Detect Water Storage by Swarm

Subjects: Remote Sensing

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The Gravity Recovery and Climate Experiment (GRACE) satellite provides time-varying gravity field models that can detect total water storage change (TWSC) from April 2002 to June 2017, and its second-generation satellite, GRACE Follow-On (GRACE-FO), provides models from June 2018, so there is a one year gap. Swarm satellites are equipped with Global Positioning System (GPS) receivers, which can be used to recover the Earth’s time-varying gravitational field. Swarm’s time-varying gravitational field models (from December 2013 to June 2018) were solved by the International Combination Service for Time-variable Gravity Field Solutions (COST-G) and the Astronomical Institute of the Czech Academy of Sciences (ASI). On a timely scale, Swarm has the potential to fill the gap between the two generations of GRACE satellites.

GRACE Swarm GRACE follow on gap TWSC global basins

1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite is the first satellite mission dedicated to Earth gravity sounding, launched by the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR). In the decade since its launch in March 2002, GRACE has been widely used to detect Earth-mass transport, including total water storage change (TWSC) [1][2], changes in the Antarctic and Greenland ice caps [3][4], and global sea-level changes [5][6], making important contributions to Earth science-related research and functioning as an important tool for estimating changes in terrestrial water reserves. However, in September 2017, one of the batteries in the GRACE-2 satellite failed, and its mission was successfully ended in mid-October 2017 [7][8]. Now, the GRACE time-varying gravity field model provided by the three major international centers, the Jet Propulsion Laboratory (JPL), the University of Texas Space Research Institute (CSR), and the German Geosciences Research Center (GFZ), is currently up to date only as of June 2017. The successor to the GRACE mission, GRACE Follow-On (GRACE-FO), was successfully launched on 22 May 2018 in California, USA, and its measurement principle is similar to that of GRACE, so its model can be used to continue the study of TWSC. However, the GRACE-FO time-varying gravity field model data are now published from June 2018, which means that there is a one-year gap between GRACE and GRACE-FO, so, valid and reliable data need to be found to fill this gap and ensure the consistency of the time-varying gravity field information time series.

On 22 November 2013, the European Space Agency (ESA) successfully launched an Earth observation satellite constellation, Swarm, consisting of three satellites, similar to the Challenging Mini-satellite Payload (CHAMP) mission. Although its mission is mainly to monitor the Earth’s magnetic field variations, it can also be applied to study the time-varying gravity field because it carries high-precision Global Navigation Satellite System (GNSS) receivers and other key gravity detection equipment, thus filling the observation gap between GRACE and GRACE-FO [9]. The published Swarm time-varying gravity field models are the model from December 2013 to June 2019, solved by COST-G, and the model from December 2013 to October 2018, solved by ASI. The Swarm of both institutions allows the continuity of GRACE and GRACE-FO observations on a time scale, so it is particularly important to determine the feasibility and effectiveness of the Swarm-based model to recover changes in terrestrial water storage. In recent years, several scholars have used the Swarm time-varying gravity field model to detect water storage changes in basins. Lück et al. (2018) studied the possibility of Swarm bridging GRACE and GRACE-FO, and the possibility of using Swarm time-varying gravity field with significantly lower resolution to replace GRACE time-varying gravity field in missing months [10]. Meyer et al. (2019) provided a long-term time series of monthly gravity field solutions by combining laser satellite data, GPS and K/Ka band observations of GRACE mission and GPS observations of three Swarm satellites. In their study, the lunar gravity field from Swarm was used to fill the gap between GRACE and GRACE-FO tasks [11]. Li et al. (2019) used the Swarm time-varying gravity field to estimate terrestrial water storage changes in the Amazon Basin and the water storage deficit caused by the 2015/2016 drought event. Comparing GRACE data, hydrological models, and hydrological station data, they found that the Swarm results were in good agreement with GRACE, hydrological models, and virtual hydrological station estimates, providing a new and effective way to detect terrestrial water storage changes and drought events. It also has the potential to replace the GRACE satellite to detect extreme droughts and floods in the Amazon basin [12]. Cui et al. (2020) compared Swarm with the GRACE/GRACE-FO models in terms of model accuracy, observation noise, and inverted TWSC and the results verified that Swarm time-variable gravity field has the potential to extract TWSC signals in the Amazon River Basin and can serve as a complement to GRACE/GRACE-FO data for detecting TWSC in local areas [13]. Forootan et al. (2020) applied time-variable gravity fields (2013 onward) from the Swarm Earth explorer mission with a low spatial resolution of ∼1500 km. A novel iterative reconstruction approach was formulated based on independent component analysis (ICA) combining GRACE and Swarm fields. The reconstructed TWSC fields of 2003–2018 were compared with a commonly applied reconstruction technique and GRACE-FO TWSC fields, and the results indicated considerable noise reduction and improved long-term consistency of the iterative ICA reconstruction technique. These models were applied to evaluate trends and seasonal mass changes (for 2003–2018) within the world's 33 largest river basins [14]. However, all the research does not define the best Swarm data processing and does not estimate the potential of Swarm worldly. Therefore, how to preserve the original Swarm signal as much as possible and how to better detect water storage changes in more basins will be the focus of ongoing Swarm-based research.

