A high-resolution global runoff estimate based on GIS and an empirical runoff coefficient
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ABSTRACT

This paper reviews 110 years of global runoff estimation. By employing the method of ordinary least square regression on a sample region’s runoff coefficient, an empirical formula of a runoff coefficient is calculated for China. Based on this empirical formula applied with a high-resolution grid of precipitation, runoff is calculated resulting in an equally high-resolution map of global runoff using a geographic information system (GIS). The main results are (1) the global total runoff volume is 47,884 km³, (2) the average runoff depth is 359 mm, (3) the interior drainage region’s runoff volume is 1,663 km³, and (4) the average runoff depth is 58.4 mm. The results are compared with the results of the existing literature on global runoff. This study emphasizes the importance of runoff and groundwater recharge in arid and semi-arid regions where the estimation value of runoff depth is significantly increased.

Key words | geographic information system, global runoff, high-resolution, interior drainage, runoff coefficient

HIGHLIGHTS

- By employing the method of ordinary least square regression on the sample region’s runoff coefficient, the empirical formula of the runoff coefficient is calculated.
- Based on the empirical formula and high-resolution grid of precipitation, the high-resolution field of global runoff is calculated.
- Main results are that the global total runoff volume is 47,884 km³ and the average runoff depth is 359 mm.
- The interior drainage region’s runoff volume is 1,663 km³ and the average runoff depth is 58.4 mm.
- This study emphasizes the importance of runoff and groundwater recharge in arid and semi-arid regions where the estimation value of runoff depth is significantly increased.
The estimation of global water resources has a long history of more than 110 years. According to Lvovitch (1973), Penck first proposed the water balance formula: \( P = R + E \) (Precipitation = Runoff + Evaporation) in 1896. Geints modified the formula in 1903 as \( P = S + U + E \) (Precipitation = Surface runoff + Groundwater + Evaporation) and deemed that groundwater should be an integral part of the runoff calculation. Brikner estimated in 1905 that the global total runoff volume was 25,000 km\(^3\). Wust’s estimation in 1920 was 37,100 km\(^3\). Nace’s 1968 estimation was 42,600 km\(^3\), while Zubenok’s 1970 estimation was 46,337 km\(^3\). Korzoun et al. (1977) calculated that the global total runoff volume was approximately 48,000 km\(^3\), of which 1,000 km\(^3\) was runoff from interior drainage basins; the world’s total runoff was 45,560 km\(^3\) if Antarctica is excluded. Grabs et al. (1996) calculated that the global runoff was 42,709 km\(^3\), which is less than Korzoun’s estimation, but his estimation for Africa’s runoff was 8,585 km\(^3\), which is the maximum value for Africa presently. The latest estimations for global runoff are found in the 2014 GRDC’s Report 44 (Wilkinson et al. 2014), which estimates that global runoff into the ocean (excluding runoff in Antarctica and in the interior drainage basins) is 41,867 km\(^3\); and FAO’s Aquastat database in 2016 lists that the world’s interior renewable water resources (excluding Antarctica) are 42,811 km\(^3\), including surface runoff and groundwater which is not repeatedly accounted for in surface runoff (Table 1).

According to the statistics of 15 global runoff volumes for oceans and 17 global runoff volumes for continents in GRDC’s Report 44, the maximum volume is 46,931 km\(^3\), and the minimum volume is 29,485 km\(^3\), with the average of 40,342 km\(^3\) by the ocean and 40,258 km\(^3\) by continent. This paper collected 44 sets of global runoff data with an average value of 39,565 km\(^3\) and a median value of 39,381 km\(^3\). The modal’s interval is 38,829–43,438 km\(^3\), which utilizes 50% of the total number of frequencies. The minimum value is 25,000 km\(^3\), and the maximum value is 52,657 km\(^3\).

The Global Runoff Data Centre (GRDC) is located at Koblenz, Germany. It hosts the global runoff database, a collection of river runoff data from 9,200 hydrological stations.
in 160 countries, which provides reliable raw data for contemporary studies about global runoff. However, due to the lack of runoff data for interior drainage basins where runoff is mainly seasonal and underground, runoff volume is possibly underestimated by GRDC’s annual report and FAO’s Aquastat database. On the other hand, the interior drainage runoff is ignored by defining runoff as strictly runoff flowing into oceans, which does not include runoff flowing into inland lakes or playas. The runoff consumed by human use or evaporation from river surfaces and washlands before passing through a gauge station is also ignored.

Theoretically, by taking a large river basin as a research unit, it is easy to ignore the evaporation and utilization of runoff at an intermediate point in the basin, but also the higher the spatial resolution the higher the runoff volume calculated. The phenomena are more significant in regions with strong evaporation or high-water consumption by human activities. Therefore, obtaining a high-resolution global runoff field will increase the precision and accuracy of runoff measurements, leading to a more correct calculation of the runoff within small watersheds and within interior drainage basins, thus resulting in a greater overall runoff volume. The spatial resolutions of studies thus far are generally low due to researchers using large basins as research units for global runoff estimation. For instance, the University of New Hampshire (UNH) generated a global runoff field with a resolution of 0.5° longitude and latitude by using the GRDC data 2000 (Fekete et al. 2000a), but because of the coarser resolution, it is not

### Table 1: Estimation of global runoff volume (km³) for 1905–2016 based on the past literature

| Year | Source | Runoff | Year | Source | Runoff |
|------|--------|--------|------|--------|--------|
| 1905 | E. Brikner-L73 | 25,000 | 1999 | GRDC 2000, Report 22 | 39,455 |
| 1906 | R. Fritsche-L73 | 30,640 | 1999 | Shiklomanov 1999-G14 | 41,149 |
| 1920 | G. Wust-L73 | 37,100 | 1999 | Oki 1999-G14 | 40,000 |
| 1945 | M.I. Lvovitch-L73 | 37,000 | 2000 | Vörösmarty 2000-G14 | 39,294 |
| 1956 | M.I. Budyko-L73 | 37,219 | 2000 | Shiklomanov 2000 | 39,780 |
| 1961 | F. Albrecht-L73 | 33,482 | 2000 | WRI 2000-G14 | 42,650 |
| 1964 | I. Marcinec-L73 | 30,600 | 2000 | Shiklomanov 2000 | 42,780 |
| 1964 | M.I. Lvovitch-L73 | 37,320 | 2000 | Shiklomanov 2000 | 44,750 |
| 1968 | R. Nace-L73 | 42,600 | 2001 | Oki et al. 2001-WN07 | 29,485 |
| 1969 | M.I. Lvovitch-L73 | 38,150 | 2002 | Fekete et al. 2002-WN07 | 39,307 |
| 1970 | L.I. Zubenok-L73 | 46,337 | 2002 | Dai + Trenberth 2002-G14 | 37,287 |
| 1973 | Lvovitch-L73 | 38,830 | 2002 | Dai + Trenberth 2002-G14 | 38,848 |
| 1975 | Baumgartner-WN07 | 37,713 | 2002 | Dai + Trenberth 2002-G14 | 34,523 |
| 1977 | Korzoun | 45,560 | 2002 | Dai + Trenberth 2002-G14 | 40,628 |
| 1978 | UNESCO/USSR IHD-G14 | 43,296 | 2003 | Doell et al. 2003-WN07 | 36,687 |
| 1993 | Shiklomanov 1993-G14 | 44,540 | 2004 | GRDC 2004-CT04 | 40,533 |
| 1996 | GRDC 1996a-GW96 | 42,709 | 2007 | Widen-Nilsson et al.-WN07 | 38,605 |
| 1996 | GRDC 1996b-G14 | 39,900 | 2007 | Sirajul Islam 2007a-SI07 | 38,941 |
| 1997 | Shiklomanov 1997-WN07 | 42,648 | 2007 | Sirajul Islam 2007b-SI07 | 52,657 |
| 1997 | Raskin WMO 1997-G14 | 42,784 | 2009 | GRDC 2009, online only-CT09 | 36,109 |
| 1998 | Shiklomanov 1998-G14 | 42,740 | 2014 | GRDC 2014, Report 44-WK14 | 41,867 |
| 1999 | Fekete 1999b-G14 | 37,758 | 2016 | FAO Aquastat 2016, online | 42,811 |

