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Refined GIS Mapping to Reinvestigate Groundwater Mining Potential Surrounding the Manmade Reservoirs and Tributaries in the Deduru Oya Basin, Sri Lanka

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Abstract: A hydrogeologic study was carried out to understand the influence of Man-Made Reservoirs (MMR), tributaries and fracture intensity on well yields within the Deduru Oya Basin (DOB), Sri Lanka. A number of cascaded MMRs interconnected by tributaries are distributed throughout the basin. Fracture traces, lineaments and reservoir boundaries were initially demarcated using aerial photographs, however, subsequently re-plotted them on to a Google Earth map with corrections to rectify the distortion. The GPS based well locations were regenerated and plotted to obtain accurate dimensions. ArcGIS was used to redraw the buffer zones from 0-200, 200-400 and 400-600 m away from the MMRs and tributaries. After eliminating dry wells, box plots were prepared where lower and upper quartiles indicate yield variations from 18-470; 15.8-165 and 12.8–55 liters/minute respectively. It clearly exhibits decreasing yields with respect to distance away from the MMR. However, wells drilled within the alluvial plains of tributaries after filtering those controlled by the MMRs and eliminating dry wells indicate different yield variations, viz: 7-36.8; 12.8-67.5 and 6.5-142.5 liters/minute. The results assigned higher yields to the wells located away from the tributaries with steep hydraulic gradients whereas lower yields to the wells closer to the tributaries with gentle hydraulic gradients. Moreover, wells drilled at fracture interconnections indicate a potential for high yields compared with those drilled along with a single fracture. The study concludes that the potential for groundwater mining can be enhanced by identifying high recharging areas such as MMRs, zones of steeper hydraulic gradients and high fracture interconnectivity.

Keywords: Deduru Oya, fractures, reservoirs, recharge, GIS mapping, groundwater mining.

Introduction

With the increasing demand for the available surface water, the emphasis is now being laid on the extraction of shallow and deep-seated groundwater in crystalline rocks (Jayasena et al., 1986; Jayasena, 1989; Jayasena, 1993; Jayasena, 1995; Jayasena and Dissanayake, 1995). During the driest periods of the year, shallow groundwater extracted from the regolith aquifer (average up to 10 m) through dug wells may dry up. Therefore, government and private agencies pay special attention to extract deep groundwater (fractured aquifer average up to 30 m and deep lineaments) (Jayasena et al., 2018). The availability of groundwater in crystalline rocks is generally less because of the extremely low primary porosity and low interconnectivity (Bell, 1980; Jayasena et al., 1986). However, fractures, joints, deep lineaments, faults and shear zones developed due to local and regional tectonic events could generate a dense fracture network facilitating the movement and occurrence of a significant amount of groundwater.

The overall objective is to investigate the hydrogeologic behavior of a fractured crystalline rock terrain, with special reference to identifying areas with high potential for groundwater. It specifically aims at understanding the influence of fracture distribution, manmade reservoirs and diversion canals on groundwater yield in the Deduru Oya Basin (DOB) with the support of ArcGIS (Fig. 1).

Hydrogeologic and geomorphic background of the study area

The DOB originates from the headwater around 850 m above mean sea level (MSL) in the central highlands and lies between the latitudes 7° 19’ N and 7° 51’ N and the longitudes 79° 47’ E and 80° 34’ E. The elevation drops towards the northwest, and the ridge and valley topography give way to an area of isolated ridges and rock knobs near the center of the basin (Jayasena, 1989; Jayasena, 1998). The mainstream length is about 115 km and the basin covers approximately 2,600 km^2 (Somaratne et al., 2003) which mainly underlain by Precambrian metamorphic rocks. However, recent deposits formed during the Quaternary period cover as a mantle consist of alluviums about 3 km wide floodplain at the western end of the DOB, colluviums flanked by isolated ridges and rock knobs near the center of the basin (Jayasena, 1989; Jayasena, 1998) and regolith as thick as 10 m (Jayasena et al., 2018). The regolith plays a significant role in retaining a substantial amount of groundwater except in the north-central part of the basin. In terms of groundwater exploration, smaller geologic units such as Pegmatites, Dolerites and the sequence of Jurassic sedimentary rocks occur in the northwestern faulted basins significantly control the groundwater occurrence, movement and quality throughout the fractured rock environment (Jayasena et al., 1986; Jayasena, 1993; Jayasena, 1995; Jayasena and Dissanayake, 1995).