This paper targets 26 regions worldwide (see **Figure 1** and **Table 1**) and explores regional water storage change time series between December 2013 and June 2017 from two institutions (ASI and COST-G) under different treatment strategies by computing the results of GRACE (GRACE-TWSC) and comparing them with the limits of Swarm in water storage detection and the optimal processing strategy. Finally, the TWSC of the Amazon, Volga, and Zambezi Basins is constructed to demonstrate the potential of Swarm to fill the gap between the two generations of GRACE missions.

Table 1. The information of the 26 regions.

NO	Basin	Location	NO	Basin	Location	NO	Basin	Location
1	Yukon	North America	10	Nile	Africa	19	Lena	Asia
2	Mackenzie	North America	11	Congo	Africa	20	Kolyma	Asia
3	Nelson	North America	12	Zambezi	Africa	21	Amur	Asia
4	Mississippi	North America	13	Orange	Africa	22	Huang He	Asia
5	St Lawrence	North America	14	Danube	Europe	23	Yangtze	Asia
6	Amazon	South America	15	Euphrates and Tigris	West Asia	24	Ganges and Brahmaputra	Asia
7	Parana	South America	16	Volga	Asia	25	Indus	Asia
8	Niger	Africa	17	Ob	Asia	26	Murray Darling	Australia
9	Lake Chad Basin	Africa	18	Yenisey	Asia			

3. Reasons for Applying Swarm-TWSC

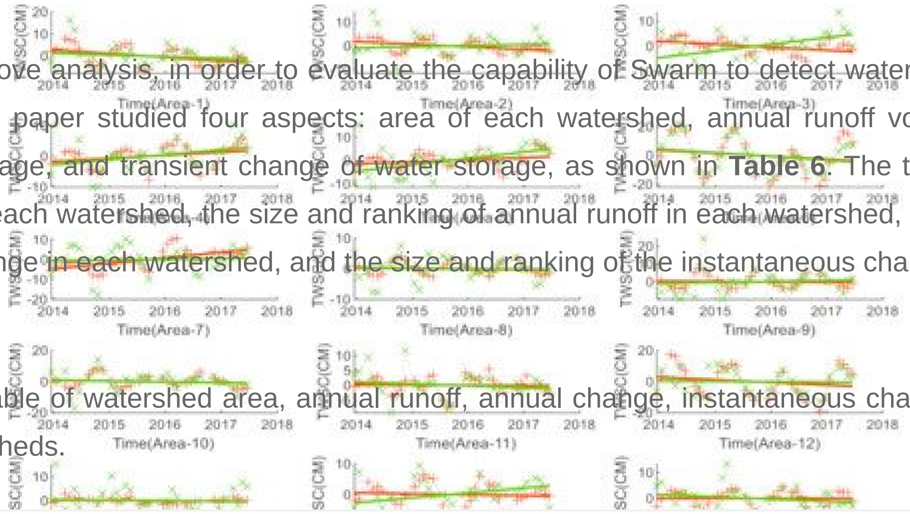
Swarm satellites have constant accuracy in detecting water storage changes in different basins and different detection capabilities in different basins, which is caused by the different characteristics of the basins. The size of the watershed affects the number of Swarm-TWSC statistical grid points, and the regional water storage variation we obtained is the sum of water storage variation for all grid points. According to statistical theory, in general, the more statistics of equal precision are introduced, the more reliable the results. Therefore, the size of the watershed area affects the accuracy of Swarm detection of regional water storage. In general, the most important factor that

2. Applicability Analysis of Swarm-TWSC

Based on the optimal data processing strategy of the Swarm model for detecting water storage variability in terrestrial areas obtained in Section 3.1, Swarm-TWSC was calculated for 26 areas and compared with GRACE-

TWSC in terms of correlation coefficient and root mean square error to evaluate the capability of the Swarm model for water storage detection.

