Responses to the Comments by Reviewers

We thank Professor Graham Fogg and an anonymous reviewer for their constructive comments. The manuscript has been significantly improved by addressing the comments. The following is our point-to-point responses to their comments.

Responses to the Comments from Reviewer #1

General comments

This work proposes an extensive review on the evaluation of Deep Soil Recharge (DSR) in arid and semi-arid regions. The validity of Annual Recharge Coefficient is questioned based on the test data of DSR measured by the improved lysimeter. The issue raised by authors is of great significance, but the section of data analysis (part 3.2) is not well structured. There is a lack of explanations on the new apparatus and details on the field test are not clear enough as well. Experiment data presented by the authors is limited to support the conclusions. Thus, the manuscript requires significant improvement before it is accepted for publication.

Response: Thank you for the positive comment. We have reorganized the section of data analysis (part 3.2) by improving the explanations on the new apparatus and details on the field test. Experimental data presented are as complete as possible. The conclusions drawn are based on a careful analysis of the complete set of data. We believe this revised manuscript meets the requirement of HESS and is now ready for publication. See page 14 to page 24 for details.

Specific comments:

1. Some of the conclusions are not supported by the test data. For example, the authors claim that "The temperature influences the DSR rate" (in line 343). The evaporation intensity varies with temperature and affects the quantity of DSR indeed. However, if temperature influence is considered, the delay time is an issue remains to be discussed.

Response: Thank you for your careful observation, we compare two precipitation events which are similar in strength (17.2 mm for April 4 and 16.8 mm for October 5) but different in the DSR delay time (36 days for April 4 and 16 days for October 5) in page 19 line 394. Temperature is the most likely factor for such a delay time. This is the primary reason for above sentences. So we draw a conclusion that temperature affects the DSR rate. However, finding out exactly how the temperature affects the DSR rate will require additional field experiments that should be pursued in the future. See page 21 for details.

2. Authors claim that "recharge is somewhat positively correlated with a few strong precipitation events (greater than 10mm), and very closely correlated with the strongest precipitation event" (line 426-428). However, the data in table 3 seems do *not support this conclusion.*

Response: In Table 3 as showed below, we showed inter-annual statistics of strong precipitation and its percentage in total annual precipitation amount. Comparing the maximum precipitation events in 2013 to 2015, we can conclude that recharge is somewhat positively correlated with a few strong precipitation events, such as the 32mm, 15mm, and 17.2mm maximum precipitation events in 2013, 2014, and 2015, respectively. Such a positive correlation is particularly strong for 2013 which has the largest maximum precipitation event of 32mm. This positive correlation is weaker for 2014 and 2015 which have moderate and somewhat similar maximum precipitation events (15mm and 172.2mm, respectively). For these two years, other factors such as rainfall temporal distribution may also be a concern. And we defined precipitation greater than 10 mm is strong rain (page 22 line 414). Because of these, we stated on page 24, line 459 that "However, precisely quantifying such a correlation between DSR and the precipitation pattern and precipitation strength requires further investigations."

Year	Number of strong precipitation	Maximum precipitation event (mm)	Cumulative strong precipitation amount (mm)	Percentage in total annual precipitation amount (%)	Annual DSR (mm)	Annual DSR /annual precipitation (%)
2013	2	32	43.4	52.28	20.2	24.33
2014	4	15	49.6	24.12	20.6	10
2015	6	17.2	86.6	46.46	9.2	4.94

3. The quantity of DSR is actually given by the mass balance of surface layer. Surface runoff, evaporation and transpiration are critical components of water balance besides precipitation. It is necessary to present more monitored data, especially about evaporation and surface runoff, to support the conclusions in the paper.

Response: This is a nice comment. Firstly, there is no runoff at the studied area which is essential desert. Secondly, as stated correctly by this reviewer, the basic idea of lysimeter is water balance. So if the point of measurement is relatively shallow, one must consider evaporation and transpiration process. However, the DSR measurement reported in this study is NOT at relatively shallow depth, instead, it is specifically at a sufficiently deep location (5.3-6.8 m) is to make sure that evaporation and transpiration are both negligible. In another word, the downward DSR measured at such a deep depth is regarded as completely recharging the underneath groundwater aquifer. Please see page 11 line 219 for details.

4. Previous studies have shown that Annual Recharge Coefficient varies with the *water table depth. To avoid the influence of water table depth, the dynamic of phreatic water table from 2013 to 2015 in the study area is suggested to be presented in the paper.*

Response: A nice suggestion. We have added the dynamic phreatic water table position in 2013-2015 in the revised paper (see page 7 line 164). It is found that the water table depth is greater than 4m in 2013-2015, so its influence to DSR is negligible.

5. In Figure 1(B), how to measure the flux at depth A? More details about the new lysimeter are required.

Response: Thank you for your careful observation, there is a rain gauge at depth B and the column between depth A and depth B is at a balance stage so flux at depth B is the same as at depth A. We have revised the caption for this figure. See page 10 line 187.

6. Precipitation events are suggested to be presented by using columns (or vertical lines) in Figures 3, 4 and 5. 7. English should be improved because the text is somewhat difficult to follow.

Response: Implemented. The English has been thoroughly checked by a native English speaker.

Responses to the Comments from Professor Neuman (Reviewer #2)

I generally like this article as it is based on three years of observations and in groundwater hydrology, specifically recharge, there is no substitute for observations are these are far and few.

Response: Thank you for the positive comment.

Specific comments:
(1) The authors seem to knock on annual recharge coefficient as well as models and state neither would work. I concur with the first one (annual recharge coefficient) but I am not so sure that you can make the same statement on models. Most models are complete depictions of hydrological cycle and if done correctly (implying that all the components of the water balance are correct), then recharge should be accurate

Response: This is a nice comment. We have revised the text to only concentrate on questioning the annual recharge coefficient, but the models. As corrected stated by this author, if the model is established properly, recharge should be accurately estimated. See page 4 line 83-99.

(2) I find the figures 3, 4 and 5 very interesting. However, there is a large component of the infiltrating water that evaporates and if that is not subtracted from the rainfall you cannot estimate the recharge. In fact you cannot just compare 2013 to 2014 to 2015 without accounting for evaporation of the infiltrating water in the inter-storm periods. I think your observation that recharge is dictated by high intensity rainfall is correct; during high intensity (and long duration rainfall) the saturation of the soil profile hastens recharge and decreases evaporation (due to lesser atmospheric demand especially if it is raining!).

Response: Very nice comment. We have addressed this concern in our response to Comment 3 from Reviewer 1 above. Firstly, there is no runoff at the studied area which is essential desert. Secondly, as stated correctly by this reviewer, the basic idea of lysimeter is water balance. So if the point of measurement is relatively shallow, one must consider evaporation and transpiration process. However, the DSR measurement reported in this study is NOT at relatively shallow depth, instead, it is specifically at a sufficiently deep location (5.3-6.8 m) is to make sure that evaporation and transpiration are both negligible. In another word, the downward DSR measured at such a deep depth is regarded as completely recharging the underneath groundwater aquifer. Please see page 11 line 219 for details.

(3) A better analysis of length of the storm, atmospheric evaporation demand (should be very easy to calculate) should help in estimating recharge (with a simple model as compared to SWAT or HYDRUS). This will in fact justify your hypothesis that recharge is dependent on a few high intensity events.

