Using Remotely Sensed Inundation to Understand Tanzania Water Resources

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Summary

Sustainable groundwater use requires knowledge of groundwater recharge via infiltration, but recharge dynamics are often challenging to fully describe. Based on previous studies, we hypothesize that recharge occurs via flooding and subsequent infiltration of water through topographic depressions in the areas near Singida and Dodoma, Tanzania. Using two Global Water Institute wells and data from the Singida region, we have shown that the period of Fall 2019-Winter 2020 in the Singida region was a time with monthly precipitation rates great enough to initiate recharge events; that well levels increased significantly (though this finding is subject to review based on the complication of using a pumping well for well level monitoring), and that 10s of km^2 of topographic depressions during this period were inundated. Our analysis supports the hypothesis: inundation of depressions may well be a critical mechanism for groundwater recharge in this area. Our conclusion is tenative at this time, as our datasets did not allow determination of the source of recharge, only that inundation timing coincided with recharge, and that spatial pattern of inundation coincided with topographic depressions. However, if proven true, remote sensing imagery could be used to better understand recharge dynamics, and groundwater-surface water interaction. We recommend any future work on this topic focus on an area already described in the literature, the Makutapora Wellfield.

Introduction

Assessing water resources in developing countries is a nearly intractable challenge for development groups. Oftentimes, needed datasets either do not exist, or cannot be shared. The Global Water Institute (GWI) effort in Tanzania encompasses several efforts in this area, including drilling groundwater pumping wells to improve access to drinking water (Figure 1). Groundwater resources are depleted by pumping, and replenished or recharged via infiltration of surface water. Unsustainable groundwater use occurs when groundwater is pumped faster than it can be recharged, leading groundwater levels to drop. Unsustainable groundwater use is widespread globally. Sustainable groundwater use is dependent upon rates of recharge. Rates of recharge depend, in turn, upon hydrological mechanisms coupling groundwater and surface, which are often poorly understood, and vary dramatically in both space and time.

A recent study by Taylor et al. (2013) found an intriguing link between intense rainfall events and groundwater recharge: see Figure 2, below. They analyzed groundwater well data from the Makutapora Wellfield, just north of Dodoma (see Figure 3 for location). They find that groundwater levels tend to decline over periods of approximately a decade, and then recharge rapidly over short time scales (less than a year; see Figure 2a). These periods of recharge were found to often correspond with periods of intense rainfall (Figure 2b).

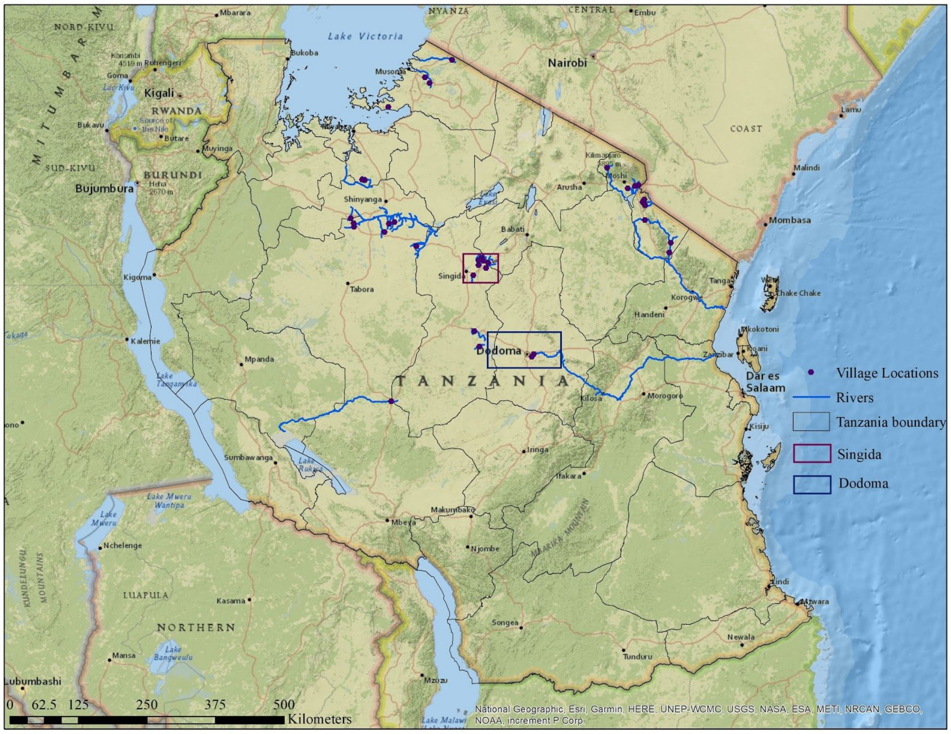


Figure 1: Tanzania, along with the GWI village locations and major rivers. The Singida and Dodoma study areas shown in Figure 3 and analyzed in this report are shown as well.

While precipitation records from in situ gages are often challenging to obtain, and measuring precipitation via remote sensing is challenging due to uncertainties in retrieval algorithms (see Lettenmaier et al., 2015 for a good discussion), remote sensing of surface water inundation is straightforward. Historically, inundation remote sensing has been performed with optical imagery, which would often be obscured in periods with intense rainfall such as those identified in the Taylor et al. study. However, with the advent of the Sentinel series of satellites, radar imagery, which is not obscured by cloud cover, is freely available globally at high spatial and temporal resolution.

Understanding dynamics of recharge processes is important, both for sustainable groundwater use, and for potential future development of surface water resources. One possible mechanism for recharge is that these intense rainfalls lead to overland flow, by saturating soils or by rainfall rates exceeding the maximum supportable infiltration rate (called the infiltration capacity). Overland flow that runs off into rivers would be less likely to lead to recharge, whereas overland flow that runs off into shallow depressions may then infiltrate over time. Thus, depressions that correspond with surface water inundation may well represent zones of recharge in the landscape.

As a preliminary step towards using satellite maps of surface water inundation to understand groundwater recharge dynamics in Tanzania, we analyzed temporal and spatial dynamics of surface water inundation during the most recent rainy season (November 2019 - April 2020). The study period was chosen in part due to the availability of Sentinel imagery, and partly due to the availability of GWI wells. We chose our primary study area to be near Singida, as the pumping wells may be able to suggest recharge periods there, and usable data was available at time of project conclusion. We here emphasize that well data are **preliminary**, and are only potentially usable to assess recharge because the pumps do not run during the nighttime. This important issue is discussed in detail later in this report. We also analyze imagery near Dodoma.

