Article

Quantifying the Individual Contributions of Climate Change, Dam Construction, and Land Use/Land Cover Change to Hydrological Drought in a Marshy River

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Abstract: Hydrological drought for marshy rivers is poorly characterized and understood. Our inability to quantify hydrological drought in marshy river environments stems from the lack of understanding how wetland loss in a river basin could potentially change watershed structure, attenuation, storage, and flow characteristics. In this study, hydrological drought in a marshy river in far Northeast China at a higher latitude was assessed with a streamflow drought index (SDI). A deterministic, lumped, and conceptual Rainfall–Runoff model, the NAM (Nedbor Afstromnings Model), was used to quantify the individual contributions of climate change, land use/land cover (LULC) change, and river engineering to hydrological drought. We found that in the last five decades, the frequency of hydrological droughts has been 55% without considering LULC change and reservoir construction in this wetland-abundant area. The frequency of hydrological drought increased by 8% due to land use change and by 19% when considering both the impacts of LULC change and a reservoir construction (the Longtouqiao Reservoir). In addition to the more frequent occurrence of hydrological droughts, human activities have also increased drought intensity. These findings suggest that LULC and precipitation changes play a key role in hydrological drought, and that the effect can be significantly modified by a river dam construction.

Keywords: hydrological droughts; climate change; LULC change; wetland loss; reservoir; NAM model; Northeast China

1. Introduction

Hydrological drought is one of the four major types of drought occurrences, alongside meteorological drought, agricultural drought, and socio-economic drought [1,2]. Hydrological drought is a natural hazard defined as a significant deficiency of water availability in a particular period and over a particular area [3,4], caused by multifaceted interactions between climate and catchment processes [5]. Thus, hydrological droughts can have direct impacts on a number of stakeholders, such as irrigation, power generation, and recreational purposes within the affected river basin [6,7]. Understanding hydrological drought and its relationship with climate change, land use change, and river engineering can be helpful for sustainable surface and groundwater water resource management [8].

Several recent studies [9–12] have found that hydrological droughts have sharply increased in both frequency and intensity in many parts of the world due to climate change and/or due to increased water demand caused by population growth and rapid expansion of the agricultural, energy, and industrial sectors. In the most recent decade, increasing attention has been devoted to identifying site-specific hydrological droughts in different basin environments. For instance, Lopes
and others [13] analyzed hydrological drought in the Amazon river basin, and found a significant trend toward more intense droughts in the southern sub-basins. Rimkus and others [14] investigated meteorological and hydrological droughts in the Neman River Basin in east Europe, and reported a close relationship between the two types of droughts. In China, many regions have been found to show a clear increasing trend in the frequency of hydrological drought, for instance, in the Xijiang River Basin [15], the upper Yangtze River basin [9], the Hexi Corridor [16], and the Aksu-Tarim River Basin [17]. Although these studies have provided new insights into site-specific variations in hydrological drought, our knowledge is still limited regarding hydrological droughts of marshy rivers that drain a large area of marsh wetlands into a river basin. According to Acreman and Holden [18], river basins with a large percentage of wetlands could be affected by wetland loss in terms of basin water attenuation, storage, and discharge, therefore, likely changing the frequency and intensity of hydrological drought.

Marshes can be sensitive to hydrological drought [19], and the knowledge about drought occurrence and intensity in marsh landscapes is especially important for sustainable management in marsh-abundant river basins, such as those in the far northeast of China. Located in China’s high-latitude northeast corner, the Naoli River Basin (NRB) is a prime example with a typical marshy river [20] that can be sensitive to climate change and human activities. While air temperature and population growth have increased rapidly in the region in the past five decades, many of the wetlands in the NRB have been converted into agricultural land, making the region one of China’s most important commodity grain production bases today [21]. Surface water is the most used water source for agriculture and public supplies. Recent studies have reported that streamflow from the NRB has been decreasing over the past 50 years [22,23], raising concerns about the long-term sustainability of water availability in this area. It is not clear whether or how the change may have caused hydrological droughts of the river, and what main factors may have been the cause. Hence, this study aims to investigate long-term discharge of the marshy Naoli River and its response to the region’s climate and land use changes. Specifically, the study aims to: (1) Quantify long-term changes of hydrological droughts in the headwater area of the Naoli River, and (2) separate the individual contributions of climate variation, land use/land cover (LULC) change, and a river dam construction to the hydrological droughts of this area.

