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Determining the Frequency of Dry Lake Bed Formation in Semi-Arid Mongolia From Satellite Data

Yuta Demura [1,2], Buho Hoshino [1,*], Kenji Baba [1], Christopher McCarthy [3], Yuki Sofue [4], Kenji Kai [5], Tsedendamba Purevsuren [1], Katsuro Hagiwara [6] and Jun Noda [6]

1 Graduate School of Dairy Sciences, Rakuno Gakuen University, Ebetsu, Hokkaido 069-8501, Japan; demura.yuta@gmail.com (Y.D.); kbaba@rakuno.ac.jp (K.B.); pujee_ts@yahoo.com (T.P.)
2 Field Researchers Corporation Co. Ltd, Sapporo, Hokkaido 060-0007, Japan
3 Graduate School of Global Environmental Studies, Kyoto University, Kyoto 606-8501, Japan; mccarthy.ch@gmail.com
4 Graduate School of Sciences, Chiba University, Chiba 263-8522, Japan; yuki.candy.s126@gmail.com
5 Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan; kai@info.human.nagoya-u.ac.jp
6 School of Veterinary Medicine, Rakuno Gakuen University, Hokkaido 069-8501, Japan; k-hagi@rakuno.ac.jp (K.H.); jnoda@rakuno.ac.jp (J.N.)
* Correspondence: aosier@rakuno.ac.jp; Tel.: +81-011-388-4913

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Abstract: In the Mongolian Plateau, the desert steppe, mountains, and dry lake bed surfaces may affect the process of dust storm emissions. Among these three surface types, dry lake beds are considered to contribute a substantial amount of global dust emissions and to be responsible for "hot spots" of dust outbreaks. The land cover types in the study area were broadly divided into three types, namely desert steppe, mountains, and dry lake beds, by a classification based on Normalized Difference Water Index (NDWI) calculated from MODIS Terra satellite images, and Digital Elevation Model (DEM). This dry lake beds extracting method using remote sensing offers a new technique for identifying dust hot spots and potential untapped groundwater in the dry lands of the Gobi region. In the study area, frequencies of dry lake bed formation were calculated during the period of 2001 to 2014. The potential dry lake area corresponded well with the length of the river network based on hydrogeological characterization (R^2 = 0.59, p < 0.001). We suggest that the threshold between dry lake bed areas and the formation of ephemeral lakes in semi-arid regions is eight days of total precipitation.

Keywords: dry lake beds; dust storm emission; remote sensing; Gobi Desert region

1. Introduction

Dust storms are a common phenomenon that may negatively affect human and animal health. In severe cases of dust storms, deaths of livestock have been reported in East Asia [1]. Because a large quantity of soil particles are produced by erosion and sedimentation transportation and deposit in dry lake beds [2], such dry lake beds represent areas where dust emissions occur [3]. Ginoux et al. (2012) found dust sources to have natural and anthropogenic origins, with natural dust sources accounting for 75% of global emissions and anthropogenic sources accounting for 25% [4]. Satellite images of dust storms in the Gobi region often show that large dust clouds are comprised of many well-defined plumes that emerge from "point" sources [5]. Farebrother et al. (2017) found a strong power relationship between the lake area and the mass of deflated lake bed sediments in Southeastern Australia [6]. In Mongolia's Gobi Desert, dry lake beds have been identified as a source of high-frequency dust storms. In fact, the Gobi Desert has been recognized as an important dust storm source region [7].

Dry lake beds are considered to contribute a substantial amount of global dust emissions and to be responsible for "hot spots" of dust outbreaks. Existing studies investigate potential water resources in the Gobi for use in many sectors, including regional planning, agriculture, and nomadic grazing. Water resources are identified through topographic and optical images obtained from remote sensing satellites and integrated into GIS to investigate and identify potential shallow water correlated to paleolakes and dry lakes beds [8]. These fields require an understanding of when and how water collects and evaporates across a given area.

This study applies the use of remote sensing to identify potential dry lake beds, taking into account the context of dry lake bed formation.