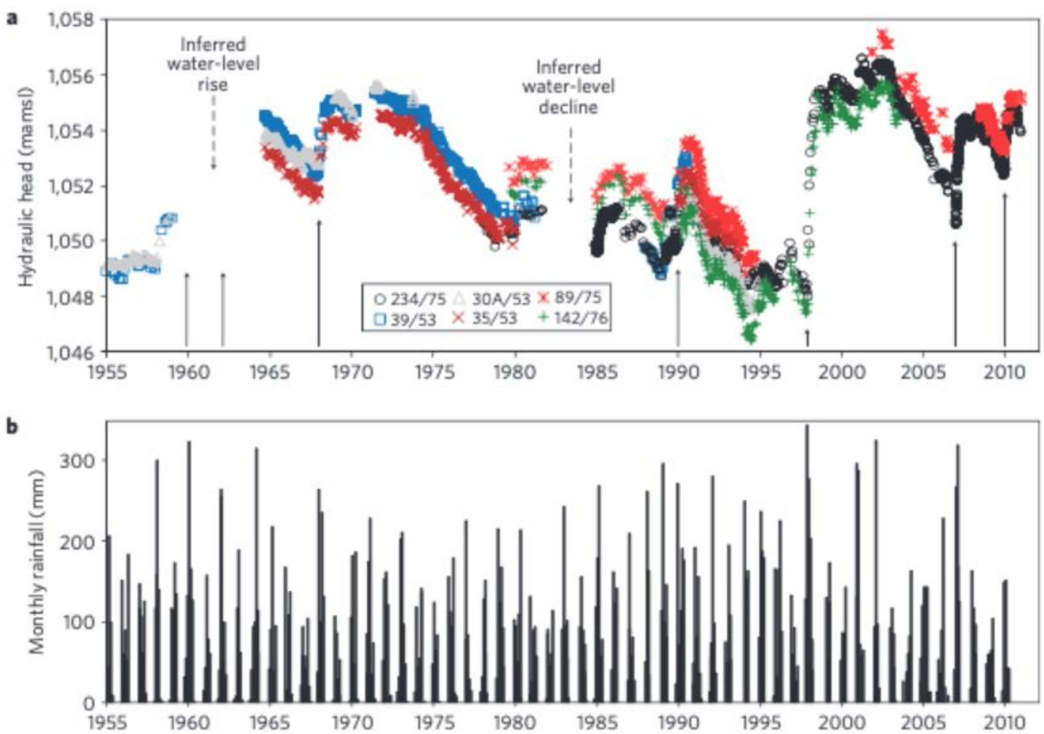
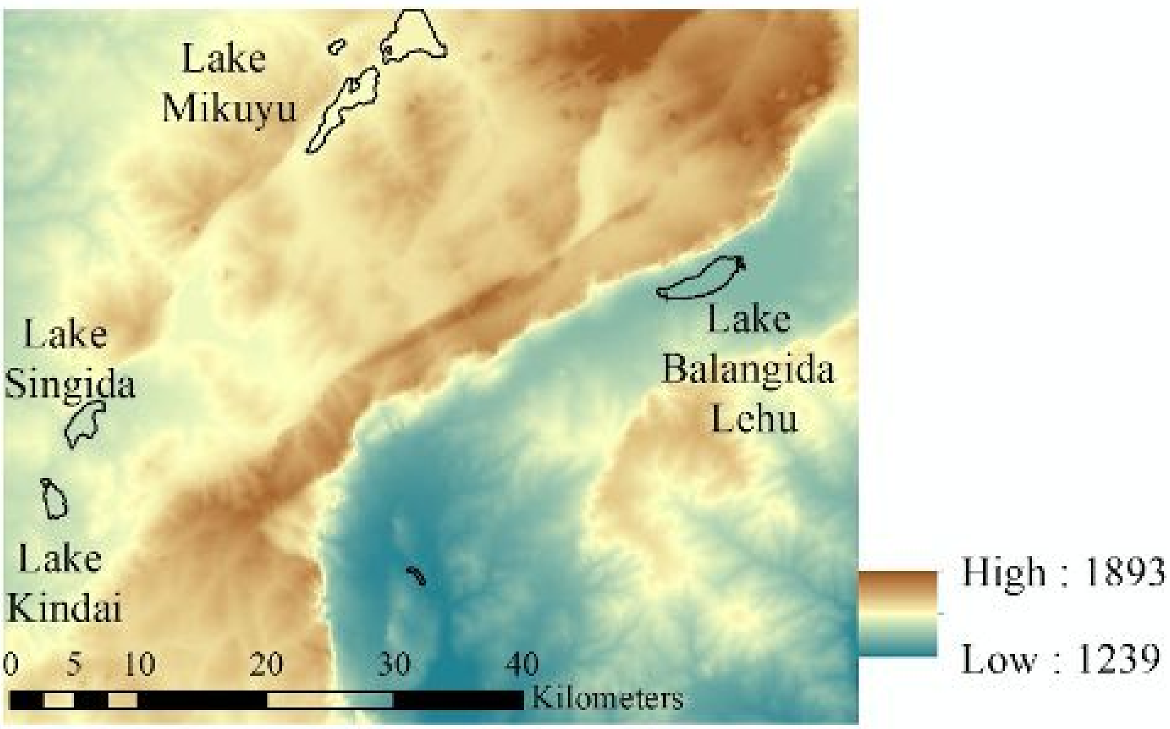


Figure 2. Well levels from the Makutapora Wellfield (a) and monthly rainfall (b). Reproduced from From Taylor et al. (2013).

Our hypothesis is that recharge in this area occurs via flooding and subsequent infiltration of water through topographic depressions. We perform two experiments in order to test this hypothesis. First, we compare the timing of recharge with the timing of extreme precipitation and inundation. If our hypothesis is true, then we would predict that the timing of recharge will correlate with both timing of extreme precipitation, and with timing of inundation in areas near the wells. We note that just because the timing of inundation correlates with timing of recharge, that does in no way mean that recharge is definitively occuring only in areas of inundation. The same intense rainfall events could conceivably cause both inundation and recharge, without a truly causal link between the two. We note that the same could be said of course of Taylor et al's study; thus, if our prediction is correct, and we find temporal correlation between inundation and discharge, this will provide one line of evidence to understand recharge processes, and support our hypothesis. Secondly, we compare the spatial pattern of inundation with topographic depressions. We predict that the spatial pattern of inundation will be similar to the spatial pattern of topographic depressions in the landscape. If this is true, it will provide further evidence of our overall hypothesis.

Study Areas

Our primary study area in the area surrounding Singida, although we also explore remote sensing imagery in the Dodoma area (Figure 3). The city of Singida lies between Lake Singida and Lake Kindai. A sometimes-flooded man-made lake of interest can be found in the low-lying region between Lake Singida and Mikuyu. The Singida study area is approximately 67 km x 56 km. The area shown in Figure 3, top, corresponds to the box noted in Figure 1, and the figures showing inundation area, below. A topographic ridge runs ~500 m above the low-lying areas that include the lake. The ridge is notable in that groundwater flow paths typically do not cross such major surface topographic features. Another ridge runs just to the east of Lakes Singida and Mikuyu. Figure 3, bottom, shows the Dodoma area, including the Makutapora Wellfield studied in the Taylor et al. (2013) paper. The Dodoma study area is approximately 133 km x 67 km.