2. Materials and Methods

2.1. Study Area

The Naoli River (NR) drains a total land area of approximately 24,200 km², geographically extending from Lat 45°43’ N to Lat 47°35’ N and from Long 131°31’ E to Long 134°10’ E (Figure 1). The climate of this higher-latitude region can be characterized as temperate humid and semi-humid continental monsoon, with a long-term annual average temperature of 3.5 °C and a long-term annual average precipitation of 518 mm, 60%–72% of which falls during May and September. The Naoli River Basin used to have a large area of wetlands, but a majority of the wetlands (about 80%) were converted into agricultural farmland during the past half century. The wetland coverage in this area decreased from 45.8% in 1954 to 9.8% in 2010, while the area’s farmland coverage increased from 8.2% to 58% during the same period (Table 1) [20].
The headwater area of the NR, upstream of the Baoqing hydrological station (Figure 1), was chosen for this study. The headwater area has a total drainage area of approximately 3767 km$^2$, providing crucial water resources for the downstream wetlands. In 2002, a 750 m long, 25.7 m tall dam across the river was completed, creating a reservoir known as the Longtouqiao Reservoir, with a maximum storage capacity of 615 million m$^3$. The reservoir receives discharge from the uppermost 1730 km$^2$ of the NRB (Figure 1), causing an immediate streamflow change downstream [24,25].

### 2.2. Change Point Detection and Division of Sub-Periods

In order to separate the individual contributions of climate change and human activities to streamflow changes that occurred from 1961 to 2014, we made a time separation of the 54-year study period by testing a changing point of annual streamflow in the river basin using the Mann–Kendall method [26–28]. The significance of a change was verified at the $\alpha = 0.05$ level, with rejection of the null hypothesis of no trend if $|Z| > 1.96$ [29,30]. Additionally, the year of 2002 was also considered separately in the time separation because of the Longtouqiao Reservoir construction. Based on the change point detection and the reservoir building, we divided the 54-year study period into three sub-periods: (1) 1961–1966, when the area had little in the way human activities; (2) from 1967 to 2001, during which time-intensive LULC change occurred; and (3) after 2002, when the dam construction was completed.

### 2.3. Impacts of Climate Change and Human Activity on Streamflow

In this study, we used a slope change ratio of cumulative quantity (SCRCQ) to quantify the contribution of climate change and human activities to the streamflow change [31,32]. Climate change...
was represented by precipitation and potential evapotranspiration (PET) changes, while human activities were represented by land use/land cover change and the Longtouqiao Reservoir construction. The slope of the linear relationship between the year and cumulative streamflow before and after the changing year was assumed to be \( S_{Sb} \) and \( S_{Sa} \) (10^8 m^3/year), respectively. The slope of the linear relationship between the year and cumulative precipitation before and after the changing year was \( S_{Pb} \) and \( S_{Pa} \) (mm), respectively. The streamflow variation ratio and precipitation variation ratio were expressed as \((S_{Sa} - S_{Sb})/|S_{Sb}|\) and \((S_{Pa} - S_{Pb})/|S_{Pb}|\), respectively. The contribution of precipitation (\( C_P \), unit: \%) to streamflow variation after the changing year was quantified as follows:

\[
C_P = \left( \frac{S_{Pa} - S_{Pb}}{S_{Sa} - S_{Sb}} \right) \times \frac{S_{Sb}}{S_{Pb}} \times 100\%
\]  

(1)