Response: This is an interesting suggestion and certainly will be pursued in a future study to justify the hypothesis that recharge is dependent on a few high intensity events. The purpose of this study, which represents a first step in such an endeavor, is to provide direct field evidences to question the concept of annual recharge coefficient. A complete modeling of the storm, atmospheric evaporation demand will be pursued elsewhere.

Typos

The manuscript suffers from poor spelling, grammar and several typos. In the following, I will provide a short list of examples.

• Line 35: make up 24.33% of the annual precipitation

Response: Implemented.

• Line 40: as well as the precipitation patterns.

Response: Implemented.

• Line 59: depth to water table

Response: Implemented.

• Line 72: vegetation live through extreme droughts

Response: Implemented.

• Line 83-85: Modeling is an efficiency way to test different hypothetical scenarios and it may be used to predict DSR in the future if the model is calibrated carefully.

Response: Implemented.

• Line 103: this instrument is located

Response: Implemented.

• Line 110: with different crops or left as bare land

Response: Implemented.

• Line 132: In order to satisfy different requirements and needs

Response: Implemented.

• Line 135: have accuracy better

Response: Implemented.

• Line 187-188: At the soil surface there is a device to measure the amount of the precipitation

Response: Implemented.

• Line 270-294: In September 1, 2012,

Response: Implemented. Describe the experiment site.

• Line 301: This is to say

Response: Implemented.

• Line 308: by the data of 2013-2015 here

Response: Implemented.

• Line 337: It is notable that

Response: Implemented.

• Figure 3: Precipitation and DSR patterns in 2013.

Response: Implemented. Figure revised.

• Line 361: Comparing with 2013

Response: Implemented.

• Line 362: That is one reason

Response: Implemented.

• Line 366: annual DSR/precipitation ratio is 24.33% in 2013 but drops to 10% in 2014

Response: Implemented.

• Line 368-370: This is the other reason why precipitation in 2014 (205.6 mm) is greater than 2013 (83 mm) but the overall DSR in 2014 is less than that in 2013.

Response: Implemented.

• Line 390: on June 5

Response: Implemented.

• Line 392: on October 5

Response: Implemented.

• Line 393: on October 21

Response: Implemented.

• Line 394: on April 4

Response: Implemented.

• Line 397-398: Comparing two precipitation events which are similar in strength but different in the DSR delay time, temperature is the most likely factor responsible for such delay

Response: Implemented.

• Figure 4: Precipitation and DSR patterns in 2014

Response: Implemented. Figure revised.

• Figure 5: Precipitation and DSR patterns in 2015

Response: Implemented. Figure revised.

• Line 450-461: Such a positive correlation is particularly strong for 2013 which has the largest maximum precipitation event of 32 mm

Response: Implemented. Explain to correlation between DSR and the precipitation pattern and precipitation strength.

• Figure 6: One-day intensive precipitation's contribution to DSR in 2013

Response: Implemented. Figure revised.

• Line 525: and is closely correlated

Response: Implemented.

• Line 526: as well as the precipitation patterns.

Response: Implemented.

• Line 532-535: This investigation is based on detailed analysis of precipitation and DSR data at the study…

Response: Implemented. Explain to what we do in this paper

Is Annual Recharge Coefficient a Valid Concept in Arid and Semi-Arid Region?

A manuscript submitted to *Hydrology and Earth System Sciences*

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March, 2017

Abstract. Deep soil recharge (DSR) (at depth more than 200 cm) is an important part of water circulation in arid and semi-arid regions. Quantitative monitoring of DSR is of great importance to assess water resources and to study water balance in arid and semi-arid regions. This study used a typical bare land on the Eastern margin of Mu Us Sandy Land in the Ordos basin of China as an example to illustrate a new lysimeter method of measuring DSR to examine if the annual recharge coefficient is valid or not in the study site, where the annual recharge efficient is the ratio of annual DSR over annual total precipitation. Positioning monitoring was done on precipitation and DSR measurements underneath mobile sand dunes from 2013 to 2015 in the study area. Results showed that use of an annual recharge coefficient for estimating DSR in bare sand land in arid and semi-arid regions is questionable and could lead to considerable errors. It appeared that DSR in those regions was influenced by precipitation pattern, and was closely correlated with spontaneous strong precipitation events (with precipitation greater than 10 mm) other than the total precipitation. This study showed that as much as 42% of precipitation in a single strong precipitation event can be transformed into DSR. During the observation period, the maximum annual DSR could make up 24.33% of the annual precipitation. This study provided a reliable method of estimating DSR in sandy area of arid and semi-arid regions, which is valuable for managing groundwater resources and ecological restoration in those regions. It also provided strong evidence that the annual recharge coefficient was invalid for calculating DSR in arid and semi-arid regions. This study shows that DSR is closely related to the strong precipitation events, rather than to the average annual precipitation, as well as the precipitation patterns.

Key words: Deep soil recharge, deep soil infiltrometer, sandy land, new apparatus, rainfall, lysimeter

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Introduction

Recharge is an important source of groundwater budget and it is also a fundamental process that links the surface hydrological processes (e.g. precipitation), vadose zone process (e.g. infiltration and soil moisture dynamics), and the saturated zone process (e.g. groundwater flow) (Sanford, 2002;McWhorter and Sunada, 1977). How to accurately estimate recharge remains a persistent challenge and an active research topic in the hydrological science community over many decades (Gee and Hillel, 1988;Scanlon, 2013;Sanford, 2002). It is generally accepted that recharge is correlated to the precipitation in some fashions, and many studies adopt the concept of a recharge coefficient (Turkeltaub et al., 2015;Kalbus et al., 2006;Allocca et al., 2014), which is the ratio of the actual recharge to the precipitation, to estimate the recharge (Fiorillo et al., 2015;Allocca et al., 2014). The magnitude of such a recharge coefficient is controlled by a complex interplay of multiple factors such as moisture dynamics in the vadose zone (Schymanski et al., 2008), depth to water table, vegetation, etc., and the recharge coefficient is often regarded as a temporally invariant value at a given location (Fiorillo et al., 2015;Min et al., 2017;Vauclin et al., 1979). Specifically, it is assumed to be primarily controlled by the total precipitation, not too much by the temporal fluctuation of precipitation events (Hickel and Zhang, 2006;Acworth et al., 2016). In this study, we will challenge the concept of using a constant recharge coefficient to estimate the recharge in arid and semi-arid regions based on a multi-year field investigation.

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As water tables in many arid and semi-arid regions are relatively deep (greater than 2 meters below ground surface) (Williams, 1999;Soylu et al., 2011), recharge in those regions is named Deep Soil Recharge (DSR), which will be the concern of this study. DSR could ease the demand of sand-fixing vegetation on moisture during extremely dry seasons (Zhang et al., 2001;Shou et al., 2016) , and it reduces water deficit, sustains life activities, and helps the vegetation live through extreme droughts (Zhang et al., 2004). In this sense, DSR is an important factor of water cycle in arid and semi-arid regions (Adolph, 1947), and it could also provide much needed references for the stability analysis of sand-fixing vegetation (Li et al., 2004;Li et al., 2014). In the following, we will briefly review the existing methods of estimating DSR.