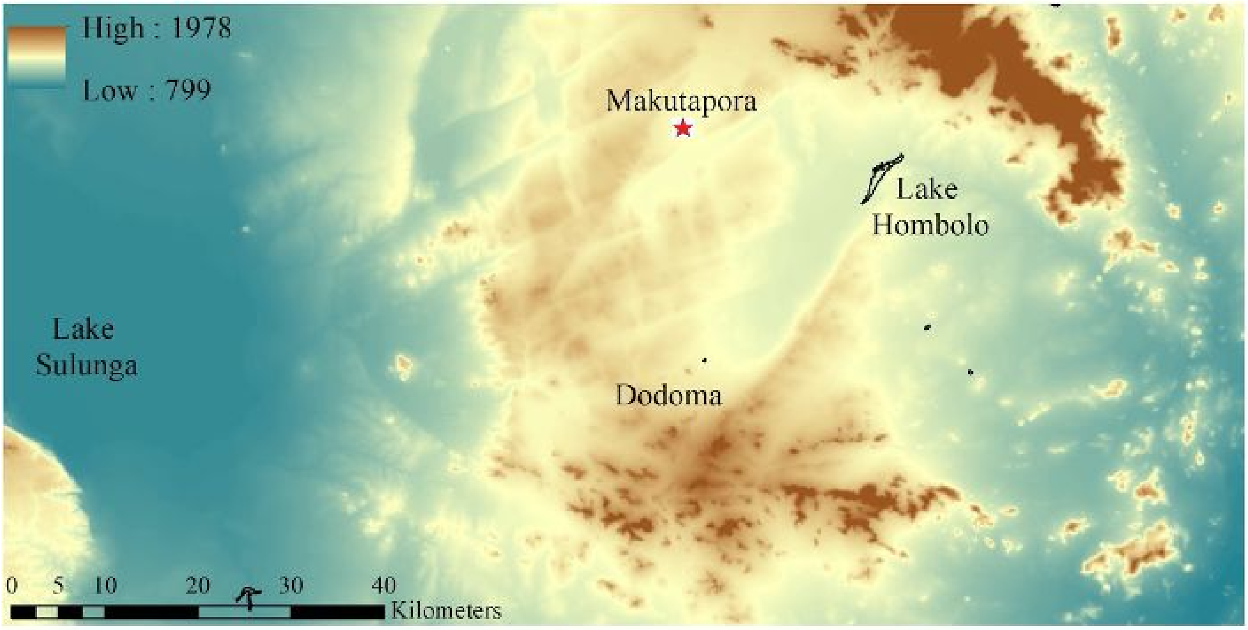


Figure 3. Topographic map from the MERIT DEM for the Singida (top) and the Dodoma (bottom) regions. Lakes are shown along with their “permanent water” outlines.

Data

We use 1) inundation imagery from Sentinel 1; 2) precipitation data from the African Rainfall Climatology (ARC), 3) GWI well data, and 4) topographic elevations from the Multi-Error-Removed Improved-Terrain (MERIT) digital elevation model (DEM). Datasets and processing notes are given on a Box folder entitled “GWI Tanzania Project/Data”; 5) Permanent water shapefiles from the Global Lake and Wetland Database (GLWD). Access and descriptions of the processed data are provided in the Appendix, below.

- Inundation maps are computed from Sentinel-1 synthetic aperture radar (SAR) at C-band (5.405 GHz), at 10 m spatial resolution.
- Precipitation data are obtained from the ARC, version 2, as described by Novella and Thiaw (2013). These data are a merger of geostationary infrared satellite observations, along with in situ gage data. Thus accuracy is likely limited by vicinity of gages to the area being studied, and the fundamental limitation of using infrared data to assss precipitation rates (Lettenmaier et al., 2015).
- Well data are obtained from the GWI wells near Singida. These loggers measure groundwater level in the wells, as well as the flowrate being extracted by the pump. Note that the pumps and the loggers are linked to solar panels, and thus run only during the day.
- Topographic maps were obtained over Tanzania from the MERIT DEM (Yamazki et al., 2017).

- Permanent water shapefiles are obtained from the GLWD (Lehner and Döll, 2004), which has a minimum size of 1 ha.

Methods

Sentinel 1 SAR was processed to obtain inundation maps by a standard change detection and thresholding approach, in Google Earth Engine. First, we obtained raw images of the region for our period of interest, and a “dry” image during the dry season, before the onset of rainfall (like one shown in Figure 4). The raw images are quite noisy, and hence all images were smoothed for a smoothing radius of 100 m. The smoothed “dry” image subtracted from the smoothed image on all days of interest. In the resulting difference image, we used a threshold value of -3. All pixels for which the reflectance value reduced by 3 or more were considered flooded. Basically, these pixels had higher reflectance in the dry image and low reflectance in the others. We used the pre-built functions in Google Earth Engine to accomplish this, and produce flood maps of the regions.

It is generally true that well level data in pumping wells cannot be used to infer recharge patterns. Pumping wells are far more reflective of pumping than anything else. However, an interesting quirk in the GWI data mean that we may be able to infer qualitative recharge patterns, even if quantitative analysis is impossible. Namely, because the wells are off through the night, water levels may be able to begin recovering. Thus, we construct a timeseries of well elevations first thing in the morning, filtered in order to ensure that the pumps are not running. In other words, all data analyzed hereafter in this report are from early morning when pumps have not yet been turned on.

ARC precipitation does not have data for all days. In order to estimate monthly precipitation from ARC, precipitation was summed over all days with available data, and then scaled by the ratio of the number of days in the month to the number of observed days.

Topographic depressions were obtained in the ArcGIS software using standard algorithms, namely mapping flow directions via elevation differentials, and identifying depressions by mapping locations where all flow directions point inwards, rather than outwards toward an outlet.