Similarly, the slope of the linear relationship between the year and cumulative PET before and after the changing year was assumed to be \( S_{Eb} \) and \( S_{Ea} \) (mm), respectively. The variation ratio of PET can be expressed as \( (S_{Ea} - S_{Eb})/|S_{Eb}|\). Therefore, the contribution of PET (\( C_E \), unit: \%) to streamflow variation after the changing year was determined by:

\[
R_{SE} = -\left( \frac{S_{Ea} - S_{Eb}}{S_{Sa} - S_{Sb}} \right) \times \frac{S_{Sb}}{S_{Pb}} \times 100\%
\]

(2)

Based on the water balance, the contribution of human activities (\( C_H \), unit: \%) to the streamflow variation was expressed as:

\[
C_H = 1 - C_P - C_E
\]

(3)

Based on Equations (1) and (2), the individual contributions of LULC (\( C_{LULC} \), unit: \%) and the Longtouqiao Reservoir (\( C_{Res} \), unit: \%) to streamflow variation were estimated by:

\[
C_{LULC} = P_{LULC} \cdot C_H
\]

(4)

\[
C_{Res} = P_{Res} \cdot C_H
\]

(5)

2.4. Hydrological Model

(1) Model Introduction

In this study, we used a deterministic, lumped, and conceptual Rainfall–Runoff model, the NAM (Nedbor Afstromnings Model), to simulate streamflow for the headwater area of the NR. The model is part of the Mike Basin software package developed by the Danish Hydraulic Institute (DHI) in Denmark, and has been widely used for different geographical regions in the world [33–38]. The model uses time series of precipitation and evapotranspiration as input, and estimates the rainfall–runoff process using the linkage rule between the four different storages, which are connected together; each is the representative of different physical specifications (Figure 2). These four storages are snow storage, surface water storage, root zone storage, and groundwater storage. However, in this study, snow storage was not used due to a lack of corresponding monitoring data. The NAM was prepared with nine parameters (Table 2) representing the rest of the storage types. More details on the NAM can be found in the “MIKE Hydro” Reference Guide [39].
Figure 2. Structure of the Nedbor Afstromnings Model (NAM) rainfall–runoff model (DHI 2016).

Table 2. Model parameterization for the NAM rainfall–runoff model.

| NAM Parameters | Parameters Descriptions                                | Units | Value Ranges        |
|----------------|--------------------------------------------------------|-------|---------------------|
| Umax           | Maximum water content in surface storage               | mm    | 10–30               |
| Lmax           | Maximum water content in root zone storage              | mm    | 50–250              |
| CKIF           | Time constant for routing interflow                    | h     | 300–1000            |
| CQOF           | Overland flow runoff coefficient                        | —     | 0.1–1               |
| CK1,2          | Time constants for routing overland flow               | h     | 3–50                |
| TOF            | Root zone threshold value for overland flow             | —     | 0.1–1               |
| TIF            | Root zone threshold value for interflow                 | —     | 0.1–1               |
| TG             | Root zone threshold value for groundwater recharge      | —     | 0.1–1               |
| CKBF           | Time constant for routing base flow                     | h     | 200–5000            |

(2) Data Input

The basic input data for the NAM model included the catchment boundary conditions and meteorological data, such as precipitation and potential evapotranspiration. In this study, we collected (1) DEM (Digital Elevation Model) data for this region from the Chinese Geospatial Data Cloud (http://www.gscloud.cn) to set up spatial boundary parameters, (2) daily precipitation, as well as daily air temperature, humidity, and radiation data from the Baoqing weather station for estimation of potential evapotranspiration, (3) discharge records from the Baoqing hydrological station for model calibration and validation, and (4) LULC data, which was collected by remote sensing interpretation, as well as from previous studies [20,23–25,36,37].

(3) Calibration and Validation of the Model

We calibrated and validated the NAM model for two periods: 1967–2014 and 2002–2014, that is, prior to and after the Longtouqiao Reservoir construction, in order to quantify the river engineering effect on streamflow. The model performance for the calibration and validation was assessed using the Nash–Sutcliffe efficiency ($E_{NS}$) [39], as follows in Table 3.