In general, there are three methods of measuring DSR in arid and semi-arid regions. The first is an empirical approach which assigns a constant recharge coefficient associated with a certain precipitation event (Allison et al., 1994;Jiménez-Martínez et al., 2010). The empirical approach is simple to use but it lacks a rigorous theoretical base, and the recharge coefficient has to be calibrated through a groundwater flow model in the region, which is often not available.

The second is a modeling approach involving numerical models such as HYDRUS (Šimůnek et al., 2012), SWAT (Arnold et al., 2012), UNSATH (Fayer, 2000), SWIM (Krysanova et al., 2005), SWAP (van Dam, 2000) to calculate DSR. Modeling is an efficienct way to test different hypothetical scenarios and it may be used to predict DSR in the future if the model is calibrated carefully. Detailed water balance models can be used for irrigated agriculture, but they usually cannot predict evapotranspiration accurately, especially when plants suffer seasonal water stress and plants cover is sparse (Gee and Hillel, 1988). When recharge is estimated as residual in water balance models, it can cause miscalculation as much as an order of magnitude (Scanlon, 2013;Voeckler et al., 2014). When using soil water flow models with measured or estimated soil hydraulic conductivities and tension gradients, similar miscalculation can also occur (Nyman et al., 2014;Gee and Hillel, 1988). In addition, the modeling usually involves upscaling of parameter values over a spatially and temporally discretized mesh from measurements which are made on specific moments and locations. Such an upscaling process is

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not always easy to execute and it could sometimes lead to serious errors. This is particularly true for arid and semi-arid regions where most precipitation may be episodic (occurring in short and unpredictable events) (Modarres and da Silva, 2007;Zhou et al., 2016), and may be confined to restricted portions of the area (Gee and Hillel, 1988).

The third includes a cluster of experimental techniques such as isotopic tracer (Klaus and McDonnell, 2013), water flux (Katz et al., 2016), and lysimeter (Scanlon, 2013). Among them, lysimeters are instruments that directly measure the hydrological cycle in infiltration, runoff and evaporation. Generally, this instrument is located in an open observation field or as a controlled device, working either solely or in groups (Good et al., 2015). In a typical lysimeter, soil are filled into a column surrounded by impermeable lateral boundaries thus water can only enter or leave the column from upper or lower boundaries (Duncan et al., 2016;Fritzsche et al., 2016). A drainage system is usually placed at the bottom (Glenn et al., 2013). The depth of soil in the column depends on the experimental purpose. Experiments can be done with the same type of soil at different depths in a single column, or in different columns but at the same depth. The soil surface can be cultivated with different crops or left as bare land. Observation can be recorded with weight or volume of water.

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Application of above-mentioned methods for assessing DSR in arid and semi-arid regions has met a variety of challenges, primarily due to the fact that precipitation events often happen in the form of short pulses with highly variable intensity (Collins et al., 2014). The intermittent and unpredictable characteristics of precipitation events lead to highly variable moisture and nutrient levels in the soils (Beatley, 1974;Huxman et al., 2004). It is unclear how the precipitation amount, time, and interval will affect the water moisture of arid and semi-arid regions, especially the change of deep soil water storage.

In this study, a new type of lysimeter is designed to accurately measure the amount of DSR in arid and semi-arid regions. With the help of a three-year (2013-2015) field investigation with this new lysimeter, one can answer the following question: Is the concept of an annual recharge coefficient valid or not for estimating DSR at a given location in an arid and semi-arid region? Before the introduction of this new type of lysimeter, it is necessary to briefly explain the challenges faced by the conventional lysimeter for studying DSR in arid and semi-arid regions.

2. Design of the new lysimeter for DSR measurement

2.1. Problems with the conventional lysimeter methods in arid and semi-arid regions

Lysimeters have been used to access the amount of water consumed by vegetation for more than three hundred years (Howell et al., 1991). The type of lysimeter that is specifically designed to measure evapotranspiration (ET), called precision weighing lysimeter, has been developed within the past six decades. In order to satisfy different requirements and needs, there are various designs of weighing lysimeters, with surface areas ranging from 1.0 m^2 to over 29 m^2 (Howell et al., 1991). The stored media mass and the type of scale such as diameter and height are factors on which the accuracy of ET measurement depends, and many lysimeters have accuracy better than 0.05 mm (Howell et al., 1991). Figure 1A shows the schematic diagram of a conventional lysimeter installation in the field. It is basically a weight meter of soil with an open upper boundary at ground surface and a perforated bottom boundary and impermeable vertical side walls. The typical depth of lysimeters varies from 0.2 m to 2 m, but is rarely greater than 2.5 m (Howell et al., 1991). The horizontal cross-section area is usually in the range of 1 m^2 to 29 m^2. Precipitated water can freely infiltrate into the soil from the top and downward flow of water at the bottom of the lysimeter is collected (through the perforation) as a function of time to calculate the recharge. Alternatively, the weight of combined water and soil inside the lysimeter

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can be accurately measured using a weight gauge to reflect any soil moisture change. Such information, combined with infiltration or evaporation at the surface, can yield the information of downward water flux at the depth of lysimeter.

The following issues deserve special attention when applying the conventional lysimeter for measuring recharge. Firstly, soil layers are inevitably disturbed when installing the instrument, so the result may not reflect the actual recharge in native (undisturbed) soils (Weihermüller et al., 2007) . Secondly, the cost is too high to use multiple lysimeters to observe large-scale infiltration (Stessel and Murphy, 1992). Thirdly, when precipitation strength is relatively light and concentrated, a large lysimeter cannot sensitively and rapidly measure DSR (Goldhamer et al., 1999;Farahani et al., 2007). The conventional lysimeter often cannot answer the following questions: To what soil layer can different levels of precipitations infiltrate? How much is the infiltration amount under different levels of precipitation? (Gee and Hillel, 1988;Ogle and Reynolds, 2004).

The conventional lysimeter as shown in Figure 1A may meet additional challenges when applied to arid and semi-arid regions. Firstly, the water table depths in arid and semi-arid regions may be much greater than the maximal depth of a conventional lysimeter (2.5 m). For instance, in Chagan Nur, southeast of Mu Us sandy land in the Ordos basin of China, the water table depth was found to be greater than 4 m. In the Gobi desert, the water table was reported to be at least 2.8 m deep (Ma et al., 2009). Therefore, the infiltration measured at the base of a conventional lysimeter may not represent the actual recharge that eventually enters the groundwater system. Secondly, the measurement accuracy of lysimeter often declines for soils with deep plant roots because the depth of lysimeter installation is limited and it may be less than the depth of those roots at site, which by itself can be important pathways for water migration. Consequently, the measured recharge of such disturbed soil by lysimeter may not represent the in-situ recharge of the native (undisturbed) soil.

To resolve the above-mentioned issues faced by the conventional lysimeter, a new type of lysimeter is designed with specific considerations of the unique precipitation patterns and soil characteristics in arid and semi-arid regions. This new lysimeter is illustrated schematically in Figure 1(B).