2. Materials and Methods

2.1. Study Area

The study area is located in Dornogobi, Dundgobi and Umnugobi provinces in semi-arid Mongolia. It is part of the drylands of the eastern Gobi, and has been identified as a source of dust storms (Figure 1) [1]. The semi-arid desert climate was determined from the Aridity Index of Millennium Ecosystem Assessment [9]. The annual average precipitation in Sainshand (Station number: 443540) is 111 mm. Precipitation from June to November accounts for approximately 82% of the annual precipitation. In contrast, the precipitation from December to May is 18% of the annual precipitation.

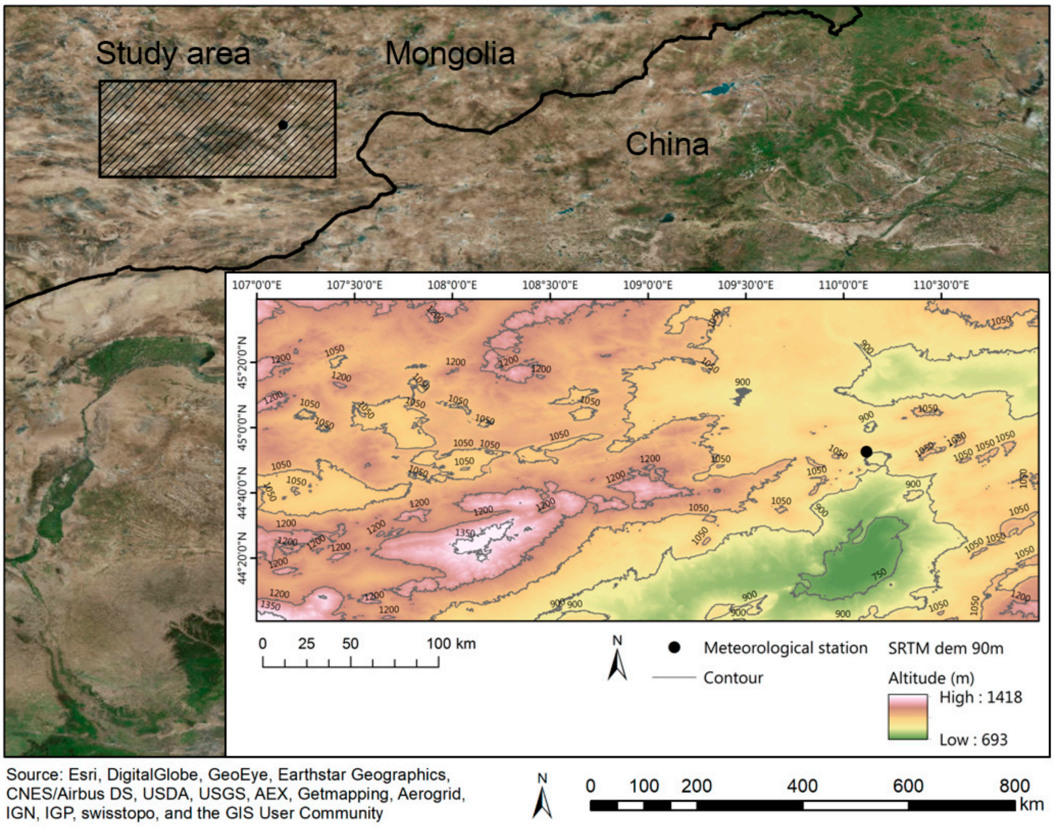

Figure 1. Map of the study area. The altitude in the area is 1030 ± 130 m. Mountains and valleys are common geographical features in the area.

2.2. Classification of the Land Cover

Within the study area there are few variations of land use and land cover. Therefore, the land cover classification was divided into mountainous regions, dry lake beds, and desert steppe using satellite remote sensing. We define a mountain as an area where the slope is greater than 1.8°. The dry lake beds are lakes that form seasonally depending on precipitation levels. Desert steppe is a typical area of the Gobi where there are a few plants and dry grasses.

The classification method for the land cover (mountains, dry lake beds, desert steppe) is shown as follows. The mountains are defined by an inclination threshold value of more than 1.8° and a higher altitude than the surrounding areas as calculated from the Digital Elevation Model (DEM). The threshold value for the angle of inclination was determined from a field survey conducted in Sainshand. The DEM (Spatial resolution: 90 m) was obtained from the Shuttle Radar Topography Mission (SRTM) and analyzed in ESRI ArcGIS10.3 and Spatial Analyst tool (Extension tool of ArcGIS10.3).