Table 3. Illustration of Nash–Sutcliffe efficiency ($E_{NS}$).

| Nash-Sutcliffe Efficiency | Poor | Good | Excellent |
|--------------------------|------|------|-----------|
| $E_{NS}$                 | $(-\infty, 0.36]$ | $[0.36, 0.75]$ | $(0.75, +\infty)$ |
(4) Performance of the NAM Rainfall–Runoff Model

The NAM was first calibrated with the meteorological and streamflow data from 1961–1964 (Figure 3a), and the observed streamflow in 1965–1966 (Figure 3b) was used for validating the model. The results during the periods of calibration and validation were assessed using $E_{NS}$ (Table 4). The natural streamflow without the impacts of human activities during 1967–2014 ($Q_{S1}$) was simulated with the calibrated parameters (Table 5). Similarly, the NAM model was then calibrated using the meteorological and streamflow data from 1967–1986 (Figure 4a) and validated with the data from 1987–2001 (Figure 4b). Based on the calibrated parameters, the streamflow without the impact of the Longtouqiao Reservoir during 2002–2014 ($Q_{S2}$) was simulated (Table 5).

![Figure 3](image1.png)

**Figure 3.** (a) Observed and simulated streamflow during the calibration period (1961–1964) and (b) the validation period (1965–1966) in the headwater area of the Naoli River in Northeast China.

**Table 4.** Evaluation of the NAM’s performance in the calibration and validation periods based on the Nash–Sutcliffe efficiency ($E_{NS}$).

| Periods   | $E_{NS}$ | Periods   | $E_{NS}$ |
|-----------|----------|-----------|----------|
| 1961–1964 | 0.954    | 1967–1986 | 0.904    |
| 1965–1966 | 0.899    | 1987–2001 | 0.821    |

Note: "#" means the calibration, "*" means the validation.

![Table 5](image2.png)

**Table 5.** Selected values of the NAM parameters during the calibration and validation periods.

| Periods   | $U_{max}$ | $L_{max}$ | $CQOF$ | $CQIF$ | $CK_{1,2}$ | $TOF$ | $TIF$ | $TG$ | $CKBF$ |
|-----------|-----------|-----------|--------|--------|------------|-------|-------|------|--------|
| 1961–1966 | 25.2      | 55.5      | 0.62   | 435.8  | 38.5       | 0.735 | 0.451 | 0.573| 302.4  |
| 1967–2002 | 10.1      | 99.8      | 0.11   | 387.6  | 23.3       | 0.414 | 0.426 | 0.767| 997.7  |

![Figure 4](image3.png)

**Figure 4.** (a) Observed and simulated streamflow during the periods of calibration (1967–1986) and (b) validation (1987–2001) in the headwater area of the Naoli River in Northeast China.
Comparing the simulated streamflow using NAM with the observed streamflow, it was found that the cumulative streamflow, impacted by LULC change and the Longtouqiao Reservoir, has obviously declined (Figure 5).

![Graph of accumulated streamflow](image)

**Figure 5.** Contrast of observed and simulated accumulation of streamflow flowing into wetlands in the Naoli River, Northeast China.

### 2.5. Analysis of Hydrological Drought

A number of drought indices have been presented over the past decades to distinguish and quantify drought events [40]. These include the Surface Water Supply Index [41], the Standardized Precipitation Index (SPI) [42], the Standardized Precipitation Evapotranspiration Index (SPEI) [43], the Reconnaissance Drought Index (RDI) [44], the Rainfall Anomaly Index (RAI) [45], the Standardized Palmer Drought Index (SPDI) [46], and the Streamflow Drought Index (SDI) [47]. Information on hydrological drought indicators is important for the design and operation of many sectors that serve society and the economy, including public water supply, irrigation, energy, navigation, and industry [1]. As such, there is an urgent need to advance hydrological drought research and operational applications. In this study, the hydrological drought was assessed by using the Streamflow Drought Index (SDI) developed by Nalbantis and Tsakiris [47], because this index (SDI) can fully represent the conditions of hydrological drought in the river.