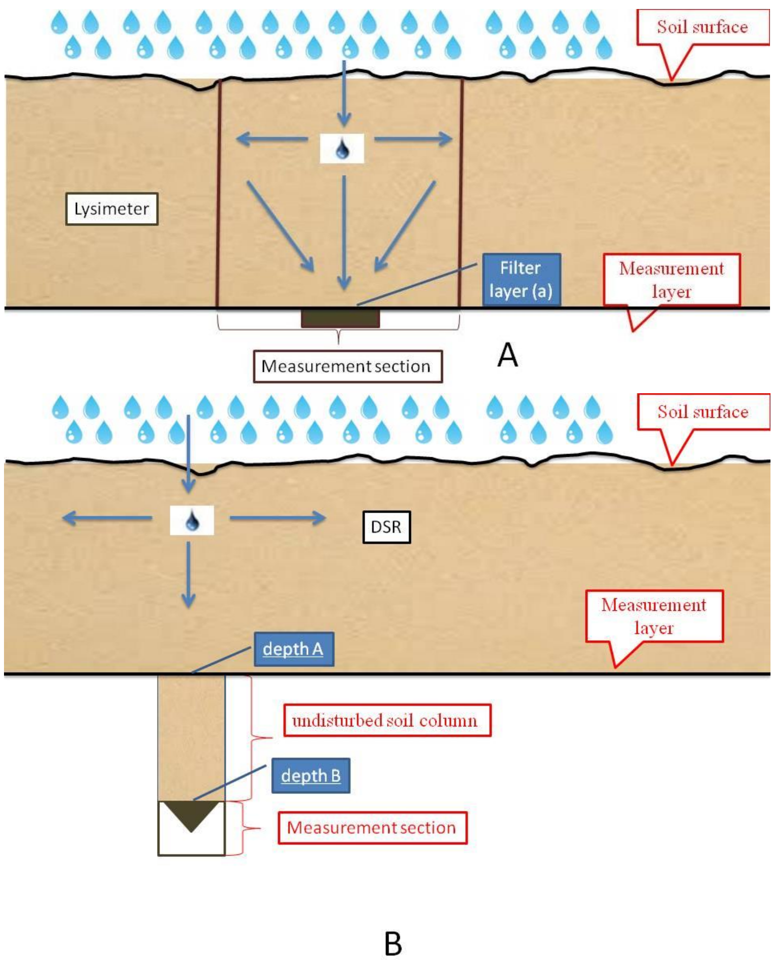

Figure 1. Schematic diagram of conventional lysimeter (A) and the new lysimeter (B).

2.2 Design of a new lysimeter for measuring DSR in arid and semi-arid regions

This new lysimeter has a few innovations (see Figure 1B) that can be outlined as follows. Instead of setting the upper boundary of the lysimeter at ground surface, the new design has its upper boundary at a designed depth (denoted as depth-A in Figure 1B) where infiltration will be measured. A cylindrical container with a diameter of 20 cm to 40 cm with impermeable walls is installed from depth-A downward to a deeper depth-B. The length of AB is determined according to the capillary rise of the in-situ soil, which can be calculated using the average grain size of soils within AB. More specifically, the length of AB is greater than the capillary rise of soils within AB and it is usually great than 0.6 m (Liu et al., 2014). At the soil surface there is a device to measure the amount of the precipitation and at the base of the instrument (depth B), a water collection device is used to measure the amount of water exit the base.

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Before the measurement, one necessary preparation is to inject water from the top of the instrument at depth-A using water pumps, the injection will stop until water starts to drip out from the base at depth-B. One usually has to wait 10 days to allow the water profile in column AB to become equilibrium. When water stops flowing out from depth-B, the soil water in the column is regarded as reaching its equilibrium state, in which the soil moisture at depth-B reaches the maximum field capacity. Under such an equilibrium status, the amount of infiltration entering the upper surface of the lysimeter will be discharged (with the same amount) from the base of the lysimeter after a certain delay time.

The proposed new method has a few innovative features that have not been considered in previous studies. Firstly, it can measure DSR at any given layer of a multi-layer soil system using a single apparatus installed in the field. Secondly, continuous real-time measurements can be recorded over any given time period, thus a time-series of DSR can be obtained, which will be very useful to understand the soil water dynamics at sandy area of arid and semi-arid regions. Thirdly, the apparatus is portable and easy to install, thus a large amount of data can be collected in various locations of a study area using multiple lysimeters, and spatial recharge distribution can also be obtained straightforwardly. This method is field tested in arid and semi-arid sandy regions of western China. It provides key references for the evaluation of water resources, water balance, and the stability assessment of sand-fixing vegetation in arid and semi-arid areas. It also provides data that are much needed for evaluating soil water contents and groundwater resources of those areas. An important feature of this new lysimeter is that it can provide reliable DSR data to examine the concept of annual recharge coefficient when comparing with the precipitation data.

3. Field testing of the new apparatus

3.1 Description of the study area

Figure 2 shows the location of the study which is located in Ejin Horo Banner, on the Eastern margin of Mu Us Sandy Land in the Ordos basin of China (geographic location: 39°05' N, 109°36' E; altitude: 1070-1556 m above mean sea level). The groundwater table between dunes are 5.3-6.8 m below ground surface. The climate is semi-arid continental monsoon climate zone. Precipitation concentrates from July to September, with relatively concentrated rainstorm. The average annual precipitation from 1960 to 2010 is 296.01 mm. The average annual temperature of this area is 6.5℃, with about 151 days of frost-free season, 1809 mm total evaporation, an average of 2900 hours of sunshine, and an average wind speed of 3.24 m/s (Wu and Ci, 2002;Karnieli et al., 2014). The study area is located in relatively gentle mobile dunes, and the soil type is Aeolian sandy soil.

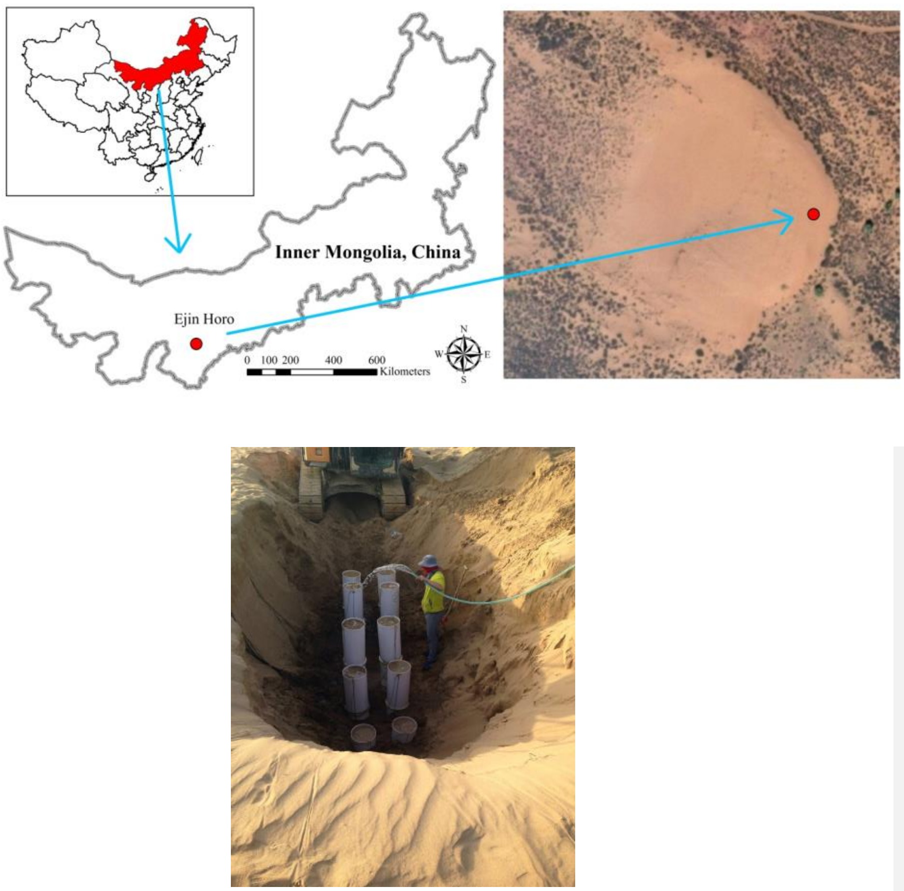

Figure 2. Geographic location of the experimental area.