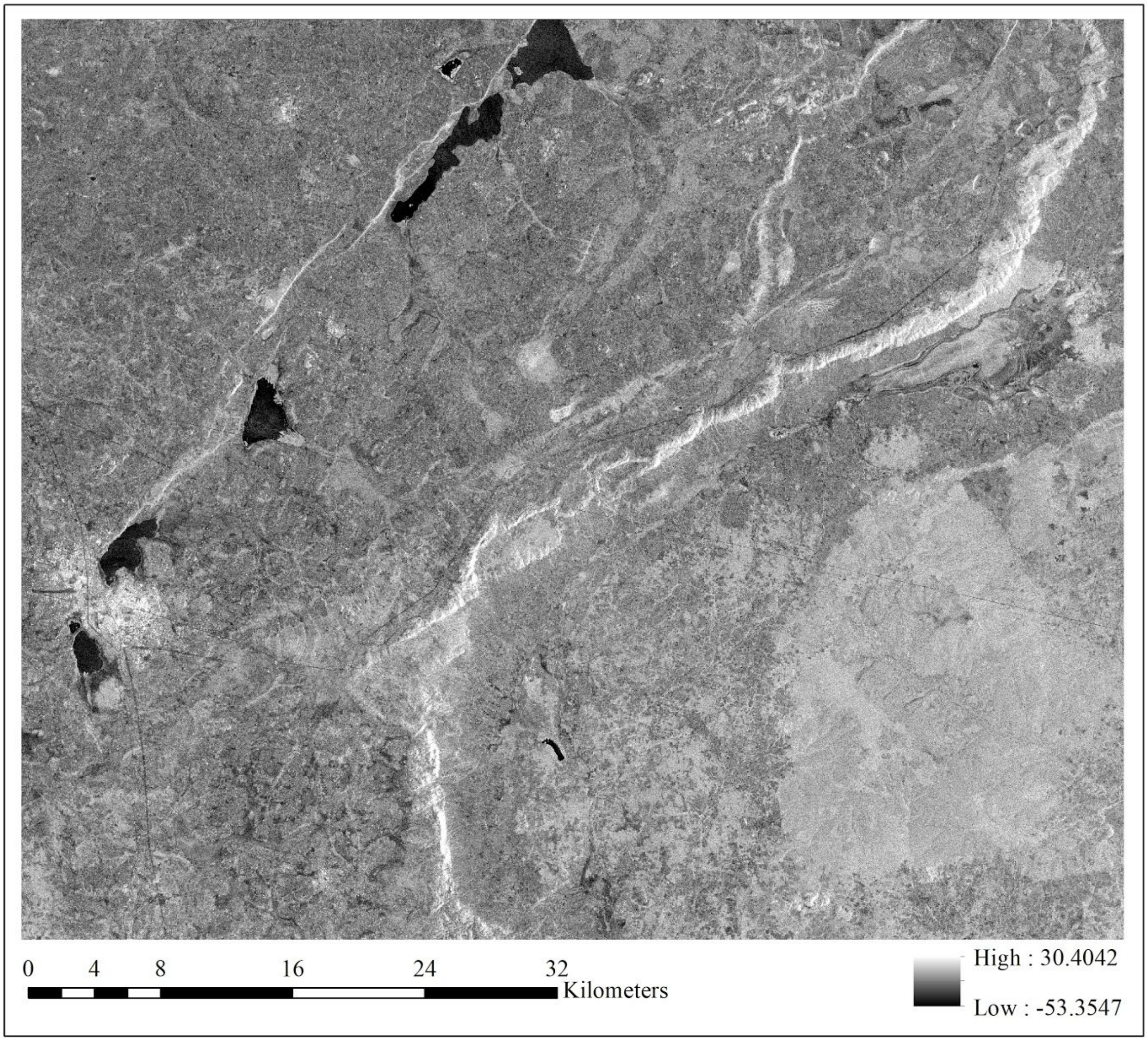


Figure 4. Example Sentinel-1 SAR image shown for the Singida study area. The base-ten logarithm of the backscattered intensity is shown. The brightest areas are the effect of topography on the radar, such as radar layover and foreshortening. The dark areas are open water where radar backscattered intensity is lowest.

Results

Examining temporal patterns of inundation, precipitation, and well levels

Total inundation days across the ~120 day period are mapped for the Singida region in Figure 5. Areas inundated the entire period are permanent water, and represent the major lakes in the region. Lakes Singida, Kindai, and Mikuyu all show temporary inundation around their borders (compare Figure 3). The man-made lake discussed in the Study Area section shows similar behavior. Lake Balangida Lehu is inundated for most of the period, but dries out entirely in some images. There are a number of locations with frequent inundation over large areas that fall to the north and east of the ridge described in the Study Area section. The two wells do not correspond with large areas of frequent inundation. However, as the images are shown at lower resolution than the actual image size, we note that multiple smaller areas of inundation are present throughout the image as well (analyzed later in this report).

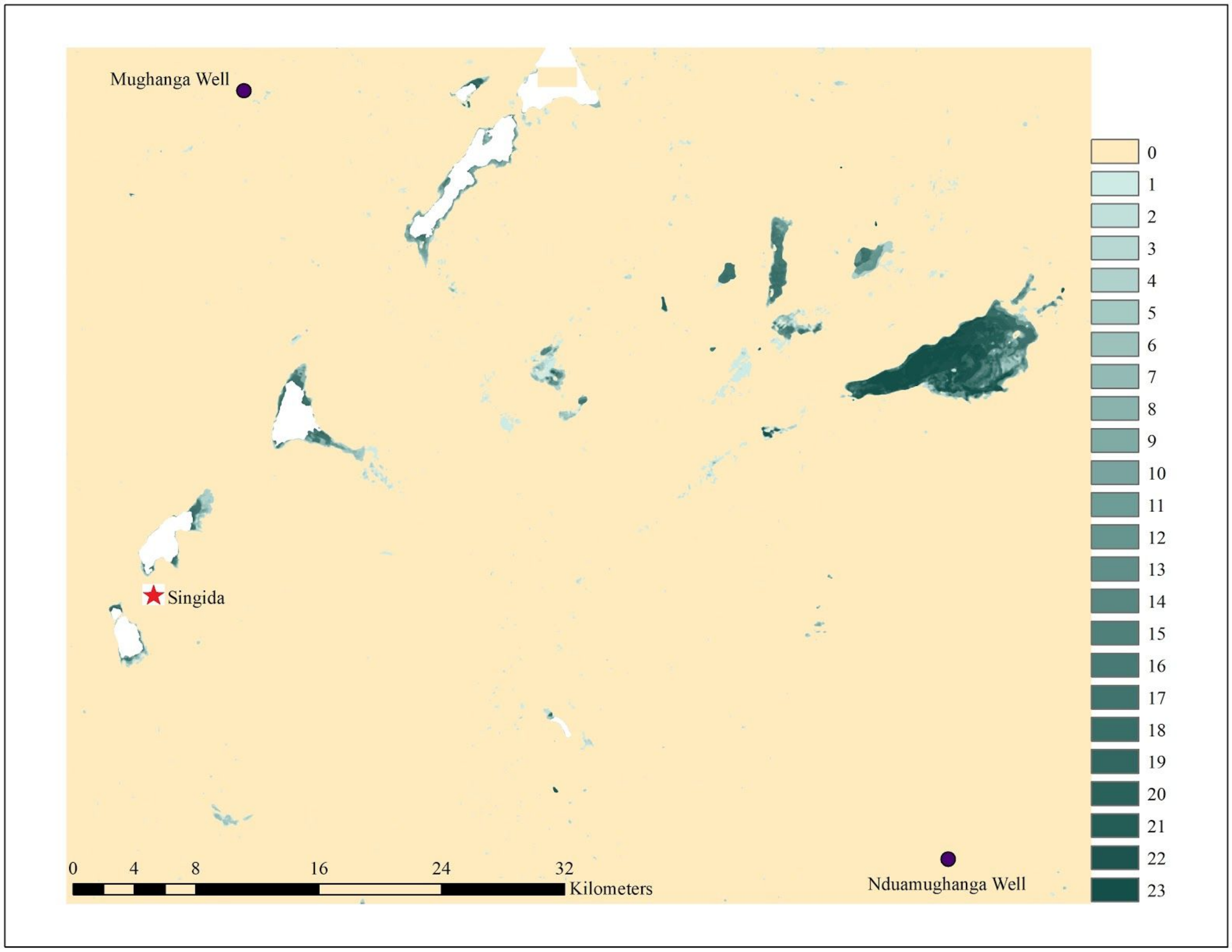


Figure 5. Total number of days in the ~120 day study period where inundation was measured in the Singida area. Permanent water such as in Lake Kindai and Lake Singida is shown in white.The Mughanga and Nduamughanga Wells are shown in the northwest and southeast corners of the image.