Note: * does not include the Antarctic continent.
Sources: -L73, Lvovitch 1973; -WN07, Widen-Nilsson et al. 2007; -G14, GRDC 2014; -SI07, Islam et al. 2007; -WK14, Wilkinson et al. 2014; -CT04, Couet & Maurer 2004; -CT09, Couet & Maurer 2009; -GW96, Grabs et al. 1996.
effective for calculating runoff on small watersheds. The spatial resolution is also 0.5° for GRDC Report 22 and Islam et al. (2007), both of which have the same limitation as that of UNH 2000. By taking the model STN-30p, GRDC’s Report 22 disregarded the data of small watersheds with an area less than 10,000 km², because 0.5° resolution cannot simulate them. Whereas the runoff depth map of China was based on the runoff data of 2,200 hydrological stations from small watersheds with an area of less than 5,000 km², therefore its spatial resolution is two times as high as the 0.5° models. By taking NASA’s runoff data of 1° latitude and longitude spatial resolution as its basis, the World Resources Institute (WRI) used small watersheds as their study unit and progressively calculated cumulative runoff (Gassert et al. 2014), which results in the repeated calculation of upper stream runoff. Although it may be used to evaluate all water resources and available water resource quantity downstream of rivers, it cannot correctly show the detailed distribution of the runoff depth due to the low spatial resolution. In addition, because it uses the GRDC data as original data, it has the problem of underestimation of the runoff depth in interior drainage basins.

Mainly based on the meteorological data of the Global Historical Climatology Network (GHCN) and the global elevation database (SRTM; Jarvis et al. 2008), Hijmans et al. (2005a, 2015b) generated the Worldclim global climate GIS grid data with 1 km ground resolution, including annual average precipitation, annual average temperature, and 17 other indicators. Trabucco & Zomer (2009) generated a Global Potential Evapo-Transpiration (PET) Geospatial Database and Global Aridity Index Geospatial Database (Precipitation/PET) with a 1 km ground resolution by using the Worldclim data. The global ground slope can be calculated by using SRTM’s 90 m high-resolution DEM (Digital Elevation Model) data. The independent variables for runoff coefficient are selected as AI (precipitation/PET) and ground slope, and the creation of these variables’ database with high spatial resolution provides the basic data for estimating the global runoff coefficient and runoff field. By using the empirical formula of a runoff coefficient for China, this paper attempts to calculate the global runoff’s high-resolution spatial distribution field accurately and precisely by employing meteorological data and slope data with high spatial resolution.

**RESEARCH METHOD**

This paper uses a simple water balance function, \( R = P - E \), where \( R \) (runoff) includes surface and groundwater runoff and aims to calculate water supply capacity at the river channel. The human consumption and water surface evaporation are not deducted from the total water resource capacity. The global scale grid resolution in this study is 0.1667° (18.52 km).

**Regression model selection**

This paper uses China as the sample area to calculate the empirical formula of a runoff coefficient through running a regression on the China data, and then calculate the global runoff coefficient and runoff depth according to this empirical formula. With the exception of arid areas, ground evaporation is closely and positively related to potential evaporation, so that the greater the potential evaporation the smaller the runoff coefficient. For instance, the tropical desert’s runoff coefficient is close to 0, while the boreal and cold temperate region’s runoff coefficient is normally large. Therefore, a runoff coefficient is directly affected by the ground slope, precipitation, and potential evaporation. Other factors, such as temperature, wind, geology, soil, and vegetation, can also indirectly influence the runoff coefficient.

If the Chinese sample’s AI (aridity index) values are plotted with Wro (runoff coefficient) values with AI on the X-axis, then two unusually high Wro value ranges will be found in the figure. One is between \( 0 \leq AI \leq 0.1 \), which is caused by the desert region’s sandy soil impeding the evaporation and increasing the groundwater runoff ratio. The other one is between \( 0.6 \leq AI \leq 1.0 \), which is caused by the steep slope’s precipitation increasing effects in the southeast-edge of the Qinghai-Tibetan Plateau, inner Mongolia Plateau, and the mountains at the southeastern half part of China in the eastern Asia’s monsoon climate zone (Figure 1).

Sixteen independent variables or their appreciated powers are considered to simulate a runoff coefficient in the sample region of China, including climate potential productivity, China precipitation modeled by a Tin grid, ground slope’s percent rise, percentage tree cover, dry season precipitation ratio, wet season precipitation ratio, hot season
precipitation ratio, cold season precipitation ratio, aridity index, wet season temperature, climate productivity/light-temperature productivity, annual mean temperature, and elevation (Table 2). The criteria restrictions for variable selection are: First, to keep the ratio variable and to discard the direct observation variable because the dependent variable is a ratio from which we can expect a higher R Square value by regression on the ratio independent variables. Second, to avoid using powered independent variables. Because the natural environment is a monotonic continuous system with a gentle and smooth transformation, while powered variables simulate violent and abrupt changes, the simulation may result in a negative runoff coefficient that is not able to capture an extremely arid region’s runoff depth. Third, to avoid using regional variables like percentage tree cover, because it has a large portion of the area with zero values that make it difficult to explain universal ground evaporation effects. Fourth, to avoid using regional climate variables like wet season precipitation ratio and dry season precipitation ratio as they only have higher values in specific climate zones like monsoonal or Mediterranean and therefore cannot explain runoff distribution globally.

Table 2 | Variables and their definition in the runoff coefficient model for China

| Variables | Definition | Units | Restricts |
|-----------|------------|-------|-----------|
| Intercept | China runoff coefficient, Runoff/Precipitation | ratio | ≤ 0.65(B) |
| Ymin0.01  | 0.01 power of climate potential productivity | 10 kg/ha | |
| P (mm)    | China precipitation (Tin grid) | mm | ≥ 100(B) |
| P0.5 (m)  | 0.5 power of China precipitation | m | |
| Sl./100   | Ground slope percent rise | ratio | |
| Sl0.5     | 0.5 power of ground slope ratio | ratio | |
| PTC0.5    | 0.5 power of percentage tree cover | ratio | ≤ 1 |
| Wpp       | Wet season precipitation ratio | ratio | < 1 |
| Hpp       | Hot season precipitation ratio | ratio | |
| Cpp0.5    | 0.5 power of cold season precipitation ratio | ratio | |
| Al        | Aridity index | ratio | < 1.8(B) |
| AI1.5     | 1.5 power of aridity index | ratio | |
| Elev (km) | Elevation | km | ≥ 0 |
| Yp/Yt     | Precipitation productivity/ light-temperature productivity | ratio | |
| AI-P-Sl   | AI*P, m*Sl | | |
| AI-P0.5   | AI*P0.5, m | | |
| SI-P0.5   | SI*P0.5, m | | |

Figure 1 | Sample Al values plotted against sample Wro values.
On the filtering and selection of variables in the regression models, temperature, surface area, and wind speed are major factors affecting surface evaporation. Temperature and wind speed are taken into account by PET (potential evapo-transpiration) in the AI (precipitation/PET) calculation. The soil’s evaporation surface area mainly depends on soil texture. Compared with loam and clay soil, sandy soil has stronger water permeability, less surface area, and weaker water evaporation due to capillary action that is conducive to groundwater recharge through precipitation. China has a small fraction of land covered by tropical rainforest. All of the models in this paper generate high-simulated Wro values that are close to or more than 1 in global tropical rainforest regions; thus, this study approximates the maximum simulated Wro value in such regions equal to 0.95.

Two model groups and six regression model results are listed in Tables 3 and 4. Model group A is an unbiased regression model that utilizes all 31,708 samples. Model A2 is a two-variable linear model that simulates the sample region’s Wros by AI and slope, and returns a regression R Square equal to 0.4118. By employing more independent variables, Model A8 and Model A4 are nonlinear regression models that return higher regression R Squares. Model A8 mainly relies on variables of precipitation powers to explain the change in the runoff coefficient and because the driest and wettest regions in the world are not located within the sample region of China, the model produces a negative runoff coefficient in desert areas and may miss the strong evaporation effects in tropical regions. In summary then, Model A8 underestimates the desert area’s runoff coefficient and overestimates the tropical rain forest region’s runoff coefficient. Model A4 is a ramification of Model A2. Model A4 adds two variables whose physical meanings are hard to explain theoretically, but they increase the regression’s R Square value by emphasizing AI’s nonlinear impact on the runoff coefficient. With an obviously higher R Square of 0.5056, it may be a better estimation model than Model A2 mathematically, but it has the same problem as Model A8 in that it overestimates the runoff coefficient in a wet region.