In term of geological structure, Mu Us Sandy Land is in the Ordos basin, a large-scale syncline sedimentary basin with nearly north-south striking axis, and is of Mesozoic and Paleozoic ages. The basin covers an area of 640 km from north to south, and 400 km from east to west. The axis of syncline is off west, and the east and west wings are asymmetric. The east wing is Monoclinic of westward tilt with a width of more than 300 km. The west wing is made of many fault-fold belts striking along the north-south direction and thrusting eastward with a width of less than 100 km. The southern boundary of the basin is Weibei plateau uplift. The southern part of this plateau uplift is descending in ladder-shape with blocks to Fenwei rift-subsidence basin. The northern boundary of this basin is Yimeng plateau uplift, with a lack of Lower Paleozoic, and its edge-fault is connected to Hetao fault basin. The basement of Ordos basin is of Precambrian crystalline metamorphic rocks.

Deposited in the basin are, in turn, Lower Paleozoic carbonate rocks, Upper Paleozoic-Mesozoic clastic rocks, and Cenozoic sedimentary rocks with a total depth of more than 6000 m. The discontinuous Cenozoic sediment is on top of the Mesozoic and Paleozoic layers, mainly of the Quaternary and partially of the Tertiary sediments. The Quaternary layer is mainly made of Aeolian sand and loess. Generally divided by a line along the Great Wall, the northwest land surface is mainly covered by wind-blown sand layers of varying thickness and a 40-120 m thick layer of alluvial-lacustrine; the southeast land surface is mainly covered by loess with various thickness from tens of meters to more than 200 m. Below the loess layers, there is Tertiary Pliocene mud rock with thickness of a few meters to tens of meters.

The hydro-stratigraphic units of the Ordos basin is quite complex, consisting of multiple connected aquifers. Following the order from bottom to top, the multiple aquifers are primarily made from various rock types of a karst aquifer consisting of Precambrian and Ordovician limestone, a fractured aquifer consisting of Carboniferous and Jurassic clastic rocks, a porous-fractured aquifer of Cretaceous clastic rocks, and a porous aquifer consisting of unconsolidated Cenozoic and Quaternary sediments. Generally speaking, Mu Us Sandy Land has relatively rich groundwater resources. The shallow groundwater reservoir is estimated to hold about 120.3 billion metric tons of freshwater. Groundwater is mainly recharged by precipitation with an annual average recharge amount of 1.4 billion metric tons. Fine sands are the dominating sediments observed in the experimental site. In the upper 200 cm soil layer in the experiment area, the percentage of fine sand (0.5-0.1 mm) are 88.56%, 77.88%, 88.23%, 88.89%, 90.28%, 83.90%, and 84.21% at depths of 0 cm, 10 cm, 30 cm, 60 cm, 90 cm, 150 cm, and 200 cm, respectively. The rest parts of the soil are primarily coarse sands. It is evident that the soil at the upper 200 cm is relatively homogeneous.

3.2 Statistical analysis of data

Research on the relationship between precipitation and DSR of bare sand land in arid and semi-arid regions is beneficial to understand the soil-water dynamics of those regions. Because vegetation is absent, complexity related to transpiration process by plants is not a concern. Based on two time series of real-time data of precipitation and DSR, one can examine the relationship between DSR and precipitation. This study can serve as a basis for further study of DSR in semi-fixed and fixed sand lands with different fractional vegetation covers.

In September 1, 2012, mobile sand dune within the study site was set as the monitoring plot (geographic location: 39°05’ N, 109°36’ E; altitude: 1310 m) with the upper 300 cm soil profile excavated. The lysimeter as shown in Figure 1B was installed following the procedure described in section 2.2 and then backfilled using the excavated soil. Infiltration passing through the upper 200 cm depth is generally regarded as DSR in this study. It is worthwhile to point out that some other investigators may use a more or less different depth threshold for defining DSR. For instance, (Zhang et al., 2008) used 140 cm instead of 200 cm depth as the threshold to define DSR. It was found that the water table depth was greater than 5 m in 2012-2015 at the study site, so its influence to DSR was negligible. A precipitation sensor (AV-3665R, AVALON, United States; precision: 0.2 mm) was placed above ground at the site. Data acquisitor (CR200X,

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Campbell, USA) was used to record DSR, of which DSR data were recorded every one hour, and the precipitation data were recorded every half hour. In order to avoid the effect of freeze-and-thaw action, the experiment was conducted between April 1, 2013 and November 30, 2015. During such a three-year period, no runoff occurs at the studied area.

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The statistics of precipitation and DSR are shown in Table 1, which reveals that there is an obvious difference of precipitation at the experimental plot from 2013 to 2015. The annual precipitation is 83 mm in 2013, 205.6 mm in 2014, and 186.4 mm in 2015. This is to say, the annual precipitations in 2014 and 2015 are 2.48 and 2.25 times of that in 2013, respectively. Such a dramatic fluctuation and uneven distribution of annual precipitation is typical of arid and semi-arid regions. The corresponding annual DSR is 20.2 mm in 2013, 20.6 mm in 2014, and 9.2 mm in 2015. This is to say that the annual DSR values in 2014 and 2015 are 1.02 and 0.46 of that in 2013. The annual DSR/precipitation ratios (or the so-called annual recharge coefficient) for 2013, 2014, and 2015 are 24.33%, 10%, and 4.94%, respectively.

It appears that there is no clear correlation between the annual DSR and the annual precipitation according to the data of 2013-2015. In another word, use of the annual recharge coefficient for the study site becomes questionable as such a coefficient implies that there is a close correlation between the annual DSR and the annual precipitation, which is not supported by the data of 2013-2015 here. Therefore, we will scrutinize the precipitation pattern and intensity more closely to decipher the connection of precipitation and DSR in the following.

Table 1: The annual precipitation-DSR relationship from 2013-2015.