We calculated SDI series (SDI-12) with a running series of monthly observed and simulated streamflows in a 12-month interval. Application of this approach was mainly due to the fact that a mild drought or a dependent drought can be removed or combined into larger independent drought events at such a time scale [48]. Moreover, there have been studies showing that the ability of the many drought indices, using a 12-month time interval, to recognize an anomaly in hydrological variables is much stronger than on a short time scale [9,49]. By comparing the observed SDI-12 with the simulated SDI-12, the impacts of climate change and human activities on the hydrological drought were identified. Based on the SDI, hydrological droughts can be divided into five levels (Table 6).

| Interpretation | Non-Drought | Mild Drought | Moderate Drought | Severe Drought | Extreme Drought |
|----------------|-------------|--------------|------------------|----------------|-----------------|
| SDI            | [0, +∞)     | [-1, 0]      | [-1.5, -1]       | [-2, -1.5]     | (-∞, -2)        |

In this study, the frequency of hydrological droughts was also used for quantifying the impacts of climate change and human activities on hydrological droughts. This can be calculated using the following formulas:

\[ P = \frac{n}{N} \]  \hspace{1cm} (6)
where \( P \) is the frequency of hydrological droughts, \( n \) is the number of samples of hydrological droughts, and \( N \) is the total number of statistical samples.

Due to human activity being relatively simple in this region, only LULC and reservoir construction were included. Based on the results of the NAM model, the individual contributions of LULC change and the Longtouqiao Reservoir to the changed volume of streamflow caused by human activities can be calculated as follows:

\[
P_{\text{Res}} = \frac{Q_{S2}(2002–2014) - Q_{O}(2002–2014)}{Q_{S1}(2002–2014) - Q_{O}(2002–2014)}
\]

\[
P_{\text{LULC}} = 1 - P_{\text{Res}}
\]

where \( P_{\text{LULC}} \) and \( P_{\text{Res}} \) are the contributions of LULC change and the Longtouqiao Reservoir construction to the changed volume of streamflow, respectively; \( Q_{O}(2002–2014) \) is the observed annual average streamflow of 2002–2014; \( Q_{S2}(2002–2014) \) is the simulated annual average streamflow without the impact of the Longtouqiao Reservoir during 2002–2014; and \( Q_{S1}(2002–2014) \) is the simulated annual average streamflow without impacts of both LULC change and the Longtouqiao Reservoir construction during the period of 2002–2014.

3. Results

3.1. The Characteristics of Streamflow Change

(1) Long-Term Streamflow

We found that the change point of streamflow occurred in 1966 (Figure 6). The 54-year study period was divided into three series: 1961–1966, when minimal human activities were occurring, 1967–2001, when major LULC change occurred, and 2002–2014, when the Longtouqiao Reservoir was built. The period of 1961–1966 was used as the baseline period, while the variability of streamflow and hydrological droughts impacted by climate change and human activities during the 1967–2001 period and 2002–2014, respectively, were analyzed. It was found that, compared with 1961–1966, the annual streamflow decreased by 38.8% (8.5 m\(^3\) s\(^{-1}\)) in 1967–2001 and 48.5% (10.6 m\(^3\) s\(^{-1}\)) in 2002–2014, respectively, and the long-term trend in the streamflow was decreasing from 1961 to 2014 (Figure 7).

![Figure 6. Change point detection of streamflow with the Mann–Kendall method for the upper Naoli River in Northeast China (UF is the forward sequence curve and UB is the inverted sequence curve).](image-url)
During the period of 2002–2014, the annual average streamflows ($\bar{Q}_{0}(2002–2014)$, $\bar{Q}_{S1}(2002–2014)$, $\bar{Q}_{S2}(2002–2014)$) were simulated using the NAM (Table 7). The contributions of LULC change and the Longtouqiao Reservoir construction to the changed volume of the streamflow caused by human activities were simulated with Equations (1) and (2), respectively (Table 6). The results showed that the streamflow, once affected by human activities, decreased by 5.9 m$^3$ s$^{-1}$ when compared with the natural streamflow ($\bar{Q}_{S1}(2002–2014)$), and the contributions of LULC change ($P_{LULC}$) and the Longtouqiao Reservoir ($P_{Res}$) to this change were 38.3% and 61.7%, respectively.