Model group B utilizes 22,500 samples by applying variable restrictions. Although it obviously increased the R Square value of the regression, for instance, Model B2’s R

| Table 3 | China’s runoff coefficient Model A regression results for 31,708 observations |
|---------|---------------------------------|---------------------------------|---------------------------------|
|         | Model A8 | Model A4 | Model A2 |
| Variables | Coefficient | T-value | Coefficient | T-value | Coefficient | T-value |
| Intercept | 0.8837 | 112.59 | 0.6585 | 83.64 | 0.065038 | 32.44 |
| P (mm) | 0.0127 | 82.13 | | | | |
| P0.5 (m) | -6.7860 | -99.54 | | | | |
| P1.5 (m) | -9.8532 | -66.53 | | | | |
| P2.0 (m) | 2.6485 | 53.65 | | | | |
| SL/100 | | | 0.6429 | 72.23 | 0.6073 | 63.05 |
| AI-P-Sl | -0.0789 | -38.54 | | | | |
| AI | | | 4.9967 | 74.38 | 0.3359 | 139.90 |
| AI0.5 | 0.6272 | 38.50 | | | | |
| AI1.5 | 0.1646 | 17.49 | | | | |
| SL-P0.5 | 0.1281 | 67.35 | | | | |
| Regre. Stat. | | | | | | |
| R Square | 0.5888 | | 0.5056 | | 0.4118 | |
| Standard error | 0.1469 | | 0.1611 | | 0.1757 | |
| Observations | 31,708 | | 31,708 | | 31,708 | |
| Independent variable | 8 | | 4 | | 2 | |
Square is almost 0.2 larger than Model A2 which used the same variable set. Actually, it is a sectional and biased regression model that eliminated extreme dry and extreme wet region's samples, i.e., with variable restrictions of $AI < 1.8$, precipitation $> 100$ mm, and real $Wro < 0.65$. The model can only precisely explain the restricted regions’ runoff behavior and if it is applied globally then the reliability of estimation in unrestricted regions decreases sharply. Model B5, a five variable nonlinear regression model with an $R$ Square equal to 0.6852, is used for a regional runoff calculation and for comparison with Model A2. It mainly relies on a precipitation variable to explain the change in the runoff coefficient, but the desert region’s runoff coefficient is underestimated while the tropical rain forest region’s runoff coefficient is overestimated. Model B5 also has the shortcoming of a negative runoff coefficient in arid regions (Figure 4). Model B8 has the largest $R$ square, 0.7016. It employs eight factors that include AI (aridity index), $Y_{\text{min}}$ (climate potential productivity), $PTC$ (percentage tree cover), $Wpp$ (wet season precipitation ratio), $Hpp$ (hot season precipitation ratio), $Cpp$ (cold season precipitation ratio), $Yp/Yt$ (Precipitation productivity/light-temperature productivity), and Elev (Elevation). The three additional independent variables improved the regression's $R$ Square by only 0.0164 as compared with Model B5.

Runoff coefficients for three regression models, Model A2, Model A4, and Model B5, are calculated for spatial comparison between them. If Model A2, Model A4, and Model B5 are plotted together with real $Wro$ on the $X$-axis and three simulated $Wros$ on the $Y$-axis, the figure then shows that the simulation lines are crossing at the $X$-axis section of $0.3 < \text{real } Wro < 0.4$ (Figure 2). Model A4’s simulation line has a slightly steeper slope than Model A2’s, while the two lines are close to each other. Model B5’s simulation line is shorter with the steepest slope, and it has a large number of negative estimated $Wro$ values at the section of real $Wro < 0.06$.

The map of a simulated runoff distribution for Model A2 shows clearly the positive value at the northern-central and southwest parts of the Arabian Peninsula, which matches the irrigation farmland and relatively higher population density in these areas that were examined in the

### Table 4 | China's runoff coefficient Model B regression results for 22,500 observations

| Variables | Model B8 | | Model B5 | | Model B2 | |
|-----------|---------|---------|---------|---------|---------|
|           | Coefficient | $T$-value | Coefficient | $T$-value | Coefficient | $T$-value |
| Intercept | 0.03336 | 3.48 | -0.2095 | -76.5 | -0.03954 | -20.06 |
| AI        | 0.37861 | 110.85 | 0.42537 | 185.51 |         |         |
| $Y_{\text{min}}$0.01 | 0.22321 | 39.64 | 0.3859 | 138.38 | 0.44247 | 47.87 |
| $P_{0.7}$ (m) |         |         | 0.2484 | 44.75 |         |         |
| $SI/100$ |         |         | 0.0918 | 29.77 |         |         |
| $SI_{0.5}$ |         |         | 0.09312 | 30.93 | 0.2484 | 44.75 |
| $PTC_{0.5}$ | -0.83056 | -28.99 | 0.0918 | 29.77 |         |         |
| $Wpp$ | 0.51619 | 19.49 | 0.1357 | 68.28 |         |         |
| $Cpp_{0.5}$ | -0.19506 | -18.46 | 0.0157 | 25.55 |         |         |
| $Yp/Yt$ | 0.13556 | 68.6 | 0.1357 | 68.28 |         |         |
| Elev (km) | 0.00002 | 32.5 |         |         |         |         |
| Regre. Stat. | 0.7016 | | 0.6852 | | 0.6106 | |
| $R$ Square | 0.1061 | | 0.1089 | | 0.1212 | |
| Observations | 22,500 | | 22,500 | | 22,500 | |
| Independent variable | 8 | | 5 | | 2 | |
popular Google Earth application where the satellite depiction was unmistakable (Figure 3). Simulated runoff distribution of Model B5 shows that negative simulated runoff values are assigned to major desert regions, such as the Sahara, central Australia, Central Asia, and the Arabian Peninsula, which obviously undermines Model B5’s reliability in extreme dry regions (Figure 4). If the models are applied worldwide, Model B5 finally overestimates the global runoff volume, by comparing with Model A2, the wet region’s runoff volume increase is more than the dry region’s runoff volume decrease (Table 5). Comparing with Model A2, Model B5’s mean of Wro is 0.0204 less, or 6% less; while its mean of runoff is 49.1 mm more, or 16% more. All of Model B5’s range and standard deviation of Wro and Runoff are obviously larger than Model A2.

By comparing the regression results of Model group A and Model group B, it is found that a sectional model can
be applied to restricted sections to improve the R Square of regression and accuracy of estimation. Such as Model B5, which is a five variable regression model with an obviously higher regression R Square. However, its application area is limited by restricted regions. A regression model with a narrower bound of an AI section is also tried in this study, but it generates a lower regression R Square. If a section restriction of \( AI = [0.450, 0.799] \) is applied for Model A2, the regression R Square is 0.3678, it is less than R Square = 0.4118 of Model A2 without AI restriction; if a section restriction of \( AI = [0.450, 0.799] \) is applied for Model A4, the regression R Square is 0.3725, which is less than the R Square = 0.5056 of Model A4 without AI restriction. Similar regression results happen if narrower section restrictions are applied to Model group B. For further discussion on model selection, a full spectrum sectional model is developed with 31,708 samples of Chinese cases and compared with Model A2 and Model B5 in the Supplementary Material.

### Model simulation and runoff calculation steps

This paper selects Model A2 for a global runoff calculation and starts with a description of the model simulation steps in this section. Assuming that the runoff coefficient is a function of the ground slope (SL), depth of precipitation (P), and PET, and because the aridity index (AI) equals \( P/\text{PET} \), the runoff coefficient function’s independent variables can be simplified as SL and AI. The empirical formula of a runoff coefficient function can be obtained by the sample data through Ordinary Least Square Regression, and then, the global runoff depth and runoff volume can be calculated according to the empirical formula. Specific steps are as follows.

