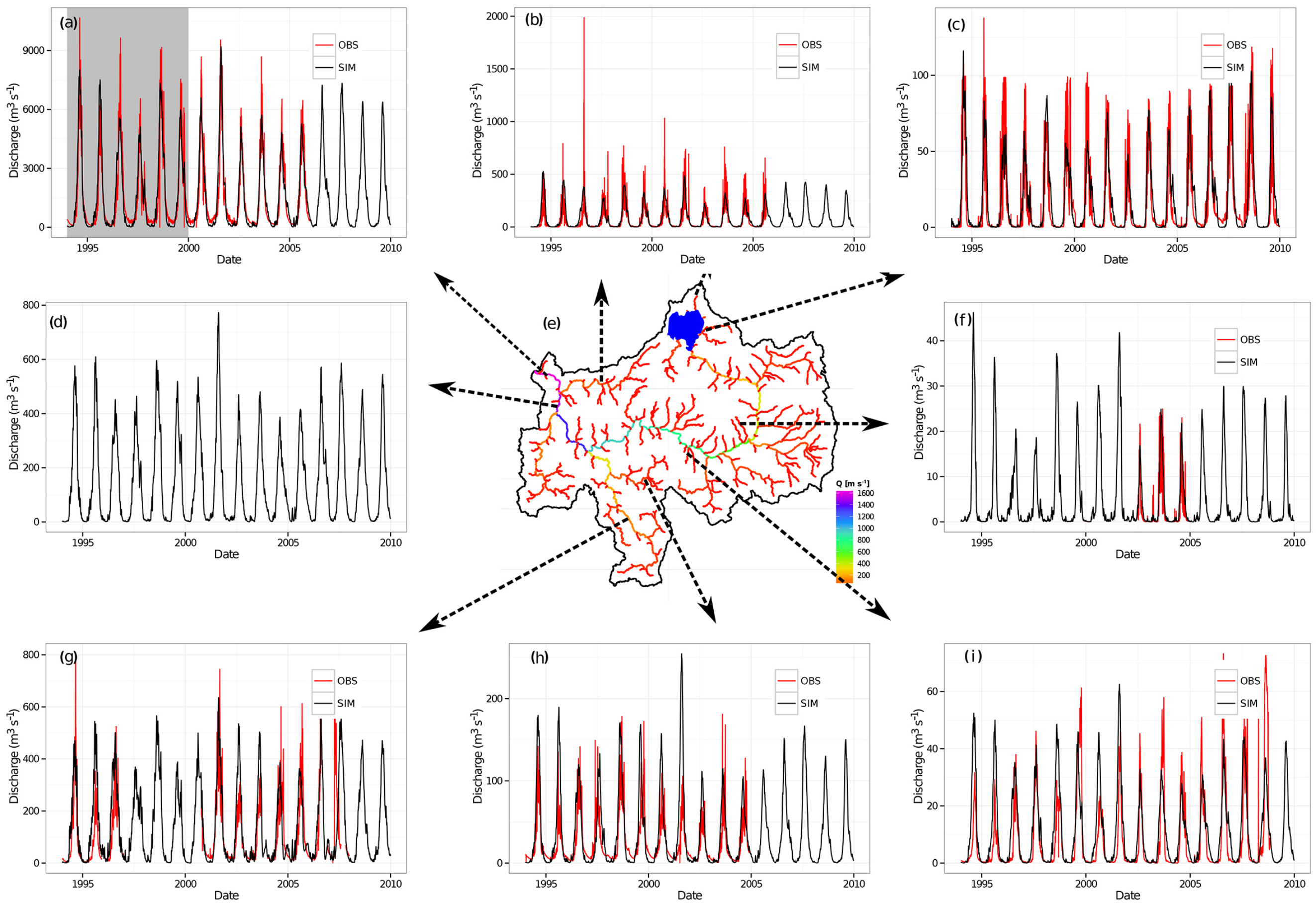

Figure 5. NewAge model simulation validation at internal subbasins. The model calibrated (shown by gray shaded period) and validated at El Diem **(a)** is used to estimate at each channel link and, where discharge measurements are available, they are verified: main Beles bridge **(b)**, Ribb River enclosed at Addis Zemen **(c)**, simulation of the main Blue Nile before joining Beles River **(d)**, Jedeb near Amanuel **(f)**, Dedisa River basin enclosed near Arjo **(g)**, Angar River basin enclosed near Nekemt **(h)**, and Nesh near Shambu **(i)**. Panel **(e)** shows the long-term estimated daily discharge for all river links of the basin.