Table 7. Contrast in the observed and simulated streamflows and the contributions of LULC change/Longtouqiao Reservoir to the change of annual average streamflow caused by human activities during 2002–2014.

| Periods          | $\bar{Q}_{0}(2002–2014)$ (m$^3$ s$^{-1}$) | $\bar{Q}_{S1}(2002–2014)$ (m$^3$ s$^{-1}$) | $\bar{Q}_{S2}(2002–2014)$ (m$^3$ s$^{-1}$) |
|------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 2002–2014 P (%)  | 11.3                                     | 17.2                                     | 14.94                                    |
|                  |                                          | 38.3 *                                   | 61.7 *                                   |

Note: *" denotes the contribution of LULC change and #" denotes the contribution of the Longtouqiao Reservoir during 2002–2014.

The fitted linear relationships between the year and observed cumulative streamflow during 1961–1966, 1967–2001, and 2002–2014 are shown in Figure 8. As shown in Figure 9, all of the relationships have high correlation coefficients above 0.98. The corresponding slopes ($S_{R}$) are listed in Table 8. Compared with the 1961–1966 period, the change rates of the slopes of the accumulative streamflow ($R_{SR}$) during 1967–2001 and 2002–2014 were calculated with Equation (3) (Table 9). According to Table 9, the slopes of the linear relationships of the accumulative streamflows decreased by $3.34 \times 10^8$ and $4.12 \times 10^8$ m$^3$ yr$^{-1}$ during 1967–2001 and 2002–2014, respectively, when compared with the baseline period. The decreasing ratios were 44% and 54.3% during 1967–2001 and 2002–2014, respectively.
The slope change rates of the accumulative precipitation (\( 2020 \), with an increase of ratios of 5.6% and 6.5%, respectively. The slope of the linear relationship of the accumulative PET increased by 37.28 mm during 1967–2001 and 43.51 mm during 2002–2014. The decreasing ratios were 15.4% and 17.6%, respectively. The slope of the linear relationship of the accumulative precipitation decreased by 91.46 and 104.69 mm, respectively, during 1967–2001 and 2002–2014.

Similarly, the changes in observed cumulative precipitation (\( S_P \)) and PET (\( S_E \)) are shown in Figure 9. It was illustrated that the correlation coefficients are all higher than 0.99 during the three periods mentioned above. The slope change rates of the accumulative precipitation (\( R_{SP} \)) and PET (\( R_{SE} \)) are also listed in Table 8. Compared with the baseline condition, the slopes of the linear relationship of the accumulative precipitation decreased by 91.46 and 104.69 mm, respectively, during 1967–2001 and 2002–2014. The decreasing ratios were 15.4% and 17.6%, respectively. The slope of the linear relationship of the accumulative PET increased by 37.28 mm during 1967–2001 and 43.51 mm during the 2002–2014 period, with an increase of ratios of 5.6% and 6.5%, respectively.

![Figure 8](image-url) Cumulative streamflow in the headwater area of the Naoli River in Northeast China.

![Figure 9](image-url) (a) Cumulative precipitation and (b) potential evapotranspiration.

Table 8. Slopes of the linear cumulative streamflow, potential evapotranspiration (PET) and precipitation, and their change ratios in the headwater area of the Naoli River in Northeast China.

| Periods    | Streamflow | Precipitation | PET |
|------------|------------|---------------|-----|
|            | \( S_R \) (10^8 m³/a) | \( S_{Ra} - S_{Rb} \) (10^8 m³/a) | \( R_{SR} \) (%) | \( S_P \) (mm) | \( S_{Ra} - S_{Rb} \) (mm) | \( R_{SP} \) (%) | \( S_E \) (mm) | \( S_{Ra} - S_{Rb} \) (mm) | \( R_{SE} \) (%) |
| 1961–1966  | 7.59       | —             | —   | 593.77       | —             | —   | 670.71       | —             | —   |
| 1967–2001  | 4.25       | −3.34         | −44.0 | 502.31       | −91.46        | −15.4 | 707.99       | 37.28         | 5.6 |
| 2002–2014  | 3.47       | −4.12         | −54.3 | 489.08       | −104.69       | −17.6 | 714.22       | 43.51         | 6.5 |

Note: “—” means the change ratios are 0 compared with the baseline period.