**Step 1:** Regress the empirical formula in the sample area.

According to the formula: \( W_{\text{ros}} = f(SLs, P, PETs) \) (1) and \( AIs = P/PETs \).
Then, we have

$$W_{ros} = f(\text{SLs, Al})$$  

(3)

Because $W_{ros} = R_{s}/P_{s}$.

$$R_{s}/P_{s} = f(\text{SLs, Al})$$  

(4)

So that the empirical formula can be expressed as follows:

$$R_{s}/P_{s} = f(\text{SLs, Al})$$  

(5)

where $W_{ros}$ is the sample area’s runoff coefficient, $\text{SLs}$ is the sample area’s ground slope, $P_{s}$ is the sample area’s precipitation depth, $\text{PETs}$ is the sample area’s potential evapotranspiration, $\text{Al}$ is the sample area’s aridity index, and $R_{s}$ is the sample area’s runoff depth.

**Step 2:** To calculate the global runoff coefficient.

Based on the empirical formula of the sample region, the global runoff coefficient is calculated.

$$Wro = f(\text{SL, Al})$$  

(6)

**Step 3:** To calculate the global runoff depth.

To calculate the global runoff depth based on global runoff coefficient and global precipitation depth, according to the formula:

$$Wro = R/P$$  

(7)

Rearranging terms

$$R = Wro \times P$$  

(8)

where $Wro$ is the global runoff coefficient, $R$ is the global runoff depth, and $P$ is the global precipitation depth.

The observation dates for the sample data employed in this study are as follows: the precipitation of China is 1951–1980 (Jiao Beichen 1984), the runoff depth of China is 1956–1979 (Fan 1989). The global precipitation depth and global aridity index are 1950–2000 (Trabucco & Zomer 2009), and the global ground slope is based on SRTM’s 90 m digital elevation database V4.1 (Jarvis et al. 2008). The GIS data for lakes, major rivers, the boundary of continents source from Natural Earth, NACIS (North American Cartographic Information Society; Patterson et al. 2016).

Steps to calculate the sample area’s empirical formula are as follows. The calculation is based on the distribution map of China’s precipitation, runoff, ground slope, and aridity index. China’s average annual runoff depth map is based on the runoff data from 2,200 hydrological stations, screened from more than 3,000 stations with drainage areas less than 5,000 km². The data have the characteristics of high spatial precision and uniform spatial coverage for China. The scale of the distribution map of China’s precipitation is 1:9,000,000, which is 2.22 times as much as the scale of the world’s continental precipitation map (1:20,000,000) by Korzoun et al. (1977). It clearly shows the medium-sized mountain’s impact on the difference of precipitation and the precipitation distribution in subbasins of large rivers. The empirical formula of the runoff coefficient is suitable to calculate global runoff, mainly due to China’s runoff depth map and precipitation map, which is mostly located at a mid-latitude region. They cover the landforms and land use types comprehensively, including diverse types of climate, geomorphology, and runoff zones with large geographical extent. In addition, the proportion of desert area in China is similar to the global proportion.

By using the ‘create TIN’ (triangular irregular network) function in ArcGIS, China’s runoff depth map and precipitation isoline map is transformed into grid data with a geographic projection. The spatial precision is taken as 0.1667°, which is three times as much as 0.5°. In the geographic projection, the SRTM’s DEM grid data is re-sampled into 0.1667° grid data in the Grid module of ARCINFO, to calculate the ground slope. The global aridity index grid is also re-sampled into 0.1667°. Using the Combine function in ARCINFO’s Grid module, the four sets of grid data for China with spatial precision of 0.1667° (runoff depth, precipitation, percentile slope, and arid index) were combined into one. Then, the runoff coefficient of the sample area is calculated, and the runoff coefficient is regressed with the ground slope, aridity index, to get the empirical formula of the runoff coefficient.

The empirical formula of the runoff coefficient obtained by running the regression for 31,708 effective grid points in
China is as follows:

\[ W_{\text{ros}} = 0.065038 + 0.335936 \cdot AIs + 0.6073 \cdot SLs \]

\[ T^2 - \text{value} = 32.44 \quad 139.90 \quad 63.05 \]

Due to the large sample size and the limited number of explanatory variables employed, the R Square value of the empirical formula is 0.4118, which is not too high, but the \( T^2 \)-value of the constant term and independent variable’s coefficient is very high, which indicates that the credibility of the empirical formula is relatively high. The R Square of the empirical formula of the runoff coefficient depends on the spatial accuracy of the sample data, the number of explanatory variables, and the random variables’ proportion of influence on runoff, such as geological characteristics, soil texture, and the seasonal characteristics of precipitation. The authors use ArcGIS to convert the sample area’s precipitation and runoff contour line into a TIN, which improves the conversion accuracy of the sample data. The R Square increased from 0.3616 to 0.4118, compared with the average value method for contour line to grid conversion.

Steps to calculate the global runoff coefficient and runoff volume are as follows: Step 1, use a global geographic projection, using the Resample command in the Grid module, to transform the grid data of global precipitation, AI and slope into 0.1667° ground resolution. Step 2, using the Combine command in the Grid module at geographical projection, to combine three sets of grid data, the global precipitation depth, the global ground slope, and the global aridity index, into one set. Step 3, in the combined grid data table, to calculate the global runoff coefficient by using the empirical runoff coefficient formula for each grid, and then calculate the global runoff depth by multiplying the precipitation depth and the runoff coefficient. Step 4, using the function of map projection transformation at the grid module, to convert the global geographic projection into Mollweide projection, and to calculate the grid’s area according to grid counts. After the Mollweide equal area projection conversion, each grid’s area is 420.09 km². Step 5, in the Mollweide projection’s data table, to calculate runoff volume by using the area and the runoff depth, to calculate precipitation volume by using the area and the precipitation depth. The global total precipitation and runoff volume data can be calculated by aggregation. Step 6, to convert the GIS layers of the river basins and continents from shape file into grid data with 0.1667° resolution in geographic projection, then to transform the grid data into Mollweide projection, respectively; finally, to merge these grid data with the runoff grid by using the Combine command in the grid module, and to calculate area, runoff volume, runoff depth, precipitation volume, and precipitation depth for river basins and continents.

This study takes 10°E as the central meridian of the Mollweide projection, which passes by Hamburg, Germany and Tunis City, Tunisia. The projection’s edge is 170°W, which crosses the Bering Strait and the Pacific Ocean by cutting through the minimum land area. The land area with severe deformation is only limited to Alaska and Hawaii in the USA, the Chukchi Peninsula in Russia, New Zealand, and the Pacific island countries.

**RESULTS**

This study’s main calculation results are that the global land area (excluding Antarctica) is 133.4067 million km², the average precipitation depth is 777.4 mm, the total precipitation volume is 103,709.8 km³; the average runoff depth is 358.9 mm, the total runoff volume is 47,884.0 km³, and the runoff coefficient is 0.4617. South America is the only continent with a runoff depth higher than the global average, which is 770.3 mm, Oceania is slightly lower than the global average. Africa’s runoff depth is 229.9 mm, the lowest, which is only 64.1% of the world average. South America’s runoff coefficient is also the highest, which is up to 0.5074, followed by Asia, North America, and Europe, which is close to or higher than the global average, Africa’s runoff coefficient is the lowest, which is only 0.3449 (Table 6).

According to the grid data by Worldclim, global precipitation depth ranged between 0 and 11,120 mm. The low-value areas are the Sahara Desert in North Africa, the Taklimakan Desert in Central Asia, the Rub Al Khali Desert in the Arabian Peninsula, and the Atacama Desert in South America, their annual precipitations are less than 50 mm. The high-value areas are the Amazon basin in South America, the Congo Basin of Africa, the island of New Guinea in
Oceania, Southeast Asia, and southeastern Himalayan Mountain in Asia, their precipitations are above 1,800 mm. The data show clearly the impact of the large- and medium-sized mountains on precipitation, as well as the monsoon region’s rainy area affected by the slope aspect and wind direction.