The magnitude and accuracy of Swarm’s water storage potential are closely related to the characteristics of the area under study. To this end, this paper is based on water storage trends detected by the GRACE time-varying gravity field model for 26 major global basins between December 2013 and June 2017, i.e., GRACE-TWSC, and the basin area, average annual runoff within the basin, and annual and instantaneous changes in basin water storage are calculated for each basin. The results can be seen in **Figure 2** and **Table 2**.



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causes mass changes in basins is changes in water, and surface water is the main component of the total water, while the size of annual runoff represents the total amount of annual surface water in basins. The quality change of basins detected by Swarm has a certain relationship with the size of runoff, so we also included it in the factors that cause good or bad effects of water storage detection by Swarm. Swarm detects total water storage variation in basins, so it is necessary to analyze this indicator to study the applicability of Swarm. Based on the trend of water storage changes in basins detected by GRACE, the average annual change of water storage can be obtained, combined with the size of the basin, and the applicability of Swarm can be assessed by this indicator. In addition, it is necessary to analyze the degree of water storage change in each basin when assessing the detection capability of Swarm in different basins.

To synthesize the above analysis, in order to evaluate the capability of Swarm to detect water storage changes in terrestrial areas, this paper studied four aspects: area of each watershed, annual runoff volume, annual mass change of water storage, and transient change of water storage, as shown in **Table 6**. The table shows the size and area ranking of each watershed, the size and ranking of annual runoff in each watershed, the size and ranking of overall quality change in each watershed, and the size and ranking of the instantaneous change in water storage in each watershed.

Table 6. Statistical table of watershed area, annual runoff, annual change, instantaneous change information and ranking for 26 watersheds.

NO	Basin	Area (10,000 km^2)	Rank	Runoff (km^3)	Rank	Average Mass Change (km^3)	Rank	Instantaneous Change (cm)	Rank	Result Rank
6	Amazon	691.5	1	6906.38	1	−145.91	1	13.66	1	1
16	Volga	138	14	254.18	14	19.73	10	4.61	5	2
12	Zambezi	138	13	311.1	13	−23.18	7	9.96	2	3
7	Parana	310.3	5	800	4	86.57	2	4.83	4	4
17	Ob	297	6	385	9	58.51	3	3.8	8	5
18	Yenisey	260.5	7	625.36	5	−19.54	11	3.38	12	6
24	Ganges and Brahmaputra	132.6	15	165.4	19	−40.97	5	8.94	3	7
10	Nile	335	3	81	21	−20.1	8	3.75	9	8
1	Yukon	83.5	22	200.6	17	−14.11	13	4.22	6	9
8	Niger	209	9	200	18	−5.43	20	1.97	22	10

NO	Basin	Area (10,000 km^2)	Rank	Runoff (km^3)	Rank	Average Mass Change (km^3)	Rank	Instantaneous Change (cm)	Rank	Result Rank
4	Mississippi	323	4	599.5	6	32.95	6	3.59	10	11
11	Congo	401	2	1292.98	2	−2.81	22	3.02	18	12
19	Lena	249	8	540	7	−10.21	16	2.57	19	13
25	Indus	116.55	16	207	15	−7.34	18	3.1	16	14
9	Lake Chad Basin	100	20	450	8	−5.06	21	3.35	13	15
2	Mackenzie	180.5	11	357.2	10	−19.86	9	2.75	21	16
23	Yangtze	180	12	1160	3	13.5	15	3.15	15	17
15	Euphrates and Tigris	104.8	18	62.06	23	51.46	4	3.06	17	18
20	Kolyma	64.4	25	123	20	0.90	26	3.35	14	19
14	Danube	81.7	23	203	16	−2.53	24	3.83	7	20
5	St Lawrence	30	26	332.39	12	2.7	23	3.47	11	21
13	Orange	102	19	15.45	25	−2.04	25	1.08	26	22
21	Amur	185.5	10	346.5	11	−16.51	12	1.6	24	23
3	Nelson	115	17	74.7	22	−13.91	14	2.69	20	24
26	Murray Darling	100	21	5.99	26	6.3	19	1.76	23	25
22	Huang He	79.5	24	58	24	−7.39	17	1.52	25	26

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17	Ob	297	385	1.97	58.51	0.86	77.13	3.89
18	Yenisey	260.5	625.36	−0.75	−19.54	−0.62	74.67	3.22
19	Lena	249	540	−0.41	−10.21	−0.5	57.62	4.16
20	Kolyma	64.4	123	0.14	0.90	−0.42	39.37	5.62
21	Amur	185.5	346.5	−0.89	−16.51	0.52	3.64	4.34
22	Huang He	79.5	58	−0.93	−7.39	0.12	−8.31	4.79
23	Yangtze	180	1160	0.75	13.5	−0.33	53.41	4.03

have the nal water hat affects ts Swarm tter (8th).