Using satellite remote sensing technology, the identification of dry lake beds has not been firmly established until now. In the case of an optical satellite, identification by spectral characteristics is difficult because the soil is bare in semi-arid regions such as Mongolia. Therefore, previous identification methods of dry lake beds have focused on geographical characteristics (such as low lying areas and plains) and the watershed topography of dry lake beds [10]. This method identifies watershed areas during a target period, with the identified watershed area defined as a potential dry lake bed. Figure 2 shows a flow chart for the identification of potential dry lake beds. Here, the Normalized Difference Water Index (NDWI) is a numerical indicator that uses the visible red and near-infrared bands of the electromagnetic spectrum to analyze remote sensing measures of water areas and wet surfaces. The NDWI can be written as Equation (1) [11].

$$\mathrm{NDWI} = (\varrho_{\mathrm{Red}} - \varrho_{\mathrm{SWIR}})/(\varrho_{\mathrm{Red}} + \varrho_{\mathrm{SWIR}}) \tag{1}$$

where, ϱ_{Red} and ϱ_{SWIR} refer to the spectral reflectance measurements acquired in the visible red and short-wavelength infrared regions, respectively. The NDWI ranges from 1 to -1. NDWI > 0 is classified as water areas and NDWI ≤ 0 defines non-water areas [12]. In our study, MODIS-Terra eight-day 500 m atmospheric corrected reflectance products (MOD09A1) were used to evaluate the water area conditions from 18 February 2000 to 26 June 2015. The total number of images is 704, which are used in the eight-day composite image.

To remove the influence of snow and cloud cover, a mask processing using the QA (Quality Assessment) band of MOD09A1 was conducted. Firstly, the area of potential dry lake beds extracted maximum NDWI from all pixels in NDWI images from September 2000 through July 2014 (Figure 3). Then, to determine elevation and ground level, a mask processing of the maximum NDWI pixels with the angle of inclination less than 1.8° calculated by DEM was performed. In addition, the algorithm for re-sampling used the Nearest Neighbor method, which maintained an original pixel level. Finally, all NDWI pixels greater than 0 were extracted as an area of potential dry lake beds. The precision of potential dry lake beds location was compared with the result of aerial photointerpretation where Spot image (space resolving power: 2.5 m) was used to inspect the classification accuracy. Spot image is a data source acquired from the French National Space Research Center used for Google Earth of Google Inc. Positional information of the aerial photointerpretation included 454 data points within the study area. Furthermore, extracted potential dry lake beds were clarified by comparing the geographical characteristics of river networks and watersheds. There are no perennial streams found within the river networks of semi-arid regions such as lake beds and wadis, and following a rainfall occurrence, intermitted surface flows appear within the lower portions. The areas form as sheet flow and conveyance (channel) areas [13]. The area of length of a simple linear regression is one way to model a relationship between river networks and potential dry lake beds because it is supposed that potential dry lake beds are connected with river networks for hydrology. The river network 15 s HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple scales) was provided by WWF (World Wildlife Fund).

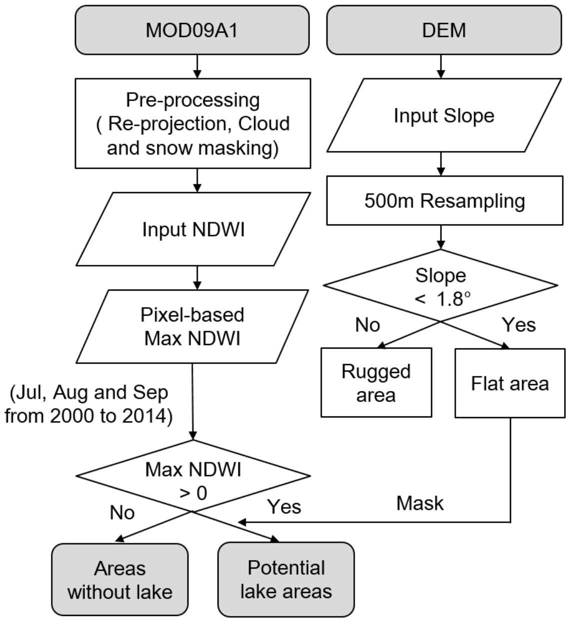

Figure 2. The identification method of potential dry lake beds based on Terra/MODIS and Digital Elevation Model (DEM).