The distribution pattern of the runoff coefficient and runoff depth is similar to the precipitation depth. With the introduction of the slope parameter in this study, the detail changes of runoff coefficient and runoff depth in accordance with topography are revealed, which reflect the ground slope’s impact on runoff depth. Especially, it is shown clearly that the obvious increase of runoff depth on the mountains of the desert area in this study, which is significant for the study of water resource distribution in arid regions (Figures 5 and 6). Compared with the runoff grid data of UNH 2000, this study’s zero runoff area in arid and semi-arid regions is greatly reduced, and it is replaced

| Region          | Area (1,000 km²) | Precipitation (mm) | Precipitation (km³) | Runoff (mm) | Runoff (km³) | Runoff coefficient |
|-----------------|------------------|--------------------|---------------------|-------------|--------------|-------------------|
| Global          | 135,406.7        | 777.4              | 103,709.8           | 358.9       | 47,884.0     | 0.4617            |
| Asia            | 43,296.6         | 632.9              | 27,401.4            | 313.4       | 13,571.2     | 0.4953            |
| Europe          | 9814.6           | 651.4              | 6392.9              | 296.4       | 2908.9       | 0.4550            |
| Africa          | 30,206.6         | 666.7              | 20,137.3            | 229.9       | 6944.4       | 0.3449            |
| North America   | 23,281.8         | 678.6              | 15,798.1            | 323.8       | 7538.0       | 0.4771            |
| South America   | 18,039.5         | 1518.3             | 27,388.6            | 770.3       | 13,896.0     | 0.5074            |
| Oceania         | 8767.7           | 751.8              | 6591.5              | 345.1       | 3025.6       | 0.4590            |
| Minimum         | 632.9            |                    |                     | 229.9       |              | 0.3449            |
| Maximum         | 1518.3           |                    |                     | 770.3       |              | 0.5074            |

Note: Oceania includes the whole island of New Guinea.

Figure 5 | Simulated global runoff coefficient (Mollweide Projection).
by a low runoff region. The runoff increase is particularly obvious in Australia’s and East Mongolia’s interior drainage region. The distribution of a relatively higher runoff depth zone in the Sahara Desert and the Arabian Peninsula as affected by mountains and plateaus is shown clearly.

DISCUSSION

When comparing our results with other continental runoff data, it was found that this study’s estimation is generally higher, but most of the estimates are between the maximum and minimum volume of the 24 sets of data for the 1973–2014 period. These data agree for the most part with the existing literature, and only the Oceania’s runoff volume of this study is slightly higher than the maximum value. The ratios of the median runoff volume by continents are consistent with the existing 24 datasets which are generally between 83.86 and 99.69%. While the ratios of the median runoff volume for Africa and Oceania are 59.58 and 63.35%, which are significantly lower than our results (Table 7). We found that the main reasons for these differences are that this study calculates the runoff depth based on small watershed data, including the interior drainage runoff, the groundwater, and the intermediate water surface evaporation and consumption of large river basins. Whereas most of the existing research only calculated the runoff flowing into the ocean, which does not include interior drainage runoff. Groundwater is the major runoff form in interior drainage basins, where it is difficult to measure and estimate. Even though some literature includes interior drainage basin runoff, it generally does not include groundwater. Most of the literature ignored the watershed’s lake and river channel evaporation and human consumption of the runoff before passing through the gauge station.

Setting the data ratio (other study/this study) between 0.8 and 1.25 as the standard of acceptable data agreement, for the global total runoff volume 19 of the 24 sets of data agrees with this study. This study’s data for Asia agrees the best with 22 sets, followed by the data for Europe, North America, and South America with 19, 16, and 14 sets of data agree well with this study, respectively. For Africa and Oceania, only two sets agree well with this study. Two sets of data agree well with this study with 6/7 of the continent data ratio between 0.8 and 1.25, which is Korzoun et al. (1977) and Shiklomanov (2000). In all of the 24 sets of data,
Korzoun et al. (1977) agree with this study the best, the runoff ratio of the global total runoff is 95%, the ratio of Africa’s runoff is 66.24%, the ratio of Oceania’s is 82.95%, ratios of other continents are between 87.8 and 108.5%.

About Africa’s runoff volume, the estimation result of GRDC’s Report 10 for Africa’s land area is 30.329 million km², the runoff depth is 283 mm, the total runoff volume is 8,583 km³, including the desert area’s runoff, which is overestimated. According to the runoff depth field calculated by this study, if the desert area with runoff depth less than 10 mm (interior drainage region of Western Sahara and East Saharan North) is removed from the runoff calculation, whose area is 5.94 million km², the runoff volume is 26.34 km³, the runoff volume in the remaining 24.389 million km² is 6,902 km³, assuming the runoff depth is 283 mm. In accordance with this algorithm, Africa’s

Table 7  Global runoff estimations for different continents (km³) using 22 datasets

| Year  | Datasets            | World  | Africa | Asia    | South America | North America | Oceania | Europe |
|-------|---------------------|--------|--------|---------|---------------|---------------|---------|--------|
| 1973  | Lvovitch 1973       | 38,830 | 4225   | 13,190  | 10,380        | 5960          | 1965    | 3110   |
| 1975  | Baumgartner 1975-WN07| 37,713 | 3409   | 12,467  | 11,039        | 5840          | 2394    | 2564   |
| 1977  | Korzoun et al. 1977 | 45,560 | 4600   | 14,100  | 12,200        | 8180          | 2510    | 2970   |
| 1993  | Shiklomanov 1993-G14| 44,540 | 4570   | 14,410  | 11,760        | 8200          | 2390    | 3210   |
| 1996  | GRDC 1996a-GW96     | 42,701 | 8583   | 12,562  | 13,584        | 4299          | 1228    | 2446   |
| 1997  | Shiklomanov 1997-WN07| 42,648 | 4040   | 13,508  | 12,030        | 7770          | 2400    | 2900   |
| 1997  | Raskin 1997-G14     | 42,784 | 4050   | 13,510  | 12,030        | 7890          | 2404    | 2900   |
| 1998  | Shiklomanov 1998-G14| 42,740 | 4050   | 13,510  | 12,030        | 7890          | 2360    | 2900   |
| 1999  | Fekete et al. 1999b-G14| 37,758 | 5567   | 11,425  | 11,240        | 5396          | 1308    | 2822   |
| 1999  | Shiklomanov 1999-G14| 41,149 | 3656   | 12,744  | 11,925        | 7860          | 2376    | 2588   |
| 2000  | Vörösmarty 2000-G14 | 39,294 | 4520   | 13,700  | 11,700        | 5890          | 714     | 2770   |
| 2000  | GRDC 2000-Fek2000b  | 39,459 | 4474   | 13,414  | 11,708        | 6478          | 712     | 2673   |
| 2000  | Shiklomanov 2000-Shik2000 | 39,780 | 5082   | 15,008  | 14,350        | 8917          | 2880    | 3410   |
| 2001  | Oki et al. 2001-WN07 | 29,485 | 3616   | 9385    | 8789          | 3824          | 1680    | 2191   |
| 2002  | Fekete et al. 2002-WN07 | 39,307 | 4517   | 13,091  | 11,715        | 5892          | 1320    | 2772   |
| 2003  | Doell 2003-WN07     | 36,687 | 3529   | 11,234  | 11,382        | 5540          | 2239    | 2763   |
| 2004  | GRDC 2004-CT04      | 40,533 | 3590   | 13,250  | 11,896        | 6294          | 1722    | 3083   |
| 2007  | Widen-Nilsson 2007  | 38,605 | 3738   | 13,611  | 9448          | 7009          | 1129    | 3669   |
| 2007  | Sirajul Islam 2007, CT-SI07 | 38,941 | 4533   | 10,797  | 10,183        | 6456          | 1879    | 5093   |
| 2007  | Sirajul Islam 2007, B0-SI07 | 52,657 | 4473   | 15,902  | 10,713        | 9799          | 1943    | 9827   |
| 2009  | GRDC 2009-CT09      | 36,109 | 3511   | 11,603  | 11,083        | 5475          | 1685    | 2752   |
| 2014  | GRDC 2014-WK14      | 41,867 | 4250   | 13,754  | 11,796        | 6856          | 1844    | 3367   |
| 2016  | This study          | 47,884 | 6944   | 13,571  | 13,896        | 7538          | 5026    | 2909   |
| 2016  | Maximum 1973–2014   | 52,657 | 8583   | 15,902  | 14,350        | 9799          | 2880    | 9827   |
| 2016  | Minimum 1973–2014   | 29,485 | 3073   | 9385    | 8789          | 3824          | 712     | 2191   |
| 2016  | Median 1973–2014    | 40,156.5| 4137.5| 13,461  | 11,715.5      | 6667          | 1917    | 2900   |
| 2016  | Median/This study   | 83.86% | 59.58% | 99.19%  | 84.28%        | 88.45%        | 63.35%  | 99.69% |

Note: Shiklomanov 2000 is statistical results in 1921–1985, the world’s largest or smallest value is not equal to the sum of the largest or smallest value of the continents.