Total inundation days across the ~120 day period are mapped for the Dodoma region in Figure 6. Note that Lake Sulunga is inundated for some but not all of the period. Additionally, note the area north of Dodoma that is inundated for several days.

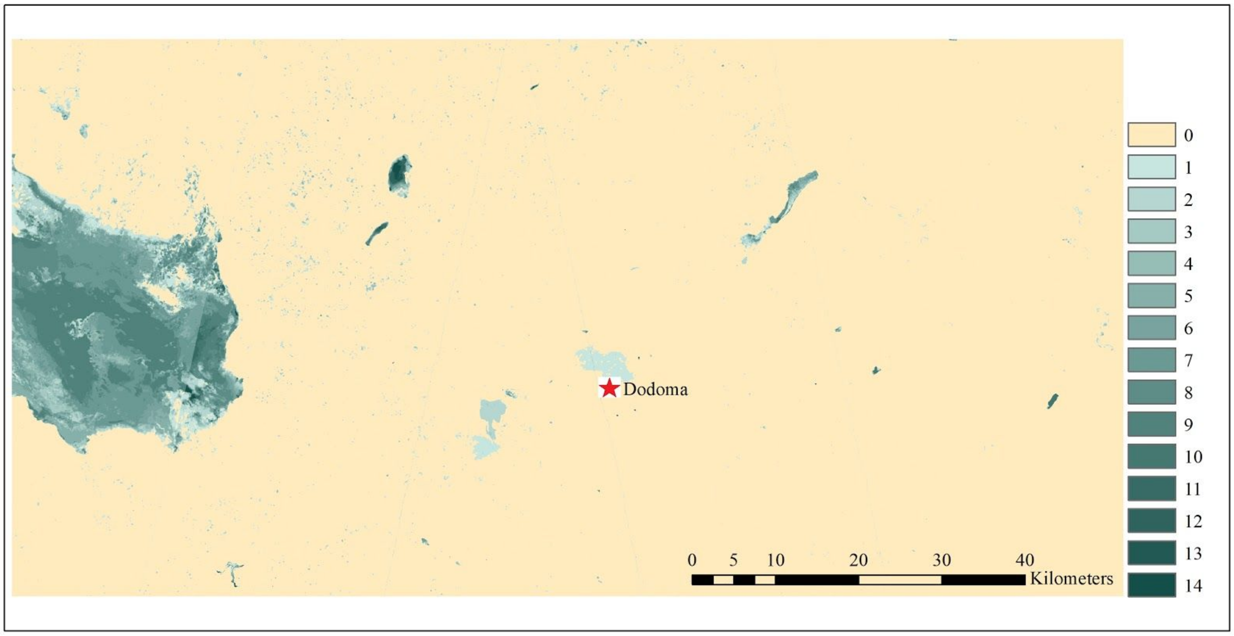


Figure 6. Total number of days in the ~120 day study period where inundation was measured in the Dodoma area.

There were GWI wells near Singida that were delivering water level data since Fall 2019, so we explored the timing of recharge, precipitation and inundation only in the Singida region: these data are shown in Figure 7. First, we discuss the groundwater level data. Over the ~120 period, the level in the Mughanga well increased from ~42 m to ~46 m, about a 4 m increase. Similarly, the level in the Nduamughanga well increased from ~35 m to ~40 m by March 1. Beginning ~March 1, the Nduamughanga well data look suspect; presumably the rapid increases and decreases are due to well operation and are present here due to unidentified errors or inconsistencies in the well level or pump operation data. Time constraints prohibited further exploration of these issues. We note here that both well increased on the order of 4 to 5 m. We first repeat the fact that well levels in a pumping well must be interpreted with utmost caution. However, remembering that the pumps are operating only during daylight hours, it appears that a rising well level is more consistent with recharge. Our rationale is that through the winter period (after the solstice on December 21), day length is increasing, which would lead (if anything) to a downward trend in water level due to longer time of pumping, assuming well pump operation was consistent. Instead, we see well levels increasing. We note that the ~4 m rise in well levels is consistent with the increase in well levels in the Makutapora Wellfield (near Dodoma) recharge events documented in the Taylor et al. (2013) study. Although further study is certainly needed to make a more informed analysis of the data, our preliminary look at the well level data appear to indicate that the period from Fall 2019-Spring 2020 has been a period of recharge in groundwater levels.

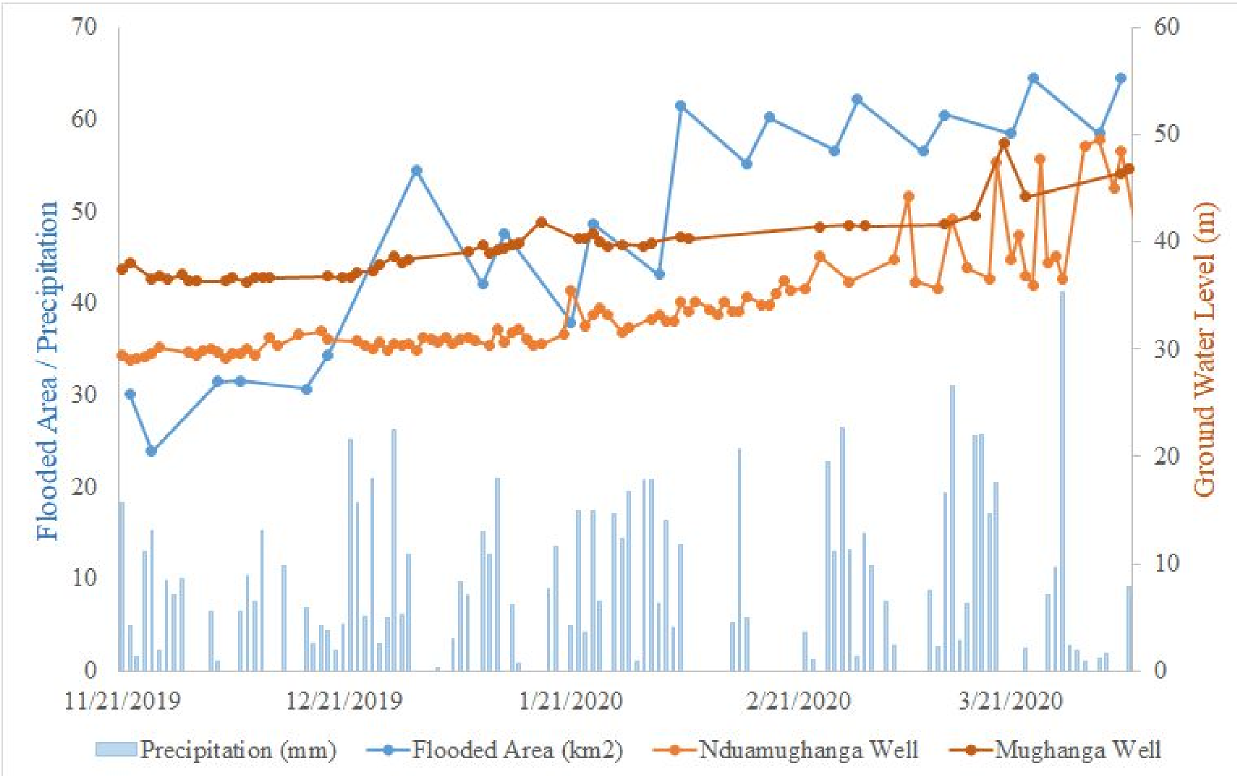


Figure 7. Groundwater level from the GWI wells at Nduamughanga and Mughanga (see Figure 5 for locations),

Secondly, we discuss the precipitation timeseries. The ARC daily precipitation data showing rainfall throughout the study period is consistent with the timing of the rainy season in Tanzania. The peak precipitation in late March peaked at 40 mm/day. The adjusted monthly precipitation values are shown in Table 1. The highest value is for March 2020, when precipitation was 305 mm. We note that precipitation values of 300 mm/month correspond to the very highest monthly precipitation values shown in Figure 2, from the Taylor et al. 2013 study. Thus, the past season from fall 2019-2020 would be, from the precipitation, expected to be a period of groundwater recharge.