In analyzing whether the Swarm’s ability to detect regional water reserve changes is related to the total change of annual water reserve of the basin itself, among the basins with a Swarm detection effect, there are 10 in the top 14. Similar to the analysis of the first two factors, the total change of annual water reserve can indeed affect Swarm’s

NO	Basin	Area (10,000 km^2)	Runoff (km^3)	GRACE-Trend (cm/Year)	Average Mass Change (km^3)	Swarm-Trend (cm/Year)	Correlation Coefficient (%)	RMSE (cm)
24	Ganges and Brahmaputra	132.6	165.4	−3.09	−40.97	−2.09	73.56	6.05
25	Indus	116.55	207	−0.63	−7.34	−0.65	52.06	4.73
26	Murray Darling	100	5.99	0.63	6.3	−1.58	−1.68	5.26

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affect Swarm's detection ability, but it is not the only factor. For example, the annual change of water reserves in watershed 11 is small (ranked 22nd), but Swarm's detection results are better (ranked 12th); the instantaneous water reserves in watershed 14 are large (7th), but Swarm's detection ability is poor (20th).

From the perspective of long-term trends (see **Figure 2** and **Table 2**), Swarm-TWSC and GRACE-TWSC show the same trend of increased and decreased water storage in basins 1, 4–8, 10–13, 16, 17, 19, 24, and 25, and the other basins have the opposite results.

Combining the above analyses, the four factors all influence Swarm's ability to detect changes in water storage in basins. In order to quantify the degree of influence of various factors, we calculated the correlation coefficients between the rankings of various factors and the Swarm detection effect so as to count the proportion of influence of the factors on the detection results (see **Table 7**).

In order to reflect the closeness of the correlation between variables, we use the correlation coefficient in this paper (see **Table 3**). The correlation coefficient is calculated by the product-difference method based on the deviation of two variables from their respective means, and reflects the degree of correlation between them by multiplying the two deviations. To get the periodic accuracy of Swarm-TWSC in 26 basins, we get the cycle repetition time of each basin between GRACE-TWSC and Swarm-TWSC (see **Table 4**).

Table 7. Statistics on the degree of influence of different factors on Swarm-TWSC in 26 watersheds.

	Area	Yearly Runoff	Total Mass Change	Instantaneous Mass Change
Correlation Coefficient (%)	58.75	52.33	60.96	77.8
Impact ratio (%)	23.66	20.99	24.45	31

Correlation Coefficient (%)	[−100, 80)	[−80, 30)	[−30, 30]	(30, 80]	(80, 100]

The results show that Swarm detects regional water storage changes on land mainly related to transient changes in regional water storage, followed by total mass change, the area of basins, and finally annual runoff.

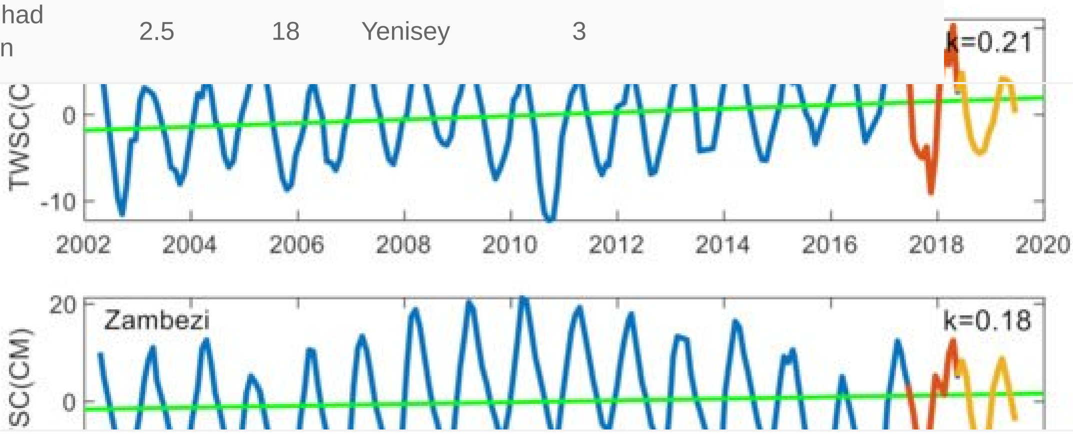
Table 4. Statistical table of cycle repetition time of 26 basins (December 2012 to June 2017).