Sources: -WN07, Widen-Nilsson et al. 2007; -G14, GRDC 2014; -SI07, Islam et al. 2007; -WK14, Wilkinson et al. 2014; -CT04, Couet & Maurer 2004; -CT09, Couet & Maurer 2007; -GW96, Grabs et al. 1996; -Fek2000b, Fekete et al. 2000.;
total runoff volume is 6,928 km$^3$, which is very close to the author’s estimation for the African runoff volume, 6,944.4 km$^3$, the agreement ratio is 99.8%.

About Oceania’s runoff, Korzoun et al. (1977) estimated that Oceania’s runoff volume is 2,510 km$^3$, including the interior drainage basins with a land area of 3.5578 million km$^2$, the runoff depth of 3 mm, and the runoff volume of 10.67 km$^3$. This study estimates that Oceania’s total runoff is 3,025.6 km$^3$; the interior basin runoff depth is 34.9 mm with the runoff volume of 124.17 km$^3$. If the difference of interior drainage runoff is added up with the total runoff is 3,025.6 km$^3$, which is only 6,944.4 km$^3$, the agreement ratio is 99.8%.

If the difference of interior drainage runoff is added up with the total runoff volume estimated by Korzoun 1977, the total runoff volume is 2,623.5 km$^3$, which is 86.7% of this study’s estimation, and the two numbers are closer to being equal. Korzoun 1977’s estimation of runoff volume into the ocean in Oceania is about 2,499.3 km$^3$, and this study estimates the external runoff volume is about 2,901.4 km$^3$; this study’s estimation value is 402.1 km$^3$ higher. The island of New Guinea’s area is 786,000 km$^2$; the runoff volume difference is equivalent to 512 mm runoff depth on the island of New Guinea. This study’s average precipitation (from Worldclim) on the island of New Guinea is 3,057 mm, the average runoff coefficient is 0.726, and the average runoff depth is 2,220 mm. Due to Korzoun 1977’s precipitation depth on New Guinea island is about 300 mm lower than Worldclim’s, and the runoff coefficient is about 10% points lower than this study’s according to the empirical formula, these two factors make Korzoun 1977’s displayed runoff depth on New Guinea island 494 mm lower than this study’s, accounting for about 96.5% of the runoff difference (512 mm).

For the case of Yellow River basin, its area is 764,146 km$^2$, the calculated runoff depth is 156.1 mm, and the runoff volume is 119.3 km$^3$, while the GRDC’s listed runoff volume for Yellow River is 73.5 km$^3$, which is only 61.6% of the result of this paper. Explanations of the Yellow River’s high runoff depth in this study are as follows. The characteristics of the Yellow River basin’s water resources utilization are large amounts of surface water and groundwater used for agriculture. In addition, a large proportion of water resource in the Loess Plateau exists in the form of soil effective water and groundwater recharge at the middle reaches of the river. The total volume of the Yellow River’s runoff is different in the current literature in accord with the difference of statistical definition and methods. The Institute of Yellow River’s Water Resources Protection (1987) stated that the Yellow River’s total runoff volume is 73.5 km$^3$, in which 65.9 km$^3$ is a surface runoff, 7.6 km$^3$ is the groundwater not repeatedly calculated with the surface runoff; ‘The report on the Yellow River’s water allocation plan’ (1987) by China’s State Planning Commission and Ministry of Water Resources and Electric Power stated that the Yellow River’s total runoff volume is 86.0 km$^3$, in which the Huayuankou hydrologic station and the lower reaches of the Yellow River’s long-term average annual natural runoff are 58.0 km$^3$, total water withdraw on the upper and middle reaches of the river may be as high as 28 km$^3$. Zhang et al. (2011) calculated that the Yellow River’s runoff volume is 71.94 km$^3$, in which surface runoff is 60.72 km$^3$, groundwater is 37.6 km$^3$, and the groundwater not repeatedly calculated with the surface runoff is 11.21 km$^3$. Zhang (2014) calculated that the development potential of rainwater resources (runoff in a broad sense) on the Loess Plateau is 73.1 km$^3$ (including 2.07 km$^3$ in the Ordos interior drainage region); we add Zhang Junfeng’s runoff volume calculation for the Longyangxia reservoir and the upper reach of the Yellow River and the lower reach of the river beyond Huayuankou hydrological station with the runoff volume of 20.93 and 3.79 km$^3$, respectively, the Yellow River basin’s total amount of water resources is 95.75 km$^3$, excluding the interior drainage basin runoff. The amount is close to this study, which is 80.26% of the runoff volume calculated by this study.

According to the current literature, the Yellow River basin’s actual area, depth of precipitation, runoff depth, and runoff coefficient are 764,146 km$^2$, 439 mm, 125.3 mm, and 0.2854, respectively. This study calculated the precipitation depth as 469.6 mm; after adjusting the depth of precipitation, the Yellow River basin’s runoff coefficient and runoff depth are 0.3050 and 133.0 mm in this study; the runoff coefficient is overvalued by 1.76 percentage points by this study, and the ratio of literature’s runoff depth over this study’s is actually 94.2%. An alternative explanation for the overestimation by this study is that the Yellow River watershed runoff coefficient is overestimated. The middle reach of the Yellow River watershed is covered by Quaternary sediment, Loess, which is easily eroded by storm rainfall, and thus, the ground slope in this region is overestimated, resulting in an
overestimation of the runoff coefficient. In reality, loess absorbs and contains the rainfall, which may have a smaller runoff coefficient than rocks.

The evidence of exploitation and utilization of groundwater in the Yellow River watershed supports the results for this study. At the northern piedmont of Qinling Mountain, precipitation forms groundwater runoff or groundwater recharge in the Guanzhong plain through mountainside infiltration. Most of the groundwater resources are extracted by well pumping before flowing into the Wei River. At the southern piedmont of Yin Mountain and the eastern piedmont of Helan Mountain, precipitation infiltrates into the Hetao plain and Ningxia plain, and forms groundwater, and a large amount of groundwater is pumped for irrigation. Most of the water is utilized and consumed through un-gauged well extraction. Those groundwaters are not included in the runoff accounting of the Yellow River. In addition, water evaporation on the lakes, wetlands, and river channel along the river, urban landscape water use, ecological water consumption, industrial and mining water consumption, residential water consumption creates the huge net dissipation of water. If this water consumption is not gauged, then it is normally not accounted for in the runoff of the Yellow River (Figure 7).

The runoff volume in interior drainage basins

This study calculated the detailed runoff pattern of the interior drainage basins. The runoff data of the interior drainage basins by continents and 31 sub-regions are calculated (Figure 8). The global interior drainage region’s total area is 28.47 million km², Asia and Africa’s interior drainage basins are the largest, which are 11.69 and 9.68 million km², respectively. These are followed by Oceania and Europe, whose interior drainage basins are 3.56 and 1.99 million km², respectively. North America and South America’s interior drainage basins are the minimum, which is only...
0.90 and 0.66 million km². The global interior drainage basins runoff depth is 58.4 mm. Oceania’s interior drainage basins have the minimum runoff depth of 34.9 mm. Runoff depths of Asia and Africa’s interior drainage basins are between 48 and 49 mm. Europe’s interior drainage basins are 184.3 mm, which is the highest. North America and South America’s interior drainage basins are slightly higher than the global average, with runoff depths of 76 and 104 mm, respectively (Table 8).