Thirdly, we discuss the flooded area timeseries in Figure 7. At the beginning of the study period, there is approximately 30 km^2 inundated area in the Singida study area, which increases to ~55 km^2 by the end of the period. From analysis of imagery from November and early April, the change in inundation is approximately evenly split between the margins of waterbodies present in November, and the filling of new water bodies. Thus, if we assume that recharge is indeed occurring during these periods of inundation, it is not solely happening by inundation of areas near permanent lakes, but in temporary depressions, as well.

Table 1. Monthly adjusted precipitation values from the ARC dataset over the Singida region. See Methods section for details on adjustment.

Month	Monthly precipitation [mm]
11/ 2019	191.4
12/2019	203.8
1/2020	235.4
2/2020	181.7
3/2020	305.0
4/2020	125.7

To summarize what we have found from exploring temporal patterns:

- Well levels in a pumping well cannot be used decisively to determine that recharge occurred during this time. However, our opinion is that the levels indicate significant (several meters) of recharge during this period. While this would seem unlikely to appear as an artifact, given what we know of the data, further work is necessary on well levels before this conclusion can be confirmed.
- Precipitation data shows monthly accumulation patterns that are consistent with periods of recharge as identified by previous studies in this region
- Remote sensing shows tens of km^2 of ephemeral flooding during this period. This pattern of inundation is consistent with the idea that inundation will occur during periods of recharge.

Examining spatial patterns of inundation and topographic depressions

We also analyzed the spatial patterns of topographic depressions and inundations: see Figure 8, and find that inundation tends to occur in depressions. For example, In Figure 8, for the Singida study area the largest depressions include the areas of inundation at their center. These areas account for much of the ~25 km^2 increase in inundation during the study period, as shown in Figure 7. Lake Singida (for location, compare with Figure 3) lays in a topographic depression as well: i.e. its watershed is endorheic. Inundation near Lake Singida increases significantly during the study period. The smaller areas of inundation often correspond spatially with the smaller depressions, though this is more difficult to make out in the figure due to its limited resolution.

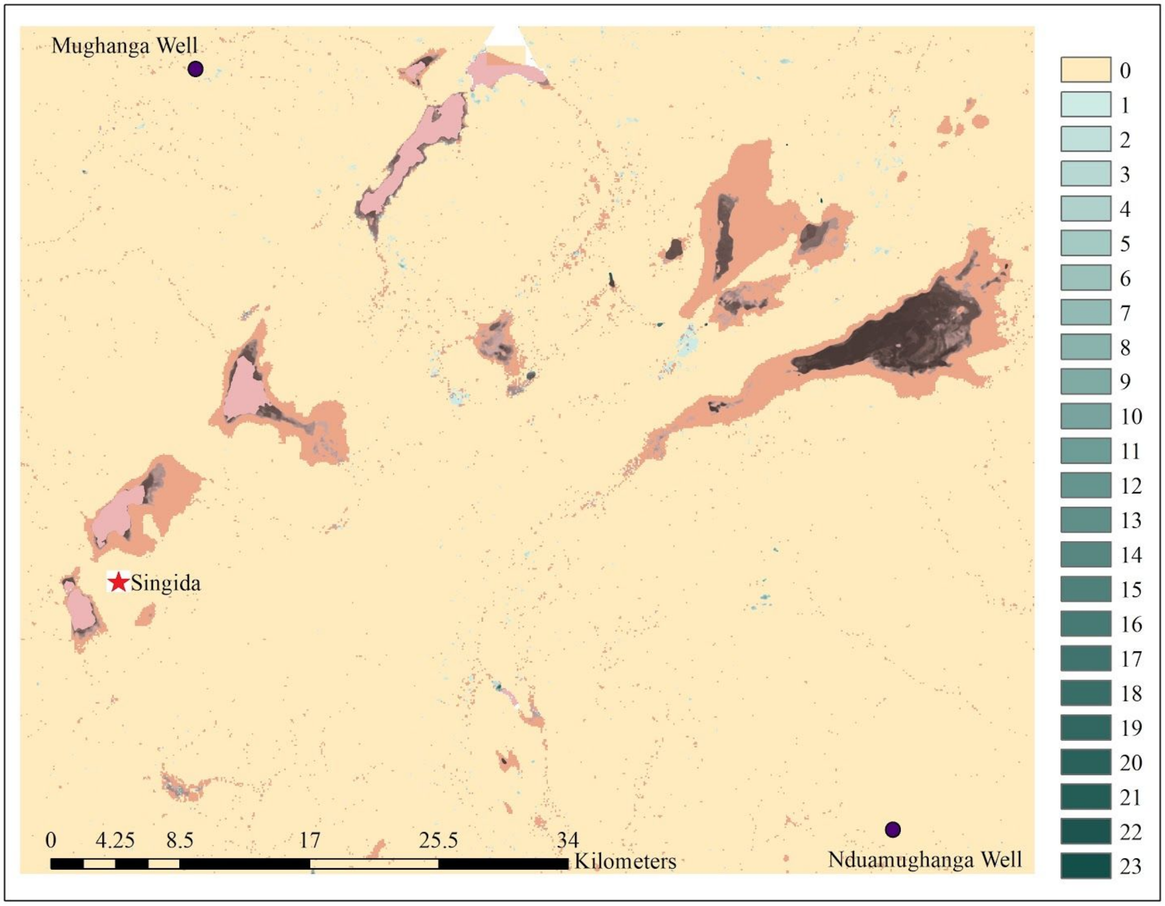


Figure 8. As Figure 5, but with topographic depressions overlaid with a semi-transparent red color. As this overlay obscures the details of flood frequency shown with various shades of green, we show both this figure and Figure 5.

Figure 9 shows the equivalent map for the Dodoma study area. Interestingly, there is no topographic depression shown for the area of inundation directly north of the city, ~5 km distant. This is the airport area. It is possible that the limited accuracy and spatial resolution of the MERIT elevation data used to identify depressions is inadequate in this case, or it is possible that no depressions exists in this area. The other large depressions in the Dodoma study region correspond with locations of inundation.