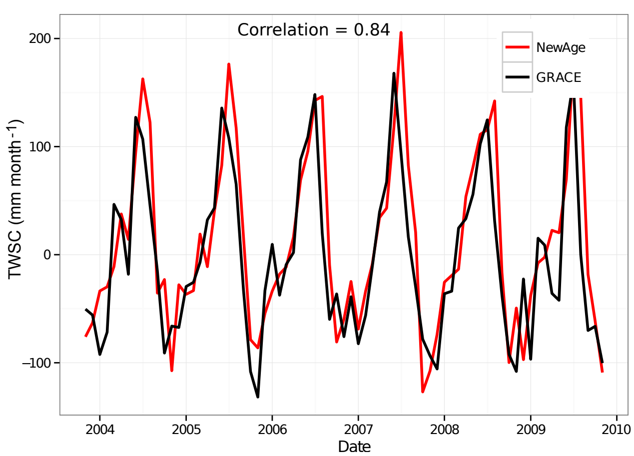

Figure 6. Comparison between basin-scale (whole UBN, 176 315 square kilometers) NewAge ds / dt and GRACE TWSC from 2004 to 2009 at monthly time steps.

to evaporate water occurs during low precipitation months (March, April, and May). Due to this slight out-of-phase trend, ET is minimal and Q and ds / dt are enhanced during wet months (Fig. 10), thus revealing that ET is water-limited more than energy-limited. The same Figure also shows the complex interplay between discharges, (variation of) storages, and evapotranspiration. A first look at Figs. 4 and 5 could lead to the conclusion that overestimation of ET brings in underestimation of Q. However, Fig. 10 shows that the role of ds / dt is not negligible at all.

5 Conclusions

The goal of this study is to estimate the whole water budget and its spatial and temporal variability of the upper Blue Nile basin using the JGrass-NewAge hydrological system and remote sensing data. The study covered 16 years from 1994 to 2009 at a finer spatial and temporal resolution than