The average runoff depth of the global interior drainage basins calculated by this study (58.4 mm) is much higher than that of the Korzuon 1977’s estimation (33.3 mm). Comparing this study’s runoff depth with the results of UNH 2000 and GRDC’s Report 22, the runoff depths are almost

Table 8 | Estimated runoff volume of the interior drainage basins by this study

| Continents | Area (10,000 km²) | Annual precipitation(km³) | Annual runoff (km³) | Annual precipitation (mm) | Annual runoff (mm) | Runoff coefficient |
|------------|------------------|---------------------------|---------------------|---------------------------|-------------------|------------------|
| Europe     | 199.04           | 1017.12                   | 366.79              | 511.0                     | 184.3             | 0.361            |
| Africa     | 967.97           | 2035.91                   | 466.71              | 210.3                     | 48.2              | 0.229            |
| Asia       | 1168.61          | 2060.48                   | 569.09              | 176.3                     | 48.7              | 0.276            |
| Oceania    | 355.78           | 965.24                    | 124.17              | 271.3                     | 34.9              | 0.129            |
| North America | 89.69        | 279.80                    | 68.13               | 312.0                     | 76.0              | 0.244            |
| South America | 65.79        | 238.30                    | 68.44               | 362.2                     | 104.0             | 0.287            |
| Sum        | 2846.87          | 6596.84                   | 1663.32             | 231.7                     | 58.4              | 0.252            |
the same for the whole interior drainage basins. Comparing with these two studies data by continents, this study’s estimation on runoff depth of Europe, Asia, and Oceania’s interior drainage basins is higher, while lower on Africa, and is in the middle on South America and North America. Because this study estimated the whole interior drainage basins, the total runoff volume of the interior drainage basins was significantly higher than that of UHN2000 and GRDC’s Report 22 (Table 9).

Table 9 | Comparison of runoff in interior drainage basins by continents

| Continents       | This study runoff (km²) | UNH runoff (km²) | GRDC runoff (km²) | This study runoff (mm) | UNH runoff (mm) | GRDC runoff (mm) |
|------------------|-------------------------|------------------|-------------------|------------------------|-----------------|------------------|
| Europe           | 366.8                   | 311.0            | 311.0             | 184.0                  | 165.0           | 157.0            |
| Africa           | 466.7                   | 211.0            | 211.0             | 48.0                   | 67.0            | 53.0             |
| Asia             | 569.1                   | 410.0            | 368.0             | 49.0                   | 26.0            | 36.0             |
| Oceania          | 124.2                   | 0.0              | 0.0               | 35.0                   | 0.0             | 0.0              |
| North America    | 68.1                    | 9.0              | 97.0              | 76.0                   | 26.0            | 179.0            |
| South America    | 68.4                    | 52.0             | 87.0              | 104.0                  | 97.0            | 108.0            |
| Sum              | 1663.3                  | 993.0            | 1074.0            | 58.4                   | 58.0            | 54.0             |

For the 31 interior drainage sub-regions estimated in this study, East Africa North and East Africa South’s runoff depths are more than 250 mm, which has the most abundant runoff in the 31 sub-regions; the runoff depth of the interior drainage basins of Europe Interior and Southwest Caspian is more than 175 mm. The interior drainage basins of Southern Andes, and Amu River and Sihl River in Central Asia have the runoff depth between 100 and 150 mm, which is obviously above the global average of the interior drainage basins. Other interior drainage sub-regions’ runoff depth are below 100 mm, in which the lowest is the Western Sahara, East Sahara North, and South Arabia, whose runoff depth is below 10 mm, while the North Arabia’s runoff depth is 16.4 mm. China’s Tarim Basin is surrounded by high runoff mountains and its runoff depth is 24 mm, which is higher than the above four desert areas’ runoff depth (Table 10).

Comparison of runoff volume in Africa’s interior drainage basins

According to this study’s calculation, the area of the interior drainage basins of Africa is 9.6797 million km², the annual

Table 10 | Global interior drainage basins runoff by sub-regions estimated by this study

| Sub-regions       | Area (10,000 km²) | Runoff (mm) | Runoff coefficient | Sub-regions       | Area (10,000 km²) | Runoff (mm) | Runoff coefficient |
|-------------------|------------------|-------------|--------------------|-------------------|------------------|-------------|-------------------|
| Europe Interior   | 199.04           | 184.3       | 0.361              | Northern Tibet    | 62.05           | 44.5        | 0.249             |
| Western Sahara    | 306.92           | 7.2         | 0.126              | Tarim Basin       | 110.82          | 24          | 0.326             |
| East Sahara North | 287.05           | 1.5         | 0.101              | Lake Balkhash     | 75.83           | 79.9        | 0.320             |
| East Sahara South | 224.71           | 85.9        | 0.214              | Qaidam Basin      | 38.27           | 46.8        | 0.302             |
| East Africa North | 41.67            | 258.7       | 0.378              | Hexi Corridor     | 54.65           | 30.2        | 0.248             |
| Southwest Africa  | 86.41            | 95.1        | 0.181              | West Mongolia     | 60.75           | 41.1        | 0.280             |
| East Africa South | 21.21            | 270.3       | 0.324              | East Mongolia     | 77.04           | 37.7        | 0.191             |
| North Arabia      | 86.83            | 16.4        | 0.130              | East Australia    | 208.24          | 37.8        | 0.133             |
| Iran Plateau      | 129.56           | 28.9        | 0.206              | West Australia    | 147.54          | 30.8        | 0.122             |
| Turkmenistan      | 42.98            | 39.0        | 0.195              | US Interior West  | 38.35           | 70.6        | 0.275             |
| Amu River         | 69.69            | 141.9       | 0.446              | US Interior East  | 15.63           | 89.4        | 0.270             |
| Sihl River        | 49.95            | 106.6       | 0.37               | US-Mexico Interior| 11.01           | 65.7        | 0.201             |
| Kazakhstan Hills  | 78.56            | 48.3        | 0.215              | Mexico Interior   | 24.7            | 80.3        | 0.212             |
| East Caspian      | 53.14            | 26.9        | 0.156              | Middle Andes      | 34.45           | 74.3        | 0.296             |
| South Arabia      | 132.29           | 9.2         | 0.121              | Southern Andes    | 31.34           | 136.8       | 0.282             |
| Southwest Caspian | 46.21            | 175.2       | 0.405              | Sum               | 2846.87         | 58.4        | 0.252             |
runoff is 466.71 km³, the annual runoff depth is 48.2 mm, and the runoff coefficient is 0.229. According to ‘The Atlas of Africa’ (Rui Mujie 1985) with the runoff data’s period in 1956–1984, the total area of Africa’s interior drainage basins is 9.58 million km², the annual runoff is 500 km³, and the annual runoff depth is 52.2 mm. The estimation is close to this study, and the ratio (over this study) of area, runoff, and runoff depth are 99.0, 107.1, and 108.3%, respectively.

For the spatial distribution of runoff depth in Africa, UNH 2000 shows that the runoff depth is 0 in the vast majority area of Western Sahara, East Sahara North, and southern piedmont of Atlas Mountains. This study shows that the two Sahara regions’ runoff depths are 7.2 and 1.5 mm, respectively, and also shows obviously the runoff existence on the south piedmont of the Atlas Mountains and the mountain areas in the hinterland of Sahara Desert. Korzuon 1977’s runoff depth in these regions is between UNH 2000’s and this study’s, it shows that the runoff depth in most of the region is below 1 mm and shows the evidence of higher runoff on the south piedmont of the Atlas Mountains and the mountain areas of Sahara Desert. For the interior drainage basins of Southwest Africa, the UNH 2000’s runoff depth in most of the region is 0, while the minimum runoff depth of this study in this region is 45 mm, and the minimum runoff depth of Korzuon 1977 is 15 mm. Generally, for the estimation of runoff depth in the interior drainage basins of Africa, this study’s is the highest, the Korzuon 1977’s value is in the middle, and the UNH 2000’s value is the lowest. The phenomenon is in conformity with the theoretical hypothesis that the higher the spatial resolution, the greater the runoff depth.

Comparison of runoff volume in Oceania’s interior drainage basins

For Oceania’s interior drainage basins, the runoff depth calculated by UNH 2000 is all 0. Korzuon 1977’s Oceania runoff depth map shows that the runoff depth of the interior drainage basins of western Australia is below 1 mm, and the interior drainage basins of eastern Australia’s is below 5 mm; this study calculated the Oceania interior drainage basins’ runoff depths are all above 12 mm, with an average of 37.8 mm in the eastern part, and 30.8 mm in the western part. For the estimation of runoff depth of the interior drainage basins of Oceania, it also showed the trend of this study’s value is the maximum, Korzuon 1977’s is in the middle, and UNH 2000’s is the minimum.