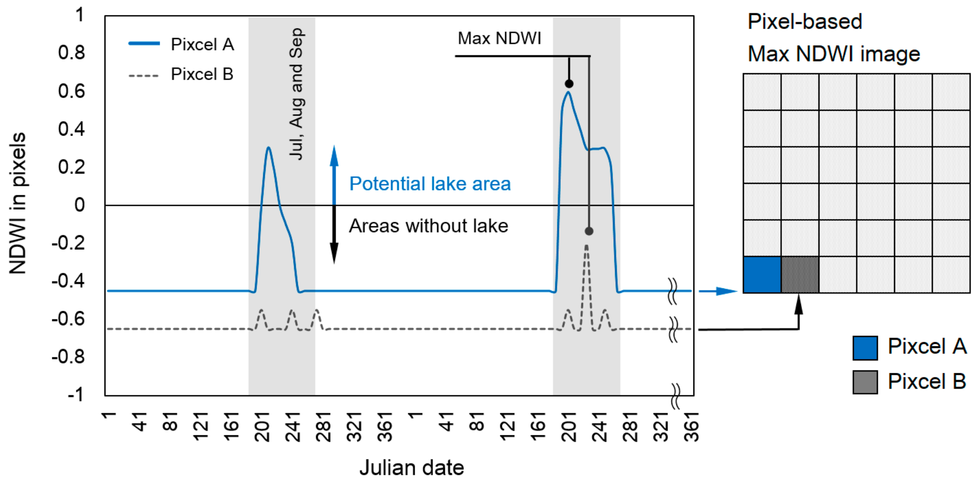

Figure 3. The pattern diagram of potential lake areas without lakes based on pixel-based maximum Normalized Difference Water Index (NDWI) images. In the schematic diagram of NDWI shown in Figure 2, pixel A is extracted as a potential lake area, and pixel B is extracted as an area without a lake from September 2000 through July 2014.

2.3. Formation of Dry Lake Beds

Precipitation in drylands is characterized by large fluctuations throughout the year [14]. In desert steppe regions such as the Gobi, the drop of permeability of the topsoil caused by rain has been confirmed [15]. From such topsoil and characteristics of rainfall patterns, precipitation may contribute to the formation of dry lake beds. Therefore, the changing tendencies of dry lake beds were identified as time series data of precipitation from 2000 through 2014. Precipitation data was extracted when ephemeral lakes were formed for the first time in each year. Then, because the scale of time and space is large, precipitation data from the GPCP (Global Precipitation Climatology Project) 1° Daily dataset was used. The total precipitation across eight days was aligned with the temporal resolution of dry lake beds data. The precipitation across eight days added up to the GPCP daily precipitation as the time scale of MOD09A1 product is eight days. The precipitation data was created from daily observations taken from 1 January 2000 to 31 July 2014.

3. Results

3.1. Classification of Land Cover

Using an aerial photointerpretation classification technique, 363 of 454 dry lake beds were extracted. This means that our classification method succeeded in identifying dry lake beds with an accuracy of approximately 80%. Mountainous areas were found from the southwestern reaches of the study area (44°10′~44°40′ N, 107°00′~109°00′ E) (Figure 4). Dry lake beds tended to be distributed in the northern mountainous areas (44°40′ N). On the other hand, desert steppe constituted the greatest percentage of land cover. In addition, mountainous areas, dry lake beds, and desert steppe varied greatly within our study area. Desert steppe and mountain regions represented 69% and 30%, respectively, with dry lake beds accounting for 1% of our study area. The area of desert steppe was approximately 56 times the area of dry lake beds.