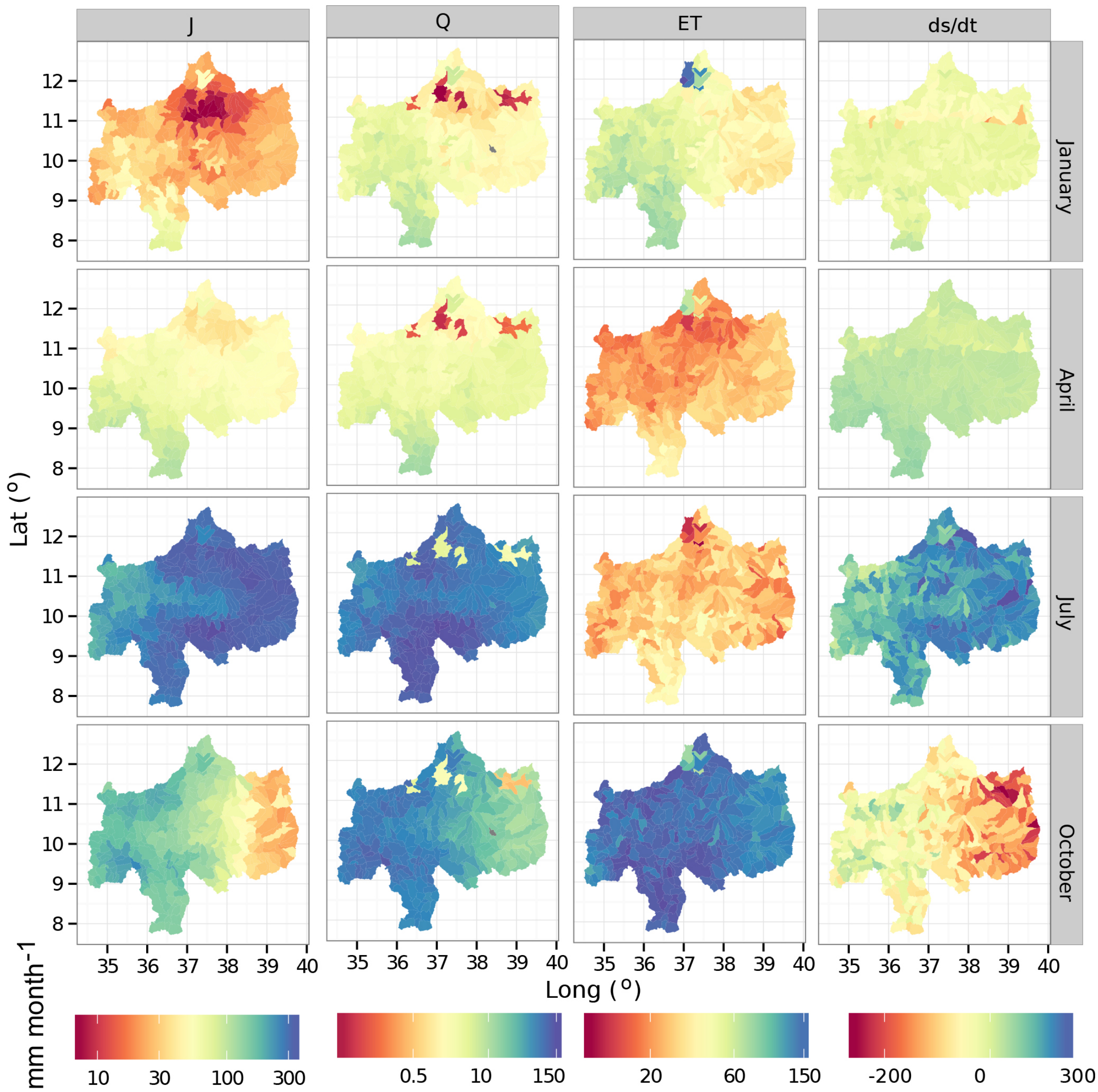

Figure 7. Spatial distribution of long-term mean monthly water budget (January, April, July, and October) in the UBN basin. For the sake of visibility, the legend is plotted separately and on logarithmic scale, except for the storage component.

in previous studies. In order to achieve this result, we used various remote sensing products, rainfall from SM2R-CCI, cloud cover from SAF EUMETSAT CFC, evapotranspiration from GLEAM and MODIS (used for comparison), and storage change from GRACE (also used for comparison). We also used all the ground data currently available, i.e., 16 discharge time series and 35 ground-based meteorological stations. The results can be summarized as follows:

- The basin-scale annual precipitation over the basin is $1360 \pm 230\,\mathrm{mm\,yr^{-1}}$ and highly variable spatially. The southern and southwestern parts of the basin receive the highest precipitation, which tends to decrease towards the eastern parts of the basin (Fig. 3).

- Generally, the interannual variability of ET is high, and tends to be higher in autumn and lower in summer. The average basin-scale ET is about $740 \pm 87\,\mathrm{mm\,yr^{-1}}$ and is the larger flux in water budget in the basin.

- The comparison of simulated ET with the satellite product GLEAM shows that GLEAM has lower temporal variability than our estimates. The correlation between GLEAM ET and NewAge ET increases from daily time steps to monthly time steps, and spatially it is higher in the east and central parts of the basin. Comparison with MODIS products was also performed (reported in the Supplement). MODIS actually shows an even larger departure from JGrass-NewAge results. Both satellite products, however, seem to introduce a systematic bias

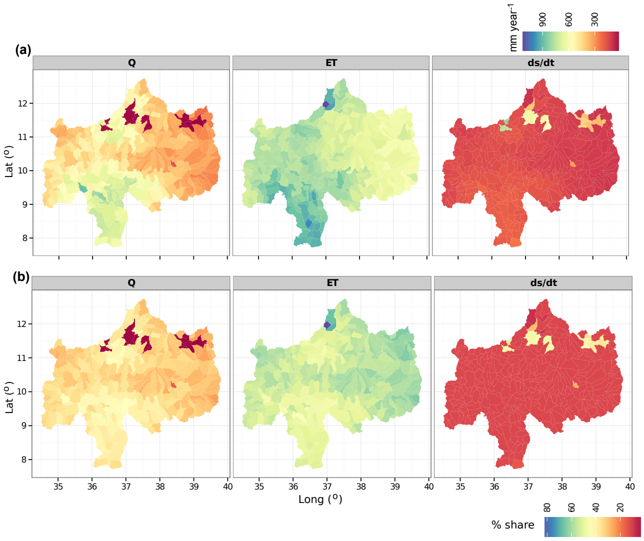

Figure 8. The spatial distributions of long-term mean annual water-budget closure: precipitation in millimeters (Fig. 3), the output terms (Q, ET, ds / dt) in millimeters **(a)**, and the percentage share of the output term (Q, ET, ds / dt) of the total precipitation **(b)**.

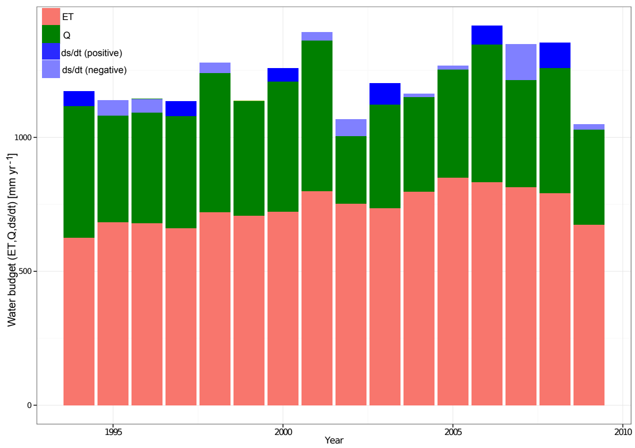

Figure 9. Water-budget components of the basin and its annual variabilities from 1994 to 2009. The relative share of each of the three components (Q, ET, and ds / dt) of the total available water J is represented by the length of the bars (NB the total length of the bar minus the negative storage is J). The positive and negative storage of the years are shown by dark blue and light blue respectively.

which would not allow the closure of the water budget according both simulated and measured discharges.

– The NewAge ADIGE rainfall–runoff component is able to reproduce discharge very well at the outlet (KGE = 0.92). The long-term annual runoff of the UBN basin is about $454 \pm 160\,\mathrm{mm\,yr^{-1}}$. The verification results at the internal sites where measurements are available reveal that the model can be used for forecasting at ungauged locations with some success.

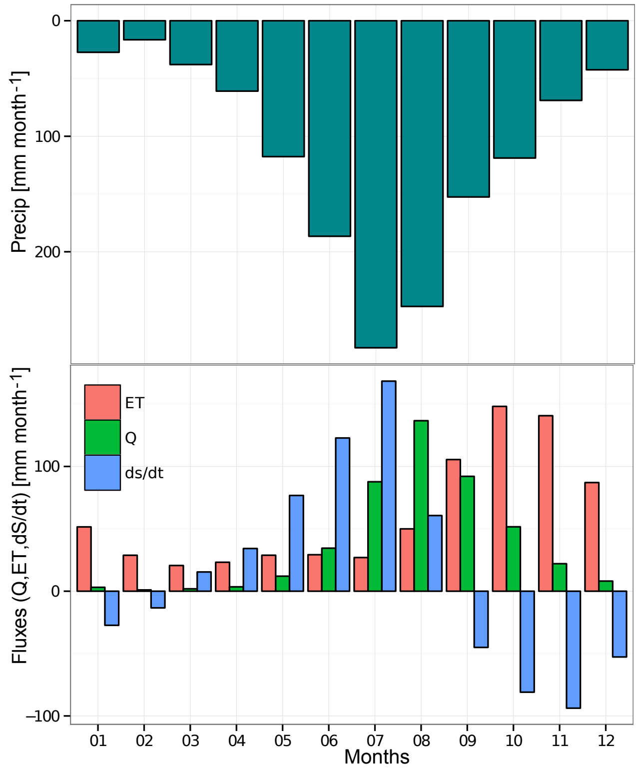

Figure 10. Monthly mean water-budget components on basin scale and in the long term, based on estimates from 1994 to 2009. The relative shares of the three components (Q, ET, and ds / dt) of the total available water J are shown.

– The performances obtained are promising (Figs. 5 and 6 and Table 4) and often greatly improve previous results.

– The NewAge storage estimations and their space–time variability are effectively verified by the basin-scale GRACE TWSC data, which show high correlation and similar amplitude.

Despite the good results obtained, it is important to note that this study is limited by the lack of in situ ET observation and low-resolution GRACE data for confirmation of storage. To this end, the results of this study would benefit from basin-specific assessments of ET and ds / dt RS products based on ground measurements, as done in Abera et al. (2016) for precipitation. We claim that the procedure we followed can be easily replicated in any other poorly gauged basin, with benefits for the hydrological knowledge of any region on Earth.

Data availability. The forcing data used for NewAge simulation, SM2R-CCI, is obtained from http://hydrology.irpi.cnr.it/people/l.brocca; the rain gauge precipitation and hydrometer discharge data were obtained from the National Meteorological Agency and the Ministry of Water and Energy of Ethiopia, respectively, and they can be requested for research. The remote sensing data used for comparison, GLEAMS ET, MODIS ET, and GRACE TWSC, are freely available and can be downloaded at http://www.gleam.eu, http://www.ntsg.umt.edu/project/mod16 and ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/landmass/RL05 respectively. Modeling components used for the simulations are available and documented through the Geoframe blog http://geoframe.blogspot.com. Additional data (i.e., GIS database, topographic information, input data, and additional results) and other notes regarding the paper can be found at Zenodo: https://doi.org/10.5281/zenodo.264004 (Abera et al., 2017).