Evidence of higher runoff depth in Oceania’s interior drainage basins is as follows. According to the water balance formula, R = P – ET, i.e., the evaporation model, as long as the interior drainage basin’s PET and the area of perennial lake and wetland, is measured, the interior drainage basin’s runoff volume can be calculated. The lake and wetland’s area is about 40,000 km² in the East Australia interior drainage basins, the average PET is 2,091 mm, the evaporation volume on water surface and wetland is 83.6 km³. The East Australia interior drainage basin’s area is 2.0824 million km², so that the underground and surface runoff depth is 40 mm. Lake and wetland’s area in the West Australia interior discharge area is about 25,000 km², the average PET is 2,091 mm, the evaporation volume on water surface and wetland is 52.3 km³. The West Australia interior discharge basin’s area is 1.4754 million km², so that the underground and surface runoff depth is 36 mm. According to the calculation above, the average runoff depth of Australia’s interior discharge region is 38.2 mm. Calculated by the empirical formula, this study concludes that the runoff volume of Australia’s interior discharge area is 124.2 km³ and the runoff depth is 34.9 mm. The results are very close to the evaporation model’s calculation results; the ratio of runoff depth estimated by evaporation model over this study’s is 109.5%.

Comparison of runoff volume in Asia’s interior drainage basins

Evidence of runoff in Asia’s four interior discharge regions is as follows. For Nura River in Kazakhstan Hill’s interior drainage region, the watershed area is 55,000 km², the terminal lake’s area is 1,980 km², the trunk river length is 978 km, and the average width of the river channel and washland is about 1 km, such that the watershed’s total area of water surface and wetland is 2,958 km². The average annual potential evapo-transpiration (PET) is about 1 m. According to the evaporation model, the total runoff of groundwater and surface water is 2.958 km³, and the average runoff depth is 53.8 mm. It is close to this study's
result that the estimated value of Kazakhstan Hill’s runoff depth is 48.3 mm and the ratio over this study’s is 111.4%. According to the GRDC data, Nura River’s average annual surface runoff is 0.9 km³, the surface runoff depth is 16.36 mm, while the WRI’s result is that the whole basin’s runoff depth is only 3.3 mm (Gassert et al. 2014).

For the Hexi Corridor interior drainage region, this study calculated the average runoff depth of the region as 30.2 mm, the sub-region of Helan mountain’s runoff depth is close to 80 mm, and Qilian mountain’s runoff depth is more than 350 mm, which is the highest in the region. This study shows that the runoff depth field reflects the precipitation increasing effect of the Yabulai Mountain. According to the author’s field investigation, groundwater and seasonal flood runoff generated by Yabulai Mountain provide the available water resources for Yabulai Salt Lake’s salt mining industry, the residents of Yabulai town and several agricultural and animal husbandry villages along the eastern piedmont area. In the Tenggeli desert, lakes, wetlands, and salt marshes are widely distributed between sandy dunes, which are the evidence of groundwater generated by the seasonal precipitation in the desert. Groundwater in the western piedmont of Helan Mountain provides plenty of water for the towns of Barunbieli, Bayanhaote, Xilingaole, and Jilantai Salt Lake’s salt mining industry. The population is mainly distributed in the narrow strip of the western piedmont of Helan Mountain, which has abundant underground water runoff. However, the runoff depths of the UNH 2000’s runoff depth map for those regions are all 0.

For the East Mongolia interior drainage region, the UNH 2000’s runoff depth map shows the runoff depth of this sub-region is 0; Korzuon 1977’s runoff depth map shows that the runoff depth is between 1 and 10 mm, with the maximum value of more than 20 mm. The runoff depth field of this study shows that the runoff depth is 10–30 mm in the central and western part of this sub-region, with the maximum value of 50 mm in the southeastern piedmont of Hangayn Mountain; the eastern part’s runoff depth is generally more than 50 mm, with the maximum value of more than 100 mm. The whole region’s average runoff depth is 37.7 mm. Evidence of runoff in Mongolia’s Gobi desert area is that the Ongi River in southern Mongolia is a perennial River, with a large area of terminal lakes and wetlands; several rivers flow north on the northern slope of Yinshan Mountain, including Albu-gai River and Tabu River, the rivers end at a salt marsh depression in the north and provide irrigation water for agricultural development along the river bank, which forms a string of small-sized oases and medium-sized oases in the terminal open land, such as Jiang’an township in Siziwangqi, Inner Mongolia. The surface and groundwater of Hunshandake Sandy Land flow into large lakes like Dalainuoer Lake with an area of 230 km² and Chagannuoer Lake with an area of 100 km², and more than 10 small lakes, it represents a strong evidence of runoff existence in this region. The rivers of Xilinguole interior drainage basins flow from Ulga River in the north into the Ulga Lake and marshland regions, forming a lake with the area of 206 km² combined with a large area of river channel wetlands, which also proves that the interior discharge area has abundant runoff (Figure 9).

For the Arabian Peninsula’s two interior drainage basins, the UNH 2000’s runoff depth map shows the runoff depth of this sub-region is 0; Korzuon 1977’s runoff depth map shows that the runoff depth is between 1 and 10 mm, with the maximum value of more than 10 mm at Hejaz Mountain. The runoff depth field of this study shows that the maximum value of more than 50 mm is located at mountains in the southwest and northwest parts of the peninsula. The runoff depth of Buraydah high runoff value area is 25 mm due to higher precipitation on the Nejd Plateau. The estimated average runoff depth is 16.4 mm for the North Arabia interior discharge sub-region, and 9.2 mm for the South Arabia sub-region. Evidence of the existence of runoff is that there are seasonal rivers of Ruma and the dry river of Batin flows from Buraydah City at central Saudi Arabia to the northeast direction and extended to the border of Kuwait and Iraq. According to a Google Earth image, there is an oasis zone centered at Buraydah City, stretching from northwest to southeast along the eastern edge of the Arabian Plateau, and there are a large number of circles representing central-pivot sprinkler irrigation in this zone. The oasis zone is located at the relatively higher precipitation area in the northeastern part of the Arab Plateau and it represents strong evidence of the existence of groundwater in this sub-region.

The case analysis of the typical interior drainage basins shows that the runoff depth field calculated by the empirical
formula is in accordance with the actual runoff distribution. Due to the spatial resolution in this study > Korzuon 1977 > UNH 2000, and the estimated runoff value is also this study > Korzuon 1977 > UNH 2000, the theoretical hypothesis is confirmed for the interior drainage basins sub-region; the higher the spatial resolution, the larger the calculated runoff values.

**CONCLUSION**

The main conclusions of this study are as follows: (1) The spatial resolution of this study is 0.1667, which is three times the resolution of most studies that have computed a runoff calculation. As a result of this higher spatial resolution, the runoff volume from our study is higher than the runoff volume reported in the majority of prior studies. Therefore, the theoretical hypothesis that a higher spatial resolution of a runoff field can lead to a higher runoff volume estimation is confirmed. (2) The difference between the runoff estimation of this study and the actual measured runoff should be the regional water consumption by evaporation from natural water surfaces and wetlands, the net water consumption by agricultural irrigation, and the net dissipation of water resources from urban and industrial land use in the watershed. (3) The current literature’s underestimation of water resources is mainly due to the exclusion of evaporation from water bodies and wetlands, plus the net dissipation of artificial water usage in watersheds, and from ignoring the runoff in interior watersheds.

Some issues need to be further addressed to improve the accuracy of runoff distribution simulation. For instance, data error transmission between different climate data sources in regional runoff calculations is one issue, while geographical location accuracy in complex terrain regions is a second issue, both of which are critical for accurate runoff model calculations. Other issues include the quality of original precipitation, runoff, and PET data which can affect the

![Figure 9](image-url)
regression model’s precision and accuracy substantially. Enhancing the density of meteorological stations and runoff gauging stations and collecting more reliable climate and runoff data are additional critical issues to improve the performance of a simulation model.

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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