Year	Precipitation (mm)	DSR (mm)	DSR/precipitation*100%

2013	83	20.2	24.33%
2014	205.6	20.6	10%
2015	186.4	9.2	4.94%

3.2.1 The relationship between precipitation pattern and DSR

Research on bare sandy soil water dynamic process usually focuses on temporal and vertical differences (Ritsema and Dekker, 1994;Postma et al., 1991). In term of temporal soil moisture variation over an annual cycle, the process could be divided as soil moisture replenishment, depletion, and relatively stable periods. In term of vertical soil moisture variation, soil water content usually first increases with depth and then decreases based on an interplay of mutual infiltration and evaporation processes. In general, soil could be divided as a surface dry sand layer, a layer with drastic moisture change, and a layer with relatively stable moisture content. Specifically, the soil deeper than 160 cm in arid and semi-arid regions would have a relatively stable moisture content. This is because of two reasons. Firstly, soil water will not be up-taken to the surface by capillary force at such depths; secondly, ground water table in arid and semi-arid regions is usually much lower than 160 cm.

In our study site, 2013 is an especially dry year with only 83 mm precipitation compared to 296.01 mm of average annual rainfall calculated over a period from 1960 to 2010. The precipitation and DSR patterns of 2013 are shown in Figure 3. The measurement accuracy of the lysimeter is 0.2 mm. During the observation period from April 1 to November 30, there are totally 25 recorded precipitation events, mostly concentrated in the period from May to August.

There is a one-time strongest precipitation event with a 24-hour precipitation amount reaching 32 mm in August 3. The DSR correlated to this event can be identified from September 21 to November 30 and reaches 17.2 mm. The delay time from precipitation event to the start of DSR is approximately 48 days. The DSR/precipitation ratio for this particular event is as high as 53.75%. Such a DSR/precipitation ratio appears to be the highest in 2013. It is notable that although the strongest precipitation event at August 3 contributes the greatest to DSR observed from September 21 to November 30, a few precipitation events with amount of 6.6 mm prior to this strongest precipitation event also contribute a minor part for DSR from July 27 to August 1. It is also notable that the DSR/precipitation ratio for the strongest precipitation event is substantially higher than the average annual recharge coefficient of 24.33% in 2013. This leads to the conclusion that DSR is closely related to the strong precipitation events, rather than to the average annual precipitation.

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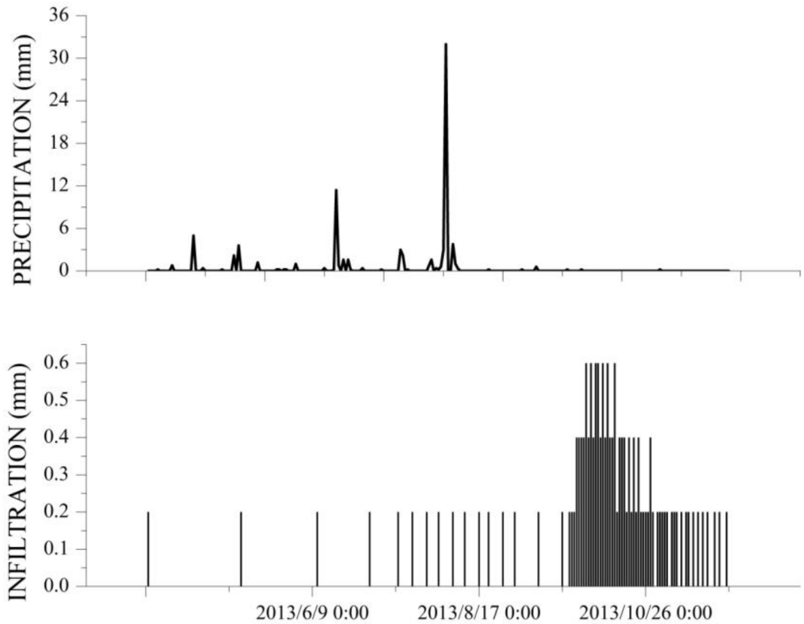

Figure 3: Precipitation and DSR patterns in 2013.

In 2014, the annual precipitation is 205.6 mm, and DSR is 20.6 mm, leading to a 10% annual average recharge coefficient, which is less than half of that in 2013. As shown in Figure 4, the frequency of precipitation events in 2014 is obviously higher than that of 2013. From April 1 to November 30, there are total 68 times of precipitation events, compared to 41 times in 2013. Furthermore, the precipitation distribution in 2014 is more uniform than that in 2013. Specifically, precipitation events are concentrated in the period from June to August, with the highest 24-hour accumulative precipitation of 15 mm on July 30. As shown in Figure 4, recorded DSR data cover a period from April 1 to November 30, and the maximum DSR occurs in October 1. Because the experimental plot is located in a transition zone between arid and semi-arid regions, summer evaporation is strong, leading to relatively less DSR during the summer season. While during the period from September 1 to November 30, atmospheric temperature drops and sunshine duration becomes shorter, which results in less surface evaporation and greater DSR during this period. Comparing with 2013, there are more summer precipitation events in 2014. That is one reason why precipitation in 2014 (205.6 mm) is greater than 2013 (83 mm) but the overall DSR in 2014 is less than that in 2013.

The strongest single-day precipitation in 2014 is 15 mm (occurred in July 30), which is less than half of the strongest single-day precipitation event of 32 mm occurred in 2013 (August 3), annual DSR/precipitation ratio is 24.33% in 2013 but drops to 10% in 2014. This once again supports the conclusion that the strong precipitation events rather than the average annual precipitation are mostly responsible for the average annual DSR. This is the other reason why precipitation in 2014 (205.6 mm) is greater than 2013 (83 mm) but the overall DSR in 2014 is less than that in 2013.

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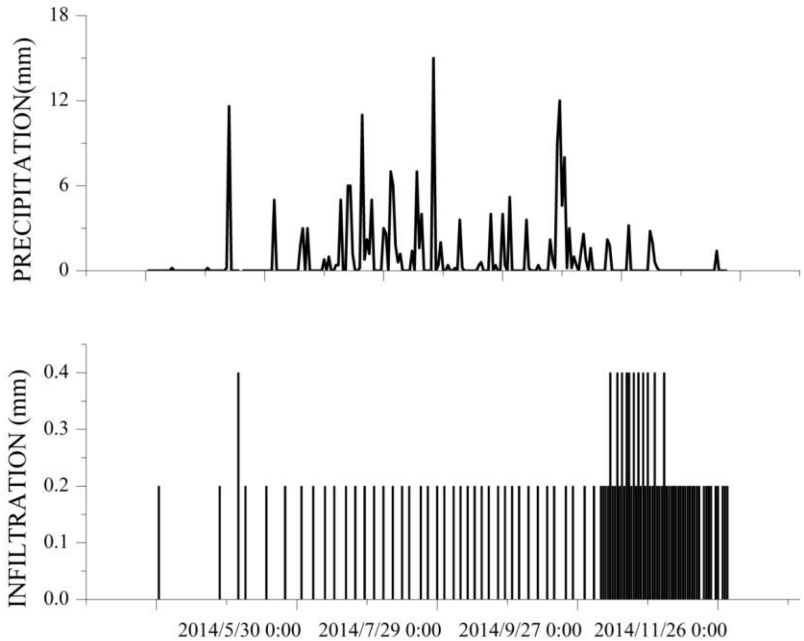

Figure 4: Precipitation and DSR patterns in 2014.