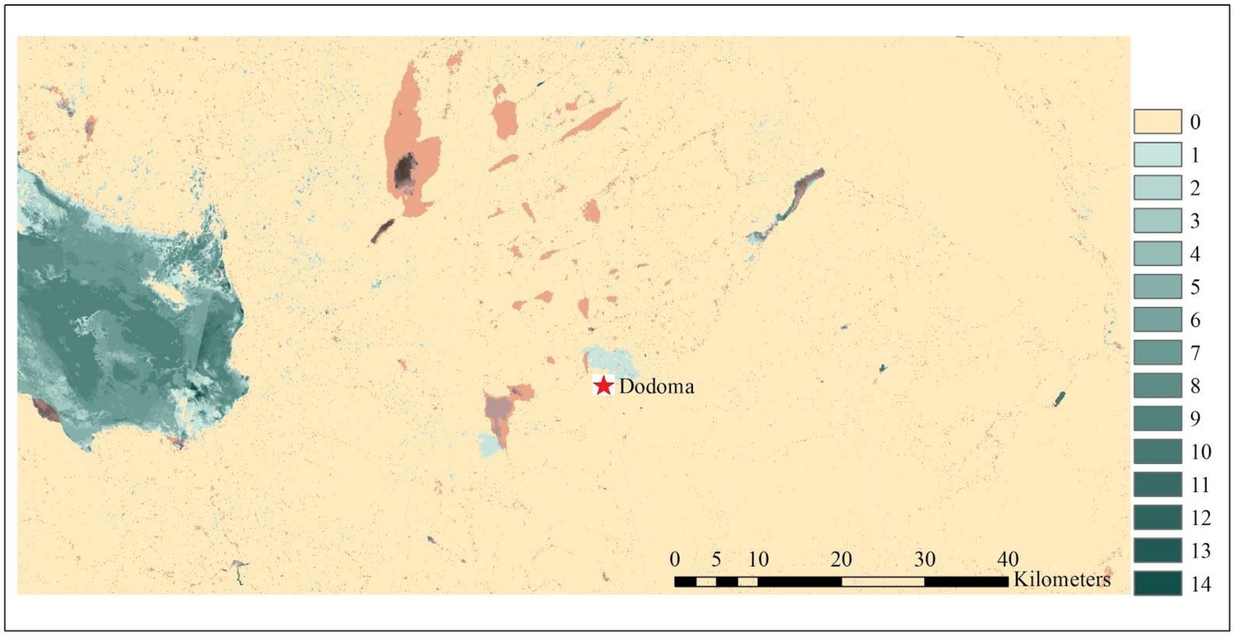


Figure 9. As Figure 6, but with topographic depressions overlaid with a semi-transparent red color.

To summarize, we find that topographic depressions generally correspond with areas experiencing inundation in the Dodoma and Singida study areas.

Discussion and Conclusion

Our hypothesis is that recharge in this area occurs via flooding and subsequent infiltration of water through topographic depressions. Using two wells and data from the Singida region, we have shown that the period of Fall 2019-Winter 2020 in the Singida region was a time with monthly precipitation rates great enough to initiate recharge events (Taylor et al., 2013), that well levels increased (though this finding is subject to review based on the complication of using a pumping well for well level monitoring), and that 10s of km^2 of topographic depressions during this period were inundated. These data support the hypothesis but are not enough to definitively prove it. Periods of high rain could cause inundation in depressions as well as recharge of wells via infiltration without the one actually causing the other.

To further explore this hypothesis we took a closer look at inundation in the immediate vicinity of the wells: Could we find depressions that appeared within a few km of the well, and thus could be providing the recharge flow directly? Figure 10 shows that inundation occurs near the Mughanga Well, but very little near the Nduamughanga Well. Moreover, even for Mughanga Well, the inundation is only during November and December, while well levels increase throughout the spring. This does not negate in any way the fact that over the region, our data support the hypothesis that inundation is occurring via these depressions. It simply says that in the two locations where we have wells (which are not, by the way, in areas with larger spatial extent of inundation: see Figure 8) there is not good evidence that this process is in play.

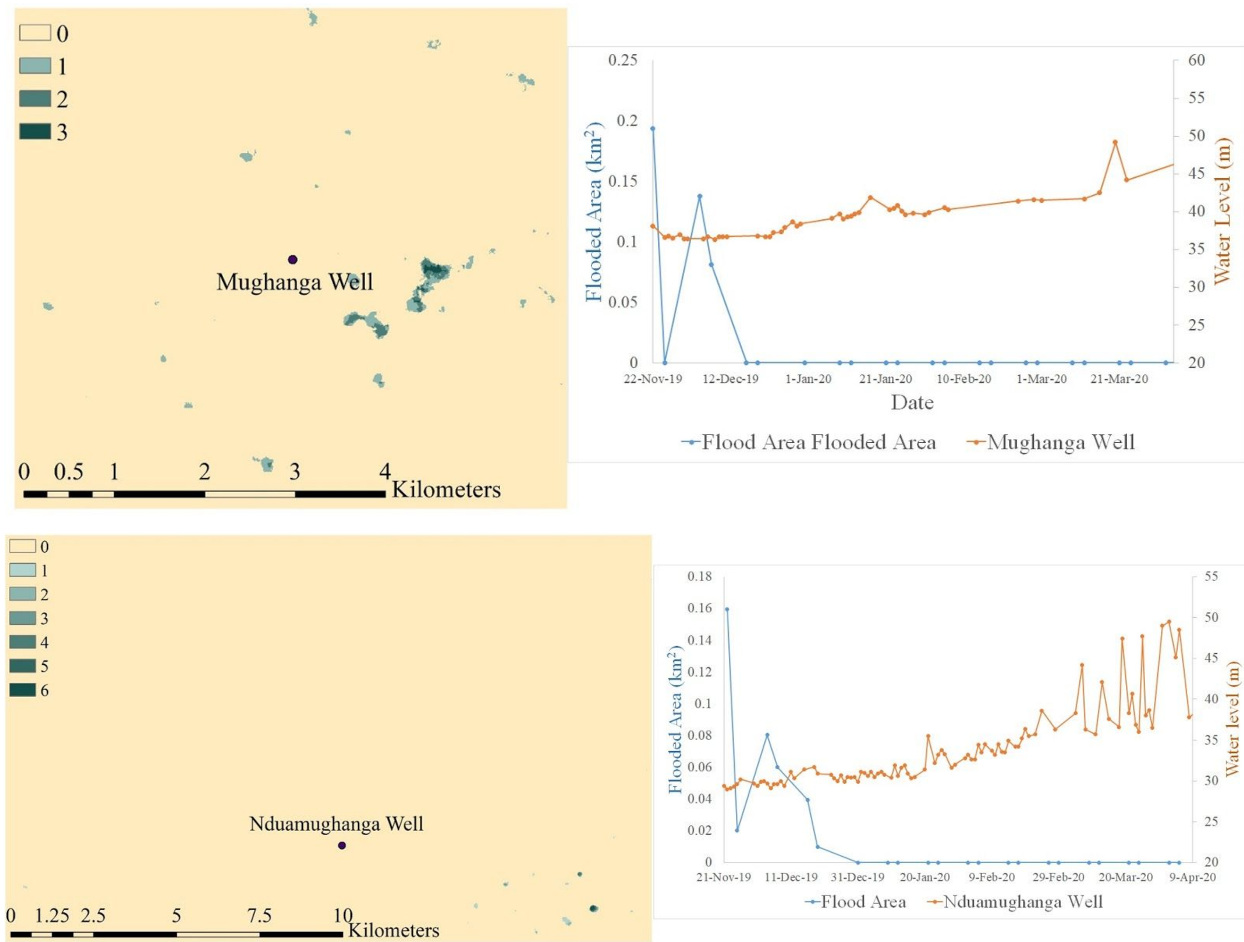


Figure 10. Flood inundation maps (left) and timeseries (right) for the two wells in the Singida region. The inundation data is identical to the data shown in Figure 5, just zoomed in. The well levels are identical to those shown in Figure 7, while the flooded area totals are summed only over the region showed in the maps shown in this figure.