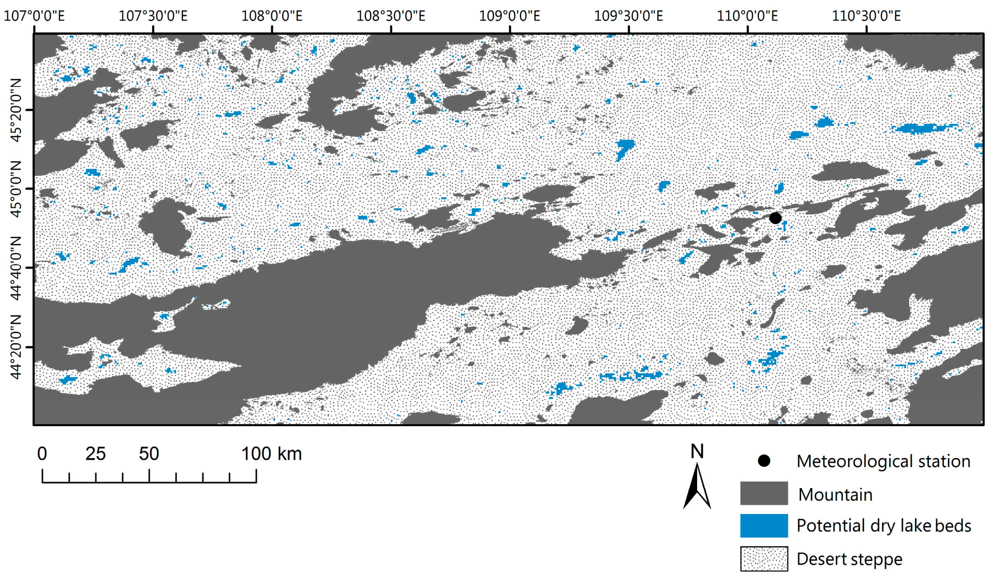

Figure 4. The distribution of three land cover types in the study area.

We then collated the identified dry lake beds with the river network found within our study site. The surface flows provide runoff within the lower dry lake beds through the river network (Figure 5). Dry lake beds in lower elevations can be understood as being part of a well-developed river network. In addition, the area of dry lake beds showed a tendency to increase (Figure 6) ($R^2 = 0.59$, $p < 0.001$, N = 109). Because of rainfall occurrence, intermitted surface flows appear within the lower portions [13], with the area of potential dry lake beds increasing as a result of an extended river network. Thus, the geographical characteristics of dry lake beds became clear when found in low elevations, which developed the river network.

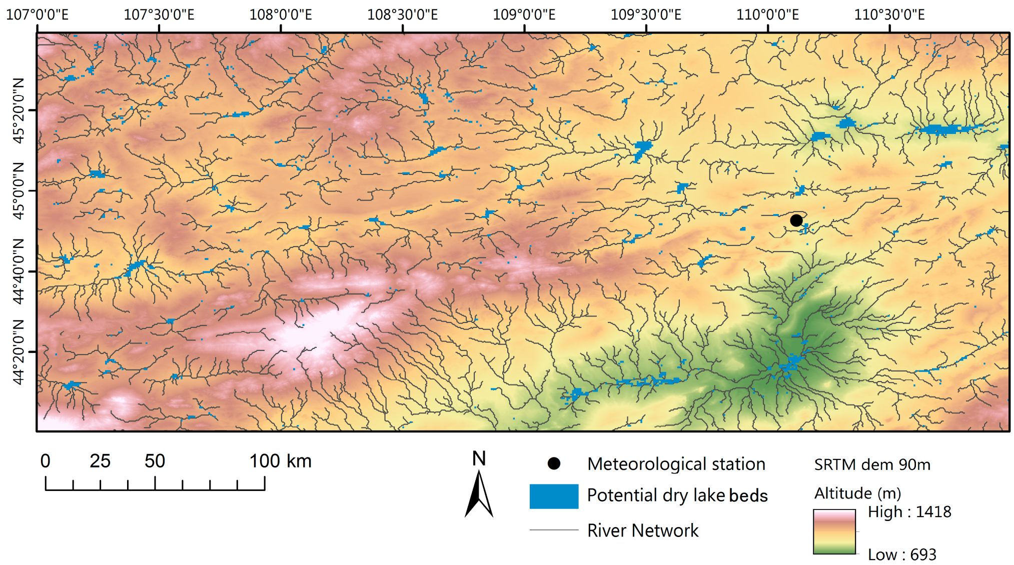

Figure 5. The distribution of potential dry lake beds and the river network.

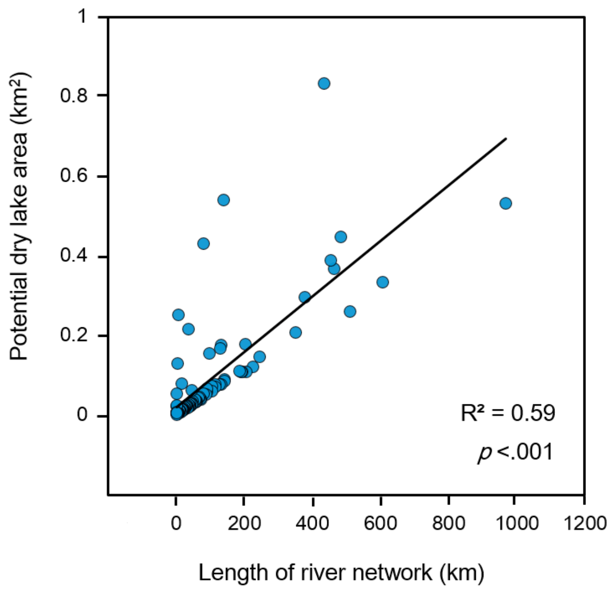

Figure 6. Correlation between potential dry lake bed areas and the length of the river network.

3.2. Formation of the Dry Lake Beds

Rashki et al. (2013) found that the dryness of lakes in the Hamoun basin was strongly associated with changes in land–atmosphere fluxes, soil moisture, and the frequency and intensity of dust storms [16]. In this study, the frequency of dry lake beds was compared with the interannual variability of precipitation to identify the time when dry lake beds in the study area appeared. Figure 7 shows the frequency of dry lake beds of the study area from 2000 through 2014 in addition to precipitation levels. The time series data shows total precipitation of the GPCP and the number of dry lake beds in the study area. The monthly mean frequency of the dry lake beds increased from 95.2% to 98.5% in the period of June to September. The monthly mean frequency of the dry lake beds increased from 97.2% to 99.9% in the period of October to May. The frequency of dry lake beds decreased from 361 to 266 in 2000 and from 361 to 301 in 2012. During this time, precipitation increased from 369 mm in the period between August 5 and August 20, 2000 to 639 mm in the period between July 4 and July 27, 2012 (Table 1). The mean precipitation of the same period was 60 mm and 88 mm, respectively.

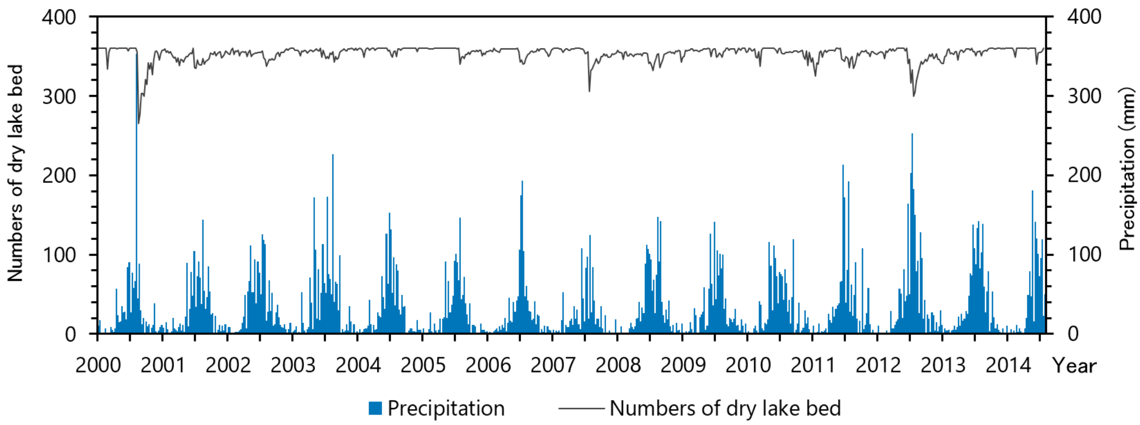

Figure 7. The correlation between the precipitation and the frequency of dry lake bed formation at each of the eight levels of pixels in study area.

Table 1. Difference in precipitation when dry lake beds decreased.