As shown in Figure 5, the total annual precipitation of 2015 is 186.4 mm, and DSR is 9.2 mm, leading to a 4.94% annual average recharge coefficient, which is significantly smaller than of 2013 (24.33%) and 2014 (10%). There are total 66 observable precipitation events in 2015. Such precipitation events are mostly concentrated from April 4 to July 6, with a total precipitation of 155 mm during this period, which represents 83.15% of the total precipitation in 2015. The measured DSR from April 4 to July 6 is only 7 mm, representing 77.78% of the total DSR in 2015. Throughout 2015, two strongest precipitation events happens on April 4 and June 5, both 24-hour precipitation events reach 17.2 mm. We observe a single-day DSR peak of 0.8 mm, 36 days after April 4, one of the two greatest single-day DSR values observed in 2015, but no peak value of DSR response to the strong precipitation on June 5. As explained before, summer stronger evaporation leads to relatively less DSR during the summer season compared with other seasons. The third greatest precipitation is 16.8 mm on October 5, which leads to a peak value of 0.8 mm of DSR on October 21, with a 16-day delay time. If comparing the precipitation events occurred on April 4 (17.2 mm) and October 5 (16.8 mm), one can see that these two precipitation events are similar in strength (17.2 mm for April 4 and 16.8 mm for October 5) but different in the DSR delay time (36 days for April 4 and 16 days for October 5). Comparing two precipitation events which are similar in strength but different in the DSR delay time, temperature is the most likely factor responsible for such delay, so this leads to a conclusion that temperature influences the DSR rate. To investigate how the soil temperature affects the DSR rate, further field experiments are needed in the future study.

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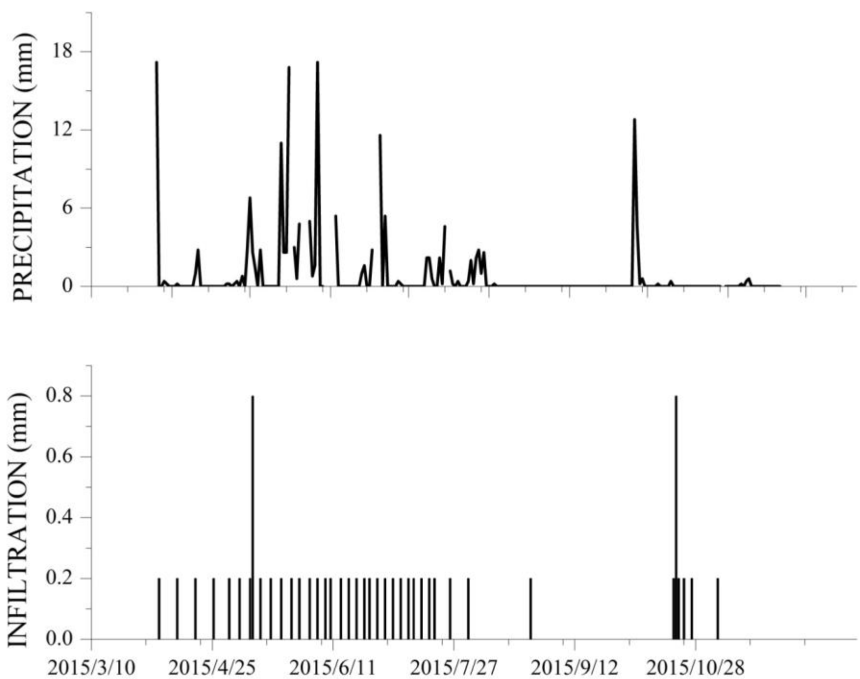

Figure 5: Precipitation and DSR patterns in 2015.

3.2.2 Relationship between precipitation intensity and DSR

Based on observational data and analysis in 3.2.1, one can see that precipitation intensity, to some extent, influences DSR. For the sake of illustration, the precipitation intensity for bare sand land is roughly classified into light, moderate, and strong events with precipitation amount less than 6 mm, between 6 mm to 10 mm, and greater than 10 mm, respectively. In general, light precipitation rarely can reach the soil zone deeper than 40 cm because of evaporation, thus it makes almost no contribution to DSR (Zhang et al., 2016). Such a classification may be revised under different vegetation covering conditions in different regions (Kosmas et al., 2000).

According to this classification, statistics of moderate to strong precipitation events and their percentage shares in the annual precipitation from 2013 to 2015 are shown in Table 2. In 2013, there are only two precipitation events with intensity greater than 6 mm. The total amount of these two precipitation events is 43.4 mm, which represents 52.29% of the annual precipitation in 2013. In 2014, there are 11 precipitation events with intensity greater than 6 mm, much more frequent than that of 2013 (2 times) and moderately more frequent than that of 2015 (8 times). The total moderate to strong precipitation in 2014 is 98.6 mm, representing 47.96% of the annual precipitation in 2014. In 2015, there are 8 precipitation events with intensity greater than 6 mm, accounting for 53.54% of the annual precipitation in 2015.

Among these three years, 2015 has the largest percentage of moderate to strong precipitation over the annual precipitation. However, at this same year, one has seen the smallest ratio of annual DSR/precipitation ratio or annual recharge coefficient (see Table 1). This implies that the annual DSR does not seem to be positively correlated to the annual total precipitation. This finding has a few profound consequences. It basically states that assigning a constant annual recharge coefficient for a particular soil regardless of precipitation patterns is not a good practice, because annual DSR is not always proportional to the total annual precipitation. Instead, it appears to be more closely related to individual precipitation events stronger than 10 mm.

Table 2: Percentage of valid precipitation in total precipitation amount.

Year	Number of precipitation >6mm (24 hr cumulative)	Amount of precipitation >6mm (mm)	Valid precipitation /annual precipitation (%)
2013	2	43.4	52.29
2014	11	98.6	47.96
2015	8	99.8	53.54

Table 3 lists the number of strong precipitation (with amount greater than 10 mm) and also the strongest precipitation amount for each of 2013, 2014 and 2015. In 2013, there are only 2 strong precipitation events, but the maximum single-day precipitation amount reaches 32 mm (August 3). The accumulative strong precipitation of 2013 is 43.4 mm, which is 52.28% of the annual precipitation in 2013. In 2014, there are 4 strong precipitation events and the maximum single-day precipitation amount is 15 mm. The accumulative strong precipitation of 2014 is 49.6 mm, which is 24.12% of the annual precipitation in 2014. In 2015, there are 6 strong precipitation events, and the maximum single-day precipitation amount is 17.2 mm. The accumulative strong precipitation of 2015 is 86.6 mm, which represents 46.46% of the annual precipitation in 2015. The annual DSR versus annual precipitation ratios are 24.33%, 10%, and 4.94% for 2013, 2014, and 2015, respectively.

As shown in Table 3, the strongest single-day precipitation (32 mm in 2013) appears to affect DSR the most in 2013. For 2014 and 2015, as the strongest precipitation events in these two years are significantly smaller than that in 2013. Such a positive correlation is particularly strong for 2013 which has the largest maximum precipitation event of 32 mm, showing that the strong single-day precipitation affects DSR. This positive correlation is weaker for 2014 and 2015 which have moderate and somewhat similar maximum precipitation events (15 mm and 17.2 mm, respectively). As shown in Figures 4 and 5, precipitation patterns in 2014 and 2015 are quite different despite the fact that the maximum precipitation events are similar to each other. The precipitation in 2014 is somewhat uniformly distributed from April to November, while the precipitation in 2015 is mostly concentrated from May to June. This observation suggests that DSRs for these two years are related to the precipitation pattern as well as the precipitation strength. However, precisely quantifying such a correlation between DSR and the precipitation pattern and precipitation strength requires further investigations.