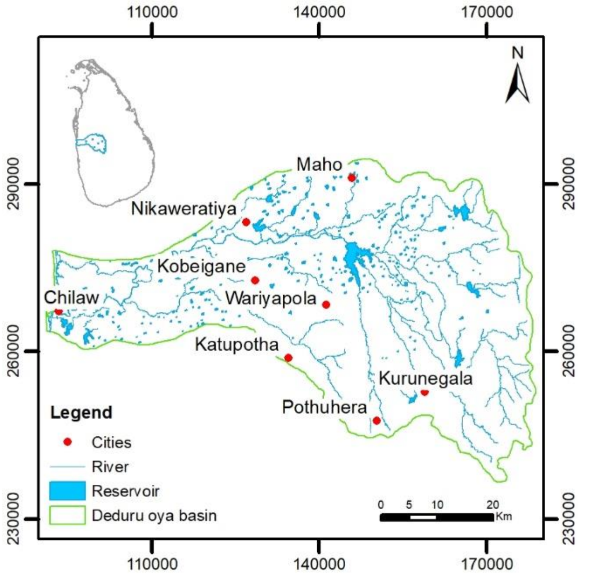

Fig. 1 Map of Sri Lanka showing the location of the DOB and its hydrological elements

Climatic, geologic and morphologic implications on MMR distribution

The DOB receives rainfall from the Northeastern and Southwestern monsoons. The mean annual rainfall gradually decreases from South to North with an average annual rainfall (ARF) of 1730 mm (Singh and Jayasena, 1984; Jayasena, 1993). The basin falls under three major climatic zones (Panabokke and Kannangara, 1975; Madduma Bandara, 1985; Jayasena, 1998). The major part, 94% of the DOB falls in the intermediate zone (ARF between 1,750 to 2,500 mm) while 5% and 1% respectively fall in the wet (ARF over 2,500 mm) and the dry zones (ARF less than 1750 mm).

Rainfall and flood irrigation water infiltrates to replenish groundwater reserve while streamflow supports for surface storages at MMR's constructed within minor or meso-catchments. Lowlands in the dry and the intermediate zones are characterized by rolling topography defining such meso-catchments. These catchments with reservoirs set up in the cascade system have been identified as Tank Cascade Systems (TCS) (Madduma Bandara, 1985; Mahatantila et al., 2008; Jayasena and Gangadhara, 2014). The average area of such unit is 21 km^2 with a range from 13 to 26 km^2 (Panabokke, 1999). The remnants of geological formations and rock knobs play a vital role in siting and governing the tank distribution (Jayasena et al., 1986; Jayasena, 1993). Most tanks were constructed on this basement where rock exposures have been used as bunds, spillways and embankments (Cooray, 1984). Tank beds cover either alluvial deposits or weathered overburden with varying thickness (Jayasena et al., 1986).

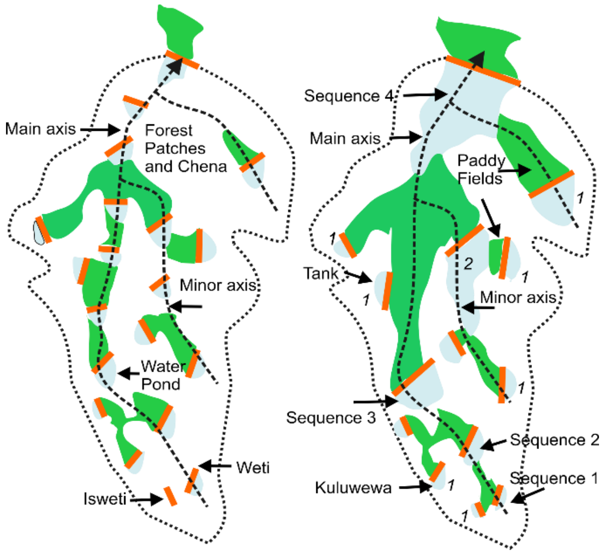

Fig. 2 Schematic diagram showing the progression of check dam-based water ponds to TCS and associated man-made features (Jayasena et al., 2011).

A recent study by Jayasena et al. (2011) delivered a strong relationship between the tank distribution in cascades and rainfall variation in the DOB. These cascades with their boundaries demarcated using topographic maps consist of 4633 small tanks for which sequence numbers were assigned (Fig. 2). The sequence numbers within the respective rainfall regimes graphically represent a log-linear relationship with the number of tanks, which resulted in "Degree of Cascading" (DOC). Theoretically, DOC could vary from 1 to infinity, however, in the DOB, it varies from 1.6 to 4.5 (Jayasena et al., 2011), indicating an increasing number of tanks in gently sloping terrains characterized by higher annual rainfall. On the contrary, tanks with larger surface extent are common in the flat areas with low rainfall indicating lower tank density towards the tail-end of the basin. Moreover, the TCS seems an outcome of organized planning rather a haphazard construction.

Groundwater potential through lineaments and fracture network

Investigation of lineaments and fracture network has considerable importance on groundwater exploration (Mallik et al., 1983; Palacky et al., 1981; Singhal et al., 1988). Lineaments are indicative of secondary porosity, and if intersected by a well, it will have the potential to supply significant and reliable quantities of water (Bruning et al., 2011). Since fractures and joints serve as passageways for water movement, a dense network of fracture system could enhance groundwater storage and production (Hossam et al., 2011). One method of identifying potential area is fracture trace analysis (Krothe and Bergeron, 1981), where Lattman and Nickelson (1958) defined the "fracture trace" as a natural linear feature less than one mile (1.6 km) long. A lineament is defined as a similar linear feature longer than a mile (1.6 km). Fracture traces and lineaments can be generated by tectonic activities or stratigraphