environment and the impact of human activities can cause huge changes in lake area.

Hulun Lake (116°58'–117°48'E and 48°31'–49°20'N), is the fifth largest inland lake in China. In the 1980s and 1990s, the lake level fluctuated between 544 m and 545 m (above sea level-ASL) with the maximum water depth ranging between 7 and 8 m (*Li* et al. 2007). The climate is semi-arid continental due to the Great Xingan Mountains shielding moist air from the ocean in the east and the Mongolian Plateau in the west. Around Hulun Lake, the average annual temperature is ranging between –21.2 °C and 20.3 °C and annual precipitation ranges between 247 and 319 mm, and more than 80 % of it falls from June to September. Annual evaporation reaches 1400 to 1900 mm, which is five to six times the annual precipitation (*Zhai* et al. 2013).

Hulun Lake is a tectonic lake consisting of a relatively large water body and its surrounding wetlands and lies in an inland graben basin in Hulun Buir, in the northeast of the Inner Mongolia Autonomous Region of China. It has an area of 2,038 km^2 (*Fig. 1*) and a mean depth of 5-6 m, which makes it the home to hundreds of thousands of people of diverse nationalities and millions of domestic animals. For example, the lake is the habitat for 241 bird species, including crane, gull, swan, wild goose, duck, and lovebird, and accounts for one-fifth of the total bird species in China (*Li* et al. 2017). Since some of the species are rare, the lake is considered as one of the few remaining treasure houses of birds in the world. The biodiversity here preserves a rich variety of biological species and is a valuable gene pool (*Yang* et al. 2015). Thus, Hulun Lake plays an important role when keeping biodiversity and enriching biological resources (*Han* and *Yang* 2002). Moreover, it was also said that Hulun Lake can adjust and impound floods. Thus, its ecological and social benefits making Hulun Lake indispensable to the development not only of agriculture and animal husbandry, but also of community and industry (*Han* and *Yang* 2002). All of these indicate that Hulun Lake plays a significant role in the regional environmental protection and is a unique research object. Thus, research about the large lake, Hulun, is necessary.

It should be noted that Hulun Lake has an important economic and social value, also because hundreds of thousands of people directly or indirectly depend on it for their subsistence or use of the ecosystem services it provides. Due to its vast area and economic and geopolitical issues, the limited spatial distribution of hydrological gauges is often the main limita-

Table 1 The ten greatest lakes in China. Source: adopted from Zhang et al. (2013)

Name	Longitude (°)	Latitude (°)	Area (km^2)	Region/Province
Bosten Lake	86.72~87.43	41.82~42.10	919	Xinjiang
Hulun Lake	116.97~117.79	48.58~49.33	1181	Inner Mongolia
Hongze Lake	118.20~118.87	33.07~33.63	1514	Jiangsu
Nam Co	90.24~91.04	30.50~30.92	2018	Tibet
Selin Co	88.52~89.35	31.54~32.12	2178	Tibet
Tai Lake	119.88~120.58	30.92~31.55	2314	Jiangsu
Dongting Lake	112.4~113.15	28.74~29.54	2623	Hulan
Poyang Lake	115.79~116.75	28.34~29.75	3289	Jiangxi
Xingkai Lake	131.97~132.85	44.52~45.34	4106	Heilongjiang
Qinghai Lake	99.62~100.74	36.55~37.23	4165	Qinghai

tion to the availability of adequate or continuous observation data. In addition, small changes to the lake have a significant impact on the surrounding environment. However, knowledge of how the lake responds to external impacts is still incomplete. Thus, this paper lists the main issues that Hulun Lake is exposed to and considers the role of future policy-making in addressing the stressors of the water body and the around wetland of Hulun Lake.

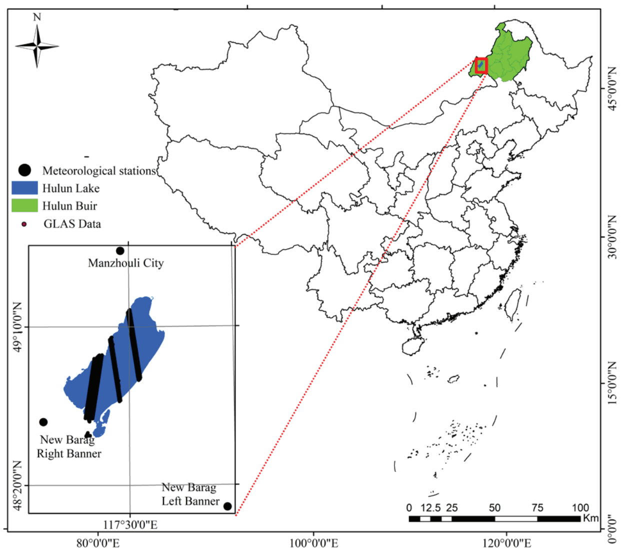

Fig. 1 Profile site of Hulun Lake, Inner Mongolia, China. Source: own drawing

3. Data and methods

3.1 Data sources

The main data sources used to calculate water level and surface area of Hulun Lake was derived from ICESat GLA14 and MODIS, respectively. The paper by *Duong* (2010) provides details on the conversion of the GLA14 data format. The area of Hulun Lake was derived from MODIS MOD09GQ 250 m. The size of each pixel was 250 x 250 m^2. Different algorithms were used, and the results were compared to access the accuracy of calculated water area. In order to reduce bias in water area estimates due to deeper or shallower water, the boundary of Hulun Lake was checked and river remains were removed with the support of Google Earth imagery. GLA14 data within the Hulun Lake boundary were selected to determine the water level. Further details on data processing can be found in *Li* et al. (2017).

3.2 Methods

To understand the complexity of water level and area dynamics in Hulun Lake based on ICESat and MODIS, this paper conducted an integrative approach combining ArcGIS, RANdom SAmple Consensus algorithm (RANSAC) (*Phan* 2012), Lake Boundary methods and Driver-Pressure-State-Impact-Response (DPSI) framework.

3.2.1 Data preprocessing

At first, Normalized Difference Vegetation Index (NDVI) was used to obtain the lake boundary, deeper or shallower areas were checked, and river remains were eliminated with the support of Google Earth. Secondly, ICESat data track was obtained using the way put forward by *Li* et al. (2017) and intersecting its tracks in shapefiles with the NDVI outline polygon shapefile to extract water bodies with ICESat tracks. RANSAC was used to distinguish inliers and outliers and obtain the research data. Finally, water level and area change were analyzed along with their affecting factors.

3.2.2 Obtaining lake boundary and area

The Normalized Difference Vegetation Index (NDVI) is always used to analyze the vegetation, but it also can be used to classify the water body. Water changes are minimal and can be seen as dark pixels in bands 1 and 2, and thus are easily distinguished. Hence, the water body can be obtained via NDVI (*Tian* and *Zhou* 2008).

$$NDVI = \frac{CH\,2 - CH\,1}{CH\,2 + CH\,1}$$

where, CH1 and CH2 stand for the spectral reflectance measurements acquired in the red (visible) and near-infrared regions, respectively.

3.2.3 Selecting ICESat lake water level

ICESat/GLAS altimetry data were used to derive time-series water level variations in Hulun Lake (*Fig. 2*). GLA14 (the global land surface altimetry data) Release 32 was selected for this study. It contains 95 different parameters in a record of different situations.

ICESat data track was obtained based on the way used by *Li* et al. (2017), and each ICESat data track intersecting with the lake (the water boundary mask) and all footprints (water levels) within the lake were carefully extracted to remove the outliers. RANSAC was used to remove the outliers in this research and different footprints required different thresholds.

As a research procedure, the threshold to detect abnormally high standard deviations based on the ICESat footprints was set to 10 cm. Further to this, data on the mean water level of each track passing through Hulun Lake was obtained. Based on this set of data, the variability of water level was calculated in the time span between 2003 and 2009.

4. Results and discussions

4.1 Water level in Hulun Lake and responses to climate extremes

Water levels in Hulun Lake are influenced by climate change. Previous studies have shown that, from 1999 to 2005, the frequency of extremely high temperature was very high in Hulun Lake (*Bai* et al. 2008; *Wang* et al. 2012b). Furthermore, extremely high temperatures (i.e. high-temperature days, warm days and warm nights) showed an increasing trend during the period from 1961 to 2010 (*Bai* et al. 2014), while the regional average frequency of cold days and the temperature of coldest days and nights decreased around Hulun Lake. The corresponding water level and area in Hulun Lake has thus declined (as shown in *Fig. 2*). Therefore, the changes in water level take place in parallel to other climate variations.

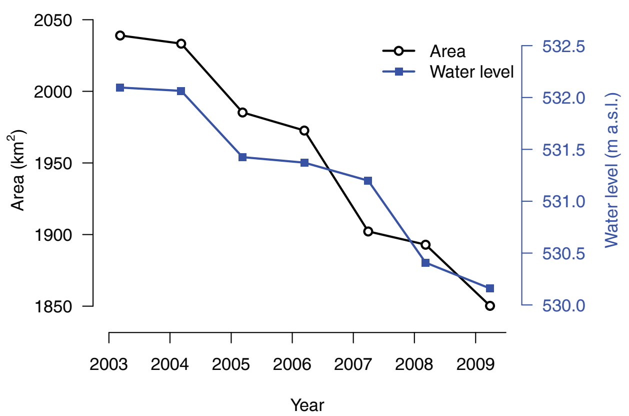

Fig. 2 Changes of Hulun Lake's area and water level in March from 2003 to 2009. Source: own investigations

Some studies also found that average high temperature has a significant negative correlation with the area of Hulun Lake, and when the temperature increases by 1°C, the area of the lake is reduced by 28-80 km^2 each year (*Zhao* et al. 2008). *Zhao* et al. 2008 found a decrease in the water level of 0.424 m/year between 1999 and 2006 and further suggested that the severe drought and lower rain total resulted in the sharp water level decrease. These results demonstrate that the water level of Hulun Lake decreased at a lower rate between 2003 and 2009 (0.33 m/year) than during 1999 to 2006.

Decreased precipitation extremes are another vital factor contributing to the water level decrease in Hulun Lake (*Zhao* et al. 2007). The decrease in water level from 2003 to 2009 could be associated with the corresponding decreasing trend in extreme precipitation events in Inner Mongolia (extreme precipitation, maximum five-day precipitation, and maximum one-day precipitation) reported by *Bai* et al. (2014) for 1961 to 2010. In addition, drought is another causal factor leading to the decrease of water level in Hulun Lake (*Zohary* 2011).

4.2 The effects of anthropogenic factors on the water level in Hulun Lake and a DPSIR framework of Hulun Lake and its surrounding area

The intensive growth of population is a key factor leading to water level decrease, and this trend is also seen in Hulun Lake. It was reported that, from 2000 (181,112) to 2010 (248,472), the population in Manzhouli City has increased by 37.2 %. Hulun Lake is the major regional water source. Its level would decrease quickly due to the increasing requirement of water resources (*Li* and *Ta* 2014). Nevertheless, human activities can also degrade the ecosystem around Hulun Lake by grassland reclamation. In order to satisfy the increasing demand for food of the huge number of people, cultivation land area is to be increased.

Intensive land use has, for instance, led to a decline in lake levels in many regions, with direct impacts on lake hydrology, ecology and ecosystem services (*Torabi* and *Kløve* 2015). The eco-environment in this region was damaged severely, which contributed to the surface water decrease and ultimately influenced the water level change in Hulun lake.

Apart from the water level causal factors (*Table 2*), Hulun Lake suffers from a variety of other stressors. Based on the literature review, the DPSIR framework of water body and the wetland around Hulun Lake was completely established (*Fig. 3*). Special location with high elevation and dry climate are regarded as the natural viewpoint in the DPSIR, and fluctuations in human population and livestock are considered as anthropogenic factors, together with weak management of the lake and a mine plant. Together, these factors are seen as the most important driving forces of water body and the wetland around Hulun Lake change. The resulting scarcity of arable land, lack of alternative livelihoods, demand for food, and tourism leads to conversion of the wetland to farmland or settlement area. Over-fishing and food production, desertification, greenhouse gas emission and pollution of the water body and the wetland around the lake are thus the most important pressures on Hulun Lake and its surrounding area. These results in the following changes: lake problems (decreased water level, area and volume, salinization, water eutrophication, habitat degradation for fish and other aquatic organism abundance), air quality problems (atmospheric nitrogen and phosphorus inputs) and land problems (soil erosion, decreased land production, increased soil nitrogen, phosphorus and metal concentrations). The impact on wetland ecosystem services are as follows: reduced fish and other aquatic organisms and the potential of cultural and ecosystem change and declined vegetation production.

Table 2 Impacts of anthropogenic activities on the water level and water quality of Hulun Lake. Source: own investigations

Impacts	Consequences
Reduction in water levels	Impacts on economic activities such as irrigation, fishing, transport
Release of pollutants	Contamination of the water and aquatic fauna and flora
Increased agriculture	Greater water demand
Overfishing	Depletion of fish stocks
Intensive water transportation	Increase release of pollutants

The responses of water body and the wetlands around Hulun Lake may include:

- strategies for lake protection (integrated water and nutrient management, water transfer from the other place to here; risk assessment of the lake).
- strategies for wetland sustainable development (protection of ecosystem; creation of a database and improvement of the monitoring technology).
- strategies for land conservation (resources and land management; developing environment-friendly tourism).

5. The role of policy-making in reducing the vulnerability of Hulun Lake and its surrounding area

The combination of effects of climate extremes and human-induced stressors made the responses of Hulan Lake more complicated as none of these changes operated in isolation. However, it is certain that these factors will create increasing hazards to water level change in semi-arid and arid areas. Scientific interdisciplinary approaches to early warning systems can address some of these uncertainties, provided a good baseline and time series information are available. Thus, developing monitoring technologies for the water level of Hulun Lake is necessary and urgent. Remote sensing data to monitor water level change in Hulun Lake are useful and highly recommended, especially ICESat data. For Hulun Lake, protecting and making full use of resource endowment should be combined and incorporated in regional planning. For the vulnerability of the buffer zone around Hulun Lake, planting forage is a good choice. It does not only help to reduce land erosion and desertification, but also assist in reducing the pressures seen in respect of land use.

Based on the above, policy-making can play a key role in reducing the vulnerability of Hulan Lake to climate change. In particular, the following measures should be considered:

a) put greater emphasis on climate change adaptation as part of the efforts to reduce vulnerability.
b) take account of current and future use of the areas in future decision-making.
c) foster increased collaboration among the many social actors to enhance the effectiveness of individual activities and reach synergies.
d) support initiatives, which, apart from supporting measures to upkeep the physical environment, foster community resilience.
e) encourage the engagement of local institutions, private landowners and other individuals in natural resource management regarding the stewardship of property.