Table 9. Contributions of climate and human activities to streamflow changes in the headwater area of the Naoli River in Northeast China.

| Periods    | \( C_P \) (%) | \( C_E \) (%) | \( C_{Hi} \) (%) | \( C_{LULC} \) (%) | \( C_{Res} \) (%) |
|------------|---------------|---------------|------------------|-------------------|------------------|
| 1967–2001  | 35.0          | 12.7          | 52.3             | 0                 | 34.4             |
| 2002–2014  | 32.5          | 12.0          | 52.3             | 0                 | 34.4             |
The contribution of climate change and human activities to the change of streamflow was simulated with Equations (3)–(7) (Table 9). The quantitative assessment results showed that both climate change and human activities had a negative effect on streamflow in the headwater area of the NR. For the 1967–2001 period, the contributions of precipitation, potential evapotranspiration (PET), and LULC change were 35%, 12.7%, and 52.3%, respectively. During the period of 2002–2014, the contributions of precipitation, PET, LULC change, and the Longtouqiao Reservoir were 32.5%, 12.0%, 21.1% and 34.4%, respectively.

3.2. The Characteristics of Hydrological Drought Changes

(1) Long-Term Hydrological Drought

Hydrological droughts in the 1961–2014 period were analyzed using SDI for twelve months (SDI-12) (Figure 10). It was found that annual hydrological droughts did not occur during 1961–1966. However, the frequency of hydrological droughts has increased substantially from 1967 to 2014. Successive hydrological droughts have occurred in the following six periods: Two-year droughts in 1967–1968, 1993–1994, and 2011–2012, a three-year drought in 1988–1990, a five-year drought in 1976–1980, and an eleven-year drought in 1998–2009. It is worth noting that severe hydrological droughts were found in 1977, 1979–1980, and 2002, and extreme droughts were found in 1978 and 1993.

(2) Contribution of Climate Change and Human Activities to Hydrological Drought

The SDI-12 was calculated based on the simulated monthly streamflow without LULC and the reservoir during 1967–2014 (Figure 11a) and 2002–2014 (Figure 11b). The frequency of hydrological droughts was calculated with Equation (8), and an obvious increase under the impacts of precipitation and PET over the past 50 years was noted with the effect of human activities. From 1967 to 2001, hydrological drought frequency increased from 53% to 58% under the impact of LULC changes. During the period of 2002–2014, the frequency of hydrological droughts without the impacts of LULC change and the Longtouqiao Reservoir was 55%. It increased to 63% with the impact of LULC change, and eventually increased to 74% when considering both the impacts of LULC change and the Longtouqiao Reservoir (Table 10). In addition to a more frequent occurrence of hydrological droughts, human activities also increased drought intensity. For instance, with the influence of LULC change, the hydrological droughts changed from mild drought to extreme drought in 1978, from mild drought to severe drought in 1979, and from moderate drought to extreme drought in 1993. Meanwhile, the hydrological droughts changed from mild drought to severe drought in 2002 after the Longtouqiao Reservoir started storing the upstream discharge.
4. Discussion

4.1. Streamflow Change of a Marshy River

Several studies have reported a decrease in streamflow in the headwater area of the NR in the past 54 years, and have attributed it to a precipitation decline in the region [22,24,50]. Overall, our findings showed a similar trend in the headwater area of the NR. Climate change plays an important role in streamflow change [51]. Compared with the period of 1961–1966, we found that there was a significant decreasing trend of precipitation in 1967–2001, and moreover, the trend was more obvious in 2002–2014. In addition, PET increased during the above two periods. The combination of these two factors has led to the negative effect of climate change on streamflow.