4. Long-Time GRACE-Swarm-GRACE-FO-TWSC

NO	Basin	Cycle Repetition Time (Year)	NO	Basin	Cycle Repetition Time (Year)	NO	Basin	Cycle Repetition Time (Year)
1	Yukon	3	10	Nile	3	19	Lena	3
2	Mackenzie	2.5	11	Congo	3	20	Kolyma	2.5
3	Nelson	2.5	12	Zambezi	3	21	Amur	1
4	Mississippi	3	13	Orange	0.5	22	Huang He	0.5
5	St Lawrence	1.5	14	Danube	3	23	Yangtze	2.5

17 years

6	Amazon	3.5	15	Euphrates and Tigris	2.5	24	Ganges and Brahmaputra	3
7	Parana	3	16	Volga	3.5	25	Indus	2.5
8	Niger	3	17	Ob	3	26	Murray Darling	1
9	Lake Chad Basin	2.5	18	Yenisey	3			



From the per ve correlation between Swa are basins 1, 2, 4–12, 14, 1 3, 16, 21, 22, and 26.

Table 5. Stati

NO	Basin	Trend	Relevance	Similar Period Ratio
1	Yukon	Same	Positive Weakly	86
2	Mackenzie	Conversely	Positive Weakly	71
3	Nelson	Conversely	Irrelevant	71
4	Mississippi	Same	Positive Weakly	86
5	St Lawrence	Same	Irrelevant	43
6	Amazon	Same	Positive Strong	100
7	Parana	Same	Positive Weakly	86
8	Niger	Same	Positive Weakly	86
9	Lake Chad Basin	Conversely	Positive Weakly	71
10	Nile	Same	Positive Weakly	86
11	Congo	Same	Positive Weakly	86
12	Zambezi	Same	Positive Weakly	86
13	Orange	Same	Irrelevant	14
14	Danube	Conversely	Positive Weakly	86
15	Euphrates and Tigris	Conversely	Positive Weakly	71
16	Volga	Same	Positive Strongly	100

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d models, jor basins CE model he seven Swarm to weighted oach may detection capability of the seven results as much as possible, which is more convincing for multiple regions and long time periods.

NO	Basin	Trend	Relevance	Similar Period Ratio
17	Ob	Same	Positive Weakly	86
18	Yenisey	Same	Positive Weakly	86
19	Lena	Same	Positive Weakly	86
20	Kolyma	Conversely	Positive Weakly	71
21	Amur	Conversely	Irrelevant	29
22	Huang He	Conversely	Irrelevant	14
23	Yangtze	Conversely	Positive Weakly	71
24	Ganges and Brahmaputra	Same	Positive Weakly	86
25	Indus	Same	Positive Weakly	71
26	Murray Darling	Conversely	Irrelevant	29

(see **Table 4** and **Table 5**). By counting the periodic repetition time periods of the two results and calculating their repetition time ratios, we can see that Swarm performs better in basins 1–4, 6–12, 14–20, and 23–25, with the same periodic repetition ratio above 70%, and performs worse in basins 5, 13, 21, 22, and 26.

The long-term trend of water storage changes in land areas is the combination of the two satellite sounding results, and to some extent covers abrupt errors at certain points in time (which can be considered coarse deviations, such as those created by unspecified instrumentation failure, etc.); the correlation between the two results can assess the reliability of the Swarm sounding results. The degree of deviation can measure the accuracy of the Swarm composite value, i.e., the accuracy of the detected water storage height variation value, and the validity of the detection results can be measured by comparing the same length of variation of Swarm-TWSC with the periodic fluctuation of GRACE-TWSC and the increasing or decreasing range of water storage variation, thus reflecting the similar proportion of its periodic variation.

Comparing these three measures, among the 26 major global land basins studied in this paper (see **Table 17**), we can get the conclusions (**Figure 3**). Swarm has the best performance in basins 6, 12, and 16 and the second-best accuracy in basins 1, 4, 7, 8, 10, 11, 17, 18, 19, 24 and 25, and can be used when the GRACE series satellites are not available. Swarm could replace GRACE to detect the water storage changes in the above regions. The accuracy of Swarm-TWSC is very bad in basins 3, 5, 13, 21, 22, and 26, so it is not recommended to use the original Swarm-TWSC to detect the water storage change in these basins. For regions 2, 9, 14, 15, 20, and 23 on the whole, Swarm can detect the periodic change of water reserves correctly. However, because the change value of water reserves detected by Swarm may have gross errors at some time points, Swarm-TWSC and GRACE-TWSC have opposite long-term change trends of water reserves. If these gross errors are eliminated, such as basin 2, and if only Swarm-TWSC between 2015 and 2017 is used, the change of water reserves during this period can be detected correctly. Therefore, this paper suggests that the

but not from a spatial perspective, however, this conclusion does not hinder the utility of reference for other scholars.

Based on the accurate performance of Swarm in detecting water storage changes in 26 watersheds around the world, this paper conducted a statistical analysis in four aspects, watershed area, runoff magnitude, total annual mass change, and transient change, and found that the accuracy of Swarm-TWSC is related to all four factors, with the transient change of watershed mass as the main factor. This finding is convenient for scholars to compare the usability of Swarm when they use it for other studies of new areas.

In this paper, only Swarm-TWSC is compared with GRACE-TWSC, because both exploration models the periodic representation of water storage changes calculated using a time-varying gravity field model from satellite measurements, and in terms of results, both calculate the total regional mass change. In summary, this paper gives an optimal data processing strategy to systematically explore the potential of Swarm in detecting regional water storage changes and analyzes the reasons for the differences in its performance accuracy in different basins. This paper provides some guidance for future research on Swarm in water storage detection.

Although some conclusions have been obtained in the study of TWSC in 26 basins around the world, there are still some shortcomings. For the regions with insufficient precision of Swarm-TWSC, the next step is to use GRACE-TWSC as the true value to explore the correlation with Swarm-TWSC, and establish the error compensation model for the two types of satellite detection results according to the correlation, then the accuracy of Swarm-TWSC can be improved.

References

Swarm time-varying gravity field can be selectively used to detect changes in water reserves in these basins if there are no GRACE series satellites or other effective means of detection.

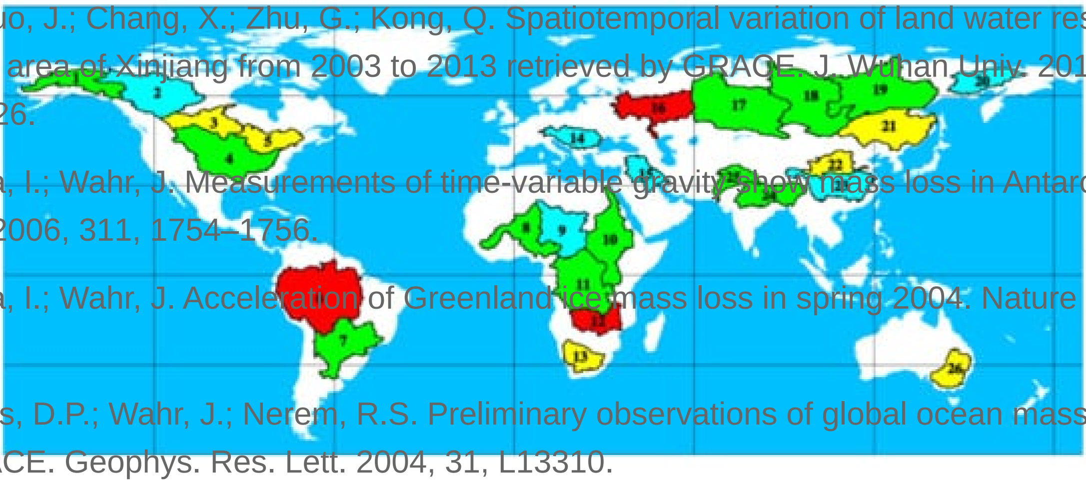

Figure 3. The accuracy classification map of water storage change detection in 26 basins by Swarm. Among them, red represents the area where Swarm is fully available, green represents the area where Swarm is available, cyan represents the area where Swarm can be selectively used, and orange line represents the area where Swarm is not available.

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