In summary, one may conclude that annual DSR in arid and semi-arid regions mainly rely on strong precipitation events, but the determination of the threshold for strong precipitation events that directly contribute to DSR is still unclear and requires further investigation.

Table 3: Inter-annual statistics of strong precipitation and its percentage in total annual precipitation amount.

Year	Number of strong precipitation	Maximum precipitation	Annual DSR (mm)	Annual DSR /annual precipitation (%)

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2013 年单次强降雨达到 32mm，2013 年总渗漏量最大，对比 2013 年与 2014,2015 年数据，显示强降雨与渗漏量正相关，虽然 2014,2015 年最大单次降雨相近（15mm，17.2mm），但是 2014 年和 2015 年最大降雨量和渗漏量并不相关，因为 2014,2015 年降雨格局不同，如图 4，5 所示，2014 年降雨平均分布在 4 月到 11 月之间，2015 年降雨比较集中分布在 5 到 6 月，这就能解释为什么单次最大降雨强度相似但是渗漏量却不同。¶

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		event(mm)		
2013	2	32	20.2	24.33
2014	4	15	20.6	10
2015	6	17.2	9.2	4.94

Under the condition of continuous precipitation, it may be difficult to discretize precipitation into individual events. The following example illustrates a procedure to deal with this situation. As shown in Figure 6, there is a 13-days continuous precipitation process in 2013 from July 27 to August 8, and the accumulative precipitation is 43.8 mm. The start of a continuous DSR distribution corresponding to this 13-day continuous precipitation event is observed 3 days after the end of this precipitation process, and the peak value of DSR occurs 46 days after the end of this precipitation process. The DSR distribution gradually recedes to zero around 78 days after the end of the precipitation process. The accumulative DSR amount over a 75-day period is 18.4 mm. The ratio of the 75-day cumulative DSR over the 13-day precipitation event is 42%.

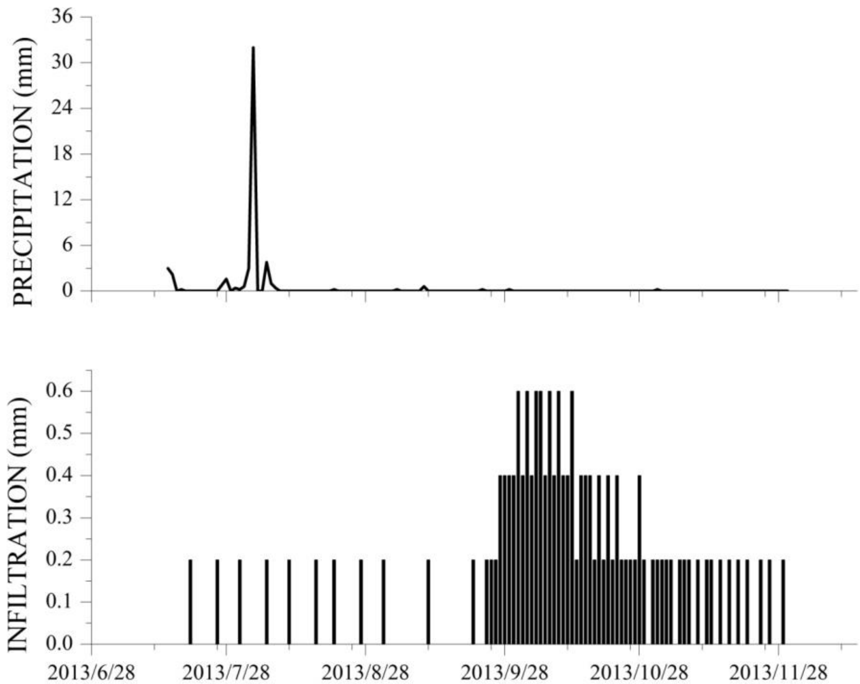

Figure 6: One-day intensive precipitation's contribution to DSR in 2013.

4. Discussion

This improved lysimeter is on the real-time dynamic monitoring of DSR, and it provides reliable evidence for an accurate evaluation of precipitation-related recharging capability of bare sand lands in arid and semi-arid regions. However, there are a number of issues that deserves further attention and requires additional investigations in the future. The moisture evaporation, the soil absorption of moisture, and the water infiltration of post-evaporative redistribution, are all very complex processes, especially in arid and semi-arid regions. It is sometimes difficult to clearly distinguish the amount of evaporation and DSR with conventional methods as outlined in the introduction. This study selects precipitation and infiltration data during the period from April 1 to November 30, so the influence of freeze-thaw process during winter is avoided, and the experimental design and data analysis is simplified. For this reasons, the next steps should be a full-term monitoring, a systematic study on DSR, as well as a study on the soil temperature and daily temperature influences on DSR.

Although this experiment does not address the issue of soil temperature effect on DSR in great details, the relationship between DSR and soil temperature is evident. In general, a higher temperature means a stronger evaporation demand, thus an often smaller DSR.

Through the analysis of this study, one can see that the use of an annual recharge coefficient for the study area is not supported by the data collected from the new lysimeter, as the annual recharge is not positively correlated with the annual total precipitation. Instead, we find that the recharge is somewhat positively correlated with a few strong precipitation events (greater than 10 mm), and is closely correlated with the strongest precipitation event (considerably greater than 10 mm), as well as the precipitation patterns. It is probably reasonable to assign different weighting factors for different precipitation strengths to calculate DSR. However, the threshold to define a strong precipitation event that makes direct contribution to DSR is not precisely quantified, and this is a subject that should be investigated in more details in the future. The determination of weighting factors for different precipitation strengths is also a subject requires further investigation.

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This investigation is based on detailed analysis of precipitation and DSR data at the study site without involving modeling effort which certainly will be explored in the future as well. This study represents our first attempt of questioning the application of recharge coefficient concept in arid and semi-arid regions.

5. Conclusions

This study uses a newly designed lysimeter to study three consecutive years (2013-2015) of DSR underneath bare sand land on the Eastern margin of Mu Us Sandy Land in the Ordos basin of China. The objective is to identify the characteristics of the DSR distribution and the factors affecting the DSR distribution. Specifically, we like to examine if the commonly used recharge coefficient concept can be applied for arid and semi-arid regions such as the Eastern margin of Mu Us Sandy Land of China. The following conclusions can be drawn from this study:

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(1) The annual recharge coefficient concept is generally inapplicable for estimating DSR in the study site.

(2) Precipitation pattern including precipitation intensity and precipitation season significantly influences DSR.

(3) The temperature influences the DSR/precipitation ratio, which is less in summer as in other seasons, given the similar precipitation intensity.

(4) DSR is not correlated with the annual precipitation. Instead, it is correlated with the strong precipitation (greater than 10 mm) events at the site. However, quantitative determination of the thresholds for such strong precipitation events that makes direct contribution to DSR is not entirely understood. Further investigation is needed on this subject.

Acknowledgements. This study was supported with research grants from the Ministry of Science and Technology of the People’s Republic of China (2013CB429901).

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