Future Work

The next step in exploring this hypothesis is to better assess the well level data. Using measured water levels in a pumping well to assess recharge is in general not good practice. While the fact that the pumps are off all night allows us to make a tentative assessment, further analysis is needed.

Secondly, we are limited in this case by the very short duration of the well logs, which do not extend even a year. The long-term well level data in the Makutapora Well Field used by Taylor et al. extend back decades. Unfortunately, however, Sentinel-1 (10 m spatial resolution) was only launched in April 2014, and data products are not available until some time after this. Landsat (30 m spatial resolution) has data extending back to the 1980s, but a two-week revisit time. Our own efforts to identify flood inundation using Landsat was unsuccessful due to extensive cloud cover during the Tanzania rainy season. A third possibility is to use MODIS measurements (500 m, daily resolution), which extend to ~2000, and thus would overlap at least two recharge events shown in Figure 2. If the spatial resolution is adequate, the daily revisits allow more opportunities to identify inundation. A fourth possibility is to purchase commercial radar imagery, though we did not look into this at all. Regardless, analysis of inundation in an area where recharge and intense precipitation are known to coincide in well-defined time intervals from previous work would be a more definitive way to explore these dynamics.

References

Lehner, B., Döll, P. (2004). **Development and validation of a global database of lakes, reservoirs and wetlands**Journal of Hydrology 296(1-4), 1 22. https://dx.doi.org/10.1016/j.jhydrol.2004.03.028

Lettenmaier, D., Alsdorf, D., Dozier, J., Huffman, G., Pan, M., Wood, E. (2015). **Inroads of remote sensing into hydrologic science during the WRR era** WATER RESOURCES RESEARCH 51(9), 7309 7342. https://dx.doi.org/10.1002/2015wr017616

Novella, N., Thiaw, W. (2013). **African Rainfall Climatology Version 2 for Famine Early Warning Systems**, Journal of Applied Meteorology and Climatology 52(3), 588-606. https://dx.doi.org/10.1175/jamc-d-11-0238.1

Taylor, R., Todd, M., Kongola, L., Maurice, L., Nahozya, E., Sanga, H., MacDonald, A. (2013). **Evidence of the dependence of groundwater resources on extreme rainfall in East Africa** Nature Climate Change 3(4), 374-378. https://dx.doi.org/10.1038/nclimate1731

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J., Sampson, C., Kanae, S., Bates, P. (2017). A high‐accuracy map of global terrain elevations Geophysical Research Letters 44(11), 5844-5853. https://dx.doi.org/10.1002/2017gl072874

Appendix: Guide to datafiles

Precipitation Data
We use precipitation data from the African Rainfall Climatology (ARC). Precipitation data from ARC from 11/16/2019 to 4/26/2020 for the entire continent of Africa is archived in Box.
Location: GWI Tanzania Project/Data/ARC
GWI Tanzania Project/Data/ARC/data contains daily tiff images for the continent of Africa. The pixel value corresponds to the amount of precipitation in mm.
GWI Tanzania Project/Data/ARC/meta contains metadata for ARC. The paper describing the dataset is included.

GWI Tanzania Project/Data/ARC contains matlab scripts to extract precipitation data for the Singida region.

Sentinel-1 Flood Maps
Sentinel-1 flood maps produced for the Singida and Dodoma region are archived. Google Earth Engine was used to obtain and classify Sentinel-1 imagery. The same code used in Google Earth Engine is included as a .txt file. To run this script, go to https://code.earthengine.google.com/ and paste the .txt file in a New Script.
Note: You might have to request permission from Google to get access to Google Earth Engine.
Location: GWI Tanzania Project/Data/Sentinel-1 Flood Maps
GWI Tanzania Project/Data/Sentinel-1 Flood Maps/Dodoma contains flood maps produced for December 2019 and January 2020. The Google Earth Engine script is GEE_Script.txt
GWI Tanzania Project/Data/Sentinel-1 Flood Maps/Dodoma/Permanent Water Shapefile contains shapefile for lakes in the region.
GWI Tanzania Project/Data/Sentinel-1 Flood Maps/Singida/2018-2019 contains flood maps produced for December 2018 and January 2019. The Google Earth Engine script is GEE_Script.txt
GWI Tanzania Project/Data/Sentinel-1 Flood Maps/Singida/2019-2020 contains flood maps produced from 22-November 2019 to 5-April-2020. The Google Earth Engine script is GEE_Script.txt
GWI Tanzania Project/Data/Sentinel-1 Flood Maps/Singida/Permanent Water Shapefile contains shapefile for lakes in the region.

Topography
We use MERIT DEM to obtain topographic elevations of the region, which is archived.
Location: GWI Tanzania Project/Data/Topography-MERIT DEM
GWI Tanzania Project/Data/Topography-MERIT DEM/Dodoma_DEM.tif is the MERIT DEM of the Dodoma region for which floods are mapped.
GWI Tanzania Project/Data/Topography-MERIT DEM/Singida_MERIT.tif is the MERIT DEM of the Singida region for which floods are mapped.
GWI Tanzania Project/Data/Topography-MERIT DEM/Tanzania_DEM.tif is the MERIT DEM for the entirety of Tanzania.

Well Datasets
The data for two pumping wells (at Mughanga and Nduamughanga) were obtained from lorentz pump site. The data is available starting from October 2019. The flow rate at the pump and water level are recorded. This data, along with analysis performed is archived.
Location: GWI Tanzania Project/Data/Well Datasets
The two excel files *Mughanga_daily.xlsx* and *Nduamughanga_daily_analysis.xlsx* contain seven sheets.
PumpDataSheet contains data downloaded for pump flow rate. This data is used to obtain a daily pump on time.
Pivot_table_pump_on_time contains a pivot table used to extract daily pump on time.

Daily Pump On Time contains the results from the earlier two sheets.
WaterLevel_DataSheet contains data downloaded for water level. This data is used to extract daily water level at the pump.
PivotTable_Water_Level contains a pivot table used to extract daily water level at the pump.
FilteredData contains water level data recorded before 7 am local time.
FilteredData_v2 contains water level data recorded before the pump was turned on.