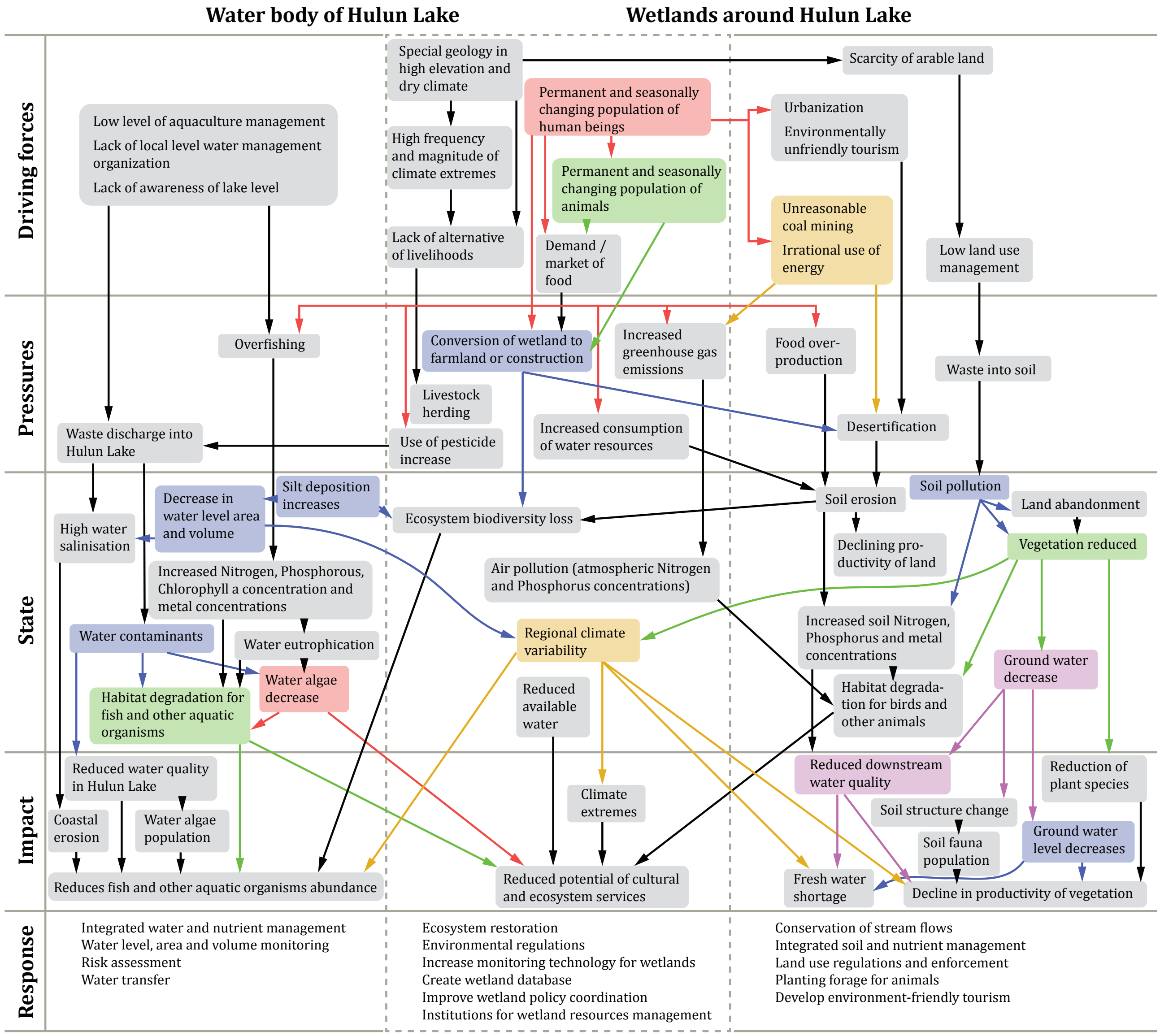

Fig. 3 DPSIR framework of Hulun Lake and its adjacent areas. Source: own summary

Finally, ecotourism around Hulun Lake, the combination of Hulun Lake and nomadic culture in Inner Mongolia, should be further developed by local people, and be supported by policymakers. This can increase the income of local people and help to promote the national culture.

6. Conclusions

This paper has shown the various pressures Hulun Lake is facing, as a result of climate change as a whole, and of extreme events in particular. It also shows evidence based on satellite data that the water level is declining, which may be caused by two main factors: climate extremes and anthropogenic activities. In particular, a combination of elements such as i) increased extreme warm temperatures, ii) decreased cold temperatures (both enhancing evaporation from the lake), and iii) decreased extreme precipitation (reducing the recharge of the lake water body), have contributed to the noticeable water level decreases. These are complemented by drought, which is also known to be among the phenomena leading to the decrease of water level in Hulun Lake. It should be pointed out that these drivers cannot be considered in separate. Rather, they ought to be perceived as combined factors, whose scope and magnitude have been the reasons for the changes in water levels. This is not to say that such changes are exclusive to Hulun Lake: other lakes in China have been experiencing similar problems, whose roots can be traced back to a combination of climate variations and substantial increases in CO_2 emissions, due to an intensive industrialization process.

Attempts to address the current pressures seen at Hulun Lake need to take into account the fact that only by tackling the roots of the problem may lead to long-term improvements. In this context, some measures in policy-making, which may prove useful are:

a) increased monitoring of the water levels so as limit or eventually stop water intensive economic activities, which may exacerbate the pressures seen in the area.
b) more specific – and stricter – regulations in respect of the use of water from the lake in agriculture.
c) the preparation of a well-prepared management plan for Hulun Lake to steer water consumption, reduce the many pressures it currently suffers particularly as it relates to the protection of the wetlands it is associated with, and hence decrease their overall vulnerability.

Finally, it is important that the framework for future policy-making is based on long-term trends and forecasts, as opposed to measures purely based on the current situation. This is to ensure a greater degree of resilience of Hulun Lake and the fauna, flora and human populations, which depend on it.

Acknowledgments

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