Bengaluru groundwater fluctuations reflected in crustal deformation

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The water crisis in Bengaluru is mainly due to a large deficit in rainfall during 2023. Less precipitation led to less recharge and subsurface storage. The recharge or subsurface loading causes elastic deformation of the crust, namely subsidence during monsoon and its recovery afterward. Such deformation can be measured using continuous GPS measurements. We see an excellent correspondence between the trends of Bengaluru rainfall over the past two decades and the vertical surface deformation derived from the continuous GPS measurements at the IISc site. Decreased precipitation in 2023 led to less annual subsidence than in the earlier four years when the rainfall increased in subsequent years from 2019 to 2022, increasing subsidence every year following the monsoon. The rainfall pattern in Hyderabad was similar to that in Bengaluru, but in terms of the magnitude of rainfall and corresponding crustal subsidence, which was estimated from the GPS measurements at the HYDE site, it was less pronounced. These two examples demonstrate the influence of the hydrological process on the crustal deformation process.

Keywords: Crustal deformation, GPS, groundwater, rainfall.

BESIDES plate tectonics, earthquakes and other geological processes, several other processes, e.g. the hydrological processes (involving continental water storage and its movement, seasonal monsoon cycle, droughts, floods and cyclones), atmospheric pressure variation, glacial isostatic adjustment due to the loss of ice mass after the last glacial maximum, anthropogenic activities (namely surface reservoir impoundment, overexploitation of groundwater, mining, etc.) cause ground deformation[1,2]. Deformation due to hydrological processes is ubiquitous and large. In the Indian subcontinent, seasonal variations involving monsoonal precipitation cause horizontal and vertical deformation of ~3–4 and ~20–30 mm respectively[3]. Larger precipitation causes larger deformation and vice-versa. The deformation due to the hydrological cycle is mostly elastic, and thus recoverable, but may also involve a non-linear contribution from poroelasticity (water diffusion at depth) and sediment compaction[4]. The magnitude of deformation may depend on the rheological properties of the region. Thus, the ground deformation measured using continuous GPS observations can capture the changes in annual rainfall pattern. In this communication, we report the response of annual and long-term rainfall patterns in Bengaluru on the ground deformation and show that the deficit in last year's rainfall, which caused the water crisis, is correspondingly reflected in the ground deformation.

Bengaluru, a metropolitan city with an 800 km^2 area and about 13.2 million population, receives ~860 mm annual rainfall. The demand for water in Bengaluru is about 18 TMC, and only about half of it is met by the supply from the Cauvery river. The rest of the demand is met from the groundwater. With the growing population and expansion of the city, the demand for water is continuously increasing. We first analysed the rainfall data of Bengaluru since 2001, which was recorded by the India Meteorological Department and downloaded from WRIS (https://indiawris.gov.in/wris/#/). The rainfall was steady between 2004 and 2018. However, after 2018, there was an increase in annual rainfall until 2022, which helped meet the growing water demand. In 2023, the rainfall (714 mm) was much less, and it was less than half of that of 2022 (1700 mm). This was the main reason for the water crisis in Bengaluru. It highlights the vulnerability of the regions located in the hard rock terrain to water scarcity in case of below-normal precipitation during a monsoon season. In the regions with extensive aquifers, e.g. the Indo-Gangetic plains, the crisis may not be that severe in such similar situation.

Such a large seasonal variation of load on the earth's surface should cause a corresponding deformation in the earth's crust, which is indeed recorded by the continuous IISc GPS site established at the IISc campus in Bengaluru. The daily data from this and other sites are processed using scientific software, results of which are available at the Magnet GPS network of Nevada Geodetic Laboratory (http://geodesy.unr.edu/NGLStationPages/stations/IISC.sta). The seasonal variation in precipitation causes Bengaluru to move up and down by ~25 mm during the October–March (winter) and April–October (monsoon) periods respectively[2,3,5] (Figure 1 *b*). Continental water movement during the monsoon each year over the Indian subcontinent also caused Bengaluru to move laterally (predominantly towards north) by ~2 mm which is recovered in the following months of the dry season. This cyclic motion is in addition to the steady plate motion of ~55 mm/year in the northeast direction. It can be seen that from 2004 to 2018, Bengaluru did not experience any long-term subsidence despite moving up and down due to monsoon each year. Higher precipitation leads to higher subsidence, as can be seen for 2022, during which the total subsidence during the monsoon was about 34 mm. The increased annual precipitation from 2019 to 2022 led to a subsequent increase in the subsidence each year after monsoon, i.e. from ~14 mm in 2019 and ~16 mm in 2020 to ~25 mm in 2021. The decreased precipitation during 2023 led to a subsidence of 32 mm, thus resulting in a marginal net uplift rate of