Period	Total Precipitation	Mean Precipitation
5 August 2000 to 20 August 2000	369 mm	60 mm
4 July 2012 to 27 July 2012	639 mm	88 mm

Potential dry lake beds were clarified from the differences in the relationship between precipitation and the formation of lakes (Figure 8). Precipitation was extracted when ephemeral lakes were formed for the first time in each year. The total precipitation over eight days was 369 mm in 2000 and at least 73 mm in 2010. In addition, ephemeral lakes were the largest in area in 2000 (Figure 7). It has also been suggested that the threshold for ephemeral lake formation in dry lake bed areas in semi-arid regions is eight days of precipitation.

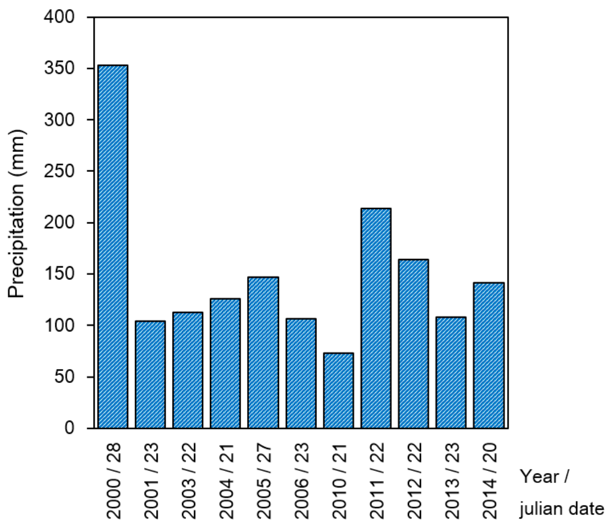

Figure 8. The total precipitation over eight days transformed dry lake beds into ephemeral lakes in potential dry lake bed areas.

4. Discussion

This study has shown that the frequency of dry lake bed formation has a strong correlation with precipitation. Dry lake beds are one important source as well as a hotspot of Asian dust emission. Dust affects Earth's climate, ecology, and economies across a broad range of scales, both temporally and spatially, and is an integral part of the Earth's climate system [6]. Dust sources, of natural and anthropogenic origins, were calculated with their respective contributions to emissions, and extensively compared against existing literature. Natural dust sources account for 75% of global emissions; anthropogenic sources account for 25% [4]. In this study we suggest a new method to identify dry lake beds using remote sensing. The classification accuracy was 80%. We believe that our accuracy was influenced by low resolution images and the limitations of aerial photointerpretation. However, it is a decent accuracy to be used in large areas such as semi-arid Mongolia. It is assumed that dry lake beds are affected by the full length of the river network and other geographic characteristics (such as elevation) as well as heterogeneous precipitation patterns. Lakes formed between June 2000 and September 2014 show drastic changes year by year, but it is suggested that lake beds dry up between October and May. In other words, the state of the Earth's surface in the area of potential dry lake beds dries during a period with no to little precipitation, and it is thought that water areas form during times of precipitation. To better understand the relationship between precipitation and the formation of dry lake beds, future studies should employ the use of high-resolution satellite images. In addition, it is necessary for the relationship of precipitation and the formation of dry lake beds to consider the geographic characteristics of the region and the influence of river networks.

5. Conclusions

This study suggests a new method to identify dry lake beds using hydrological analysis and remote sensing. The method may be used effectively in large areas such as drylands. Dry lake beds are affected by the full length of the river network and geographic characteristics (such as elevation) and precipitation patterns. Dry lake beds, which formed between June and September from 2000 through 2014, show year to year changes, but it is suggested that dry lake beds in semi-arid Mongolia dry up from October to May, which corresponds with periods of low precipitation. In our study area, the distribution of potential dry lake beds was 1%, with mountainous areas and desert steppe accounting for 30% and 69%, respectively.

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Author Contributions: Y.D. and B.H. analyzed the data and wrote the draft of manuscript and designed the study. K.B., C.M., Y.S., K.K., K.H., and J.N. participated in the field measurements and participated in the experiment of scattering soil particles. Y.D., Y.S., and T.P. established the GIS special database.

Conflicts of Interest: The authors declare that they have no competing interests.

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