In addition, the exploitation and utilization of water resources are direct influencing factors for streamflow flowing into wetlands decreasing in the headwater area of the NR [51]. In order to develop the economic potential in the headwater area of the NR, a large amount of land was cultivated
into farmland (Table 1) [24,25]. Farmland increased from 3.5% (1961) to 34% (2001), while forest decreased from 75.6% (1961) to 54.6% (2001) across the entire region. This may have destroyed the natural hydrological environment of the underlying surface, and the rapid development of irrigated agriculture aggravated the exploitation of water resources in the headwater area of the NR. Hydraulic engineering has also had an important role in the decrease of streamflow. Specifically, the trend of streamflow reduction became more obvious after the Longtouqiao Reservoir was built. According to our study, the contribution of reservoirs to streamflow changes may be significantly higher than that of LULC changes. The primary function of this reservoir is to control floods and supply irrigation water. The average amount of water used for irrigation is about $2.2 \times 10^8 \text{ m}^3 \text{ yr}^{-1}$ [25]. The irrigation area is still increasing, and the water supply will therefore likely continue to increase, which may lead to a further reduction in streamflow downstream due to the Longtouqiao Reservoir in the future.

### 4.2. Hydrological Drought of a Marshy River

Hydrological drought of the marshy Naoli River has not been thoroughly investigated in the past. Our findings from this study showed that the frequency of hydrological droughts has been increasing over the past 54 years under the impacts of climate change and human activities. This indicates that the Naoli River Basin has been on a trend towards drier conditions. In order to find the reasons for the increase of hydrologic drought, first of all, we eliminated the influence of human activities using a hydrological model (NAM). The results show that climate change was the main reason for frequent hydrological droughts in the headwater area of the NR. Second, the frequencies of hydrological droughts under the influence of human activities and without human activities were compared, and the results showed that the frequency was exacerbated, but not significantly. However, according to Figure 11, the greatest effect of human activities was that the intensity of hydrological droughts in this marshy river was exacerbated. The frequency of severe drought increased throughout 1967–2014, and extreme drought had occurred in 1978 and 1993. This may be due to increased water demand for irrigation and reservoir storage in dry years, which would exacerbate hydrological droughts downstream of the reservoir. This situation is rather unfavorable for the protection of riparian wetland.

There has been a lot of evidence demonstrating the importance of mitigating hydrological droughts for wetland protection [52–55]. The Naoli River Basin has a large area of wetlands, but most have been converted into farmland in the past half century [20], with the area of wetlands in the headwater area of the NR decreasing from 9.3% in 1961 to 0.8% in 2014. Therefore, the study of hydrological droughts will be beneficial to the protection of the remaining wetlands in the Naoli River Basin.

In spite of the uncertainties and limitations of methods, our study sheds light on the conditions of hydrological droughts in the headwater area of this marshy river, which is critical for the protection of ecosystems of river and wetlands. In addition, we plan to undertake more work on these uncertainties in future studies to improve the quantified results.

### 5. Conclusions

This study is the first to assess the individual contributions of precipitation change, potential evapotranspiration change, land use/land cover change, and a river dam construction to hydrological droughts in a marshy river in far Northeast China at higher latitudes. Based on our results, the following conclusions can be drawn:

1. Climate change, land use change (primarily wetland loss), and river dam construction have all contributed to streamflow decline in this marshy river, with the greatest contribution coming from the dam construction, followed by LULC change and meteorological factors.

2. While the streamflow of the marshy Naoli River continued declining, hydrological drought in the river has occurred more frequently and more intensely since 1967. The frequency of hydrological drought increased most obviously during the period of 2002–2014.
Climate change was the main factor for the increase of drought events, while LULC change and the dam construction contributed to the severity of the droughts. These findings suggest that future water resource management in this and other agriculture-intensive river basins of high-latitude needs to develop effective strategies in reducing river drought occurrence and intensity.

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