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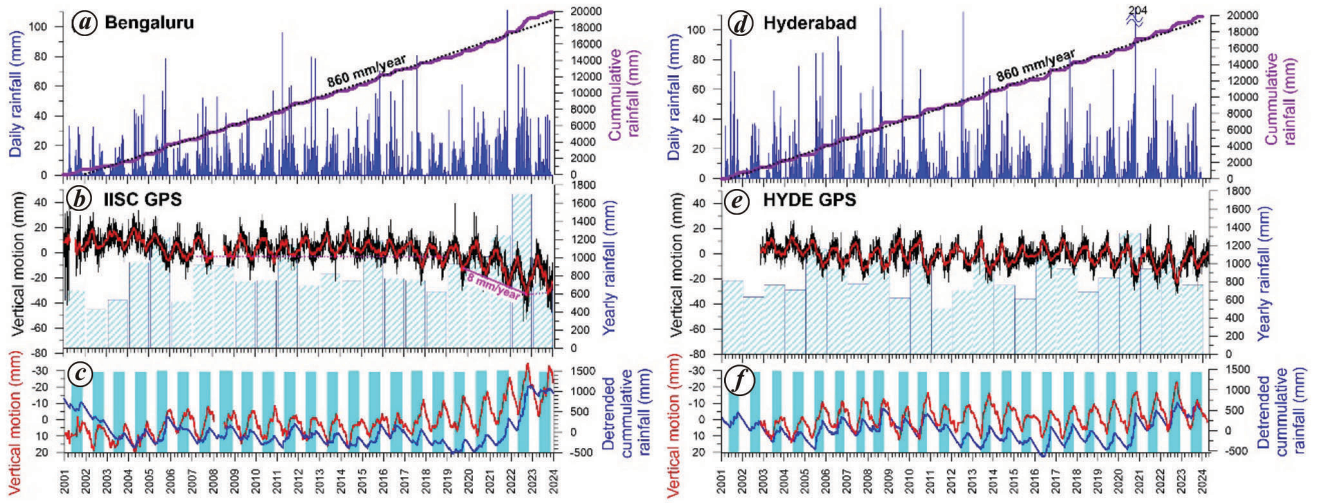

Figure 1. Rainfall and GPS-derived vertical motion at the IISc and HYDE GPS site. ***a***, Daily and cumulative rainfall. ***b***, Vertical motion over 2001–2023 derived from the daily observations of GPS measurements at IISc site along with yearly rainfall. Thirty-one days running average in vertical motion is shown with red colour. Note a significant subsidence rate (~8 mm/year) during 2019–2022 while during 2022–2023 the site experienced uplift at the rate of ~2 mm/year. The vertical motion rate over the years 2006–2018 is zero. ***c***, Detrended cumulative rainfall (obtained after subtracting 860 mm/year of annual rainfall rate from the cumulative rainfall) showing the pattern of rainfall over the years 2001–2023. Note higher rainfall during 2019–2023. As the rainfall and vertical motion are oppositely correlated, the running average of vertical motion is shown on the descending *Y*-axis to show the correspondence between the two. The cyan colour strips denote the monsoon period. Panels (***d***), (***e***) and (***f***) show the same parameters for Hyderabad.

2 mm/year during 2023 (Figure 1 *b*), compared to the subsidence rate of ~8 mm/year during 2019–2021. In the years before 2018, the long-term net vertical motion rate was almost zero, as the subsidence during the monsoon each year was almost equal to its recovery in the following period. The annual subsidence and the subsidence rate over the years are inversely proportional to the yearly rainfall and its pattern. Figure 1 *c* shows good correspondence between the detrended cumulative rainfall and the vertical motion derived from the GPS measurements at Bengaluru. Note that the two are oppositely correlated, i.e. the increased load causes more subsidence (Figure 1 *b*). But in Figure 1 *c*, the vertical motion time series is shown on the descending *Y*-axis to reflect the correspondence between the two. The deviations in the beginning (2001–2004) and at the end (2019–2023) in the two-time series from their respective average values of 2005–2018 are remarkable, and the similarity in the pattern of the two-time series highlights how the hydrological process influences the crustal deformation processes. In the earthquake-prone regions exhibiting high strain, the hydrological loading is found to modulate earthquake frequency[6,7], thereby confirming that the influence is not just surficial but extends even up to earthquake focal depths. In low-strain regions of southern India, such influence, although it causes crustal deformation, it may not trigger earthquakes.

In a similar analysis using Hyderabad GPS data and rainfall, we show that the rainfall pattern over the years has not changed much and accordingly the long-term trend in vertical motion has not changed. There seems to be a small increase in rainfall during 2019–2022, leading to slightly higher subsidence each year, but it is not as pronounced as in the case of Bengaluru. Even in the case of Hyderabad, the rainfall was less during 2023, which led to correspondingly less subsidence during the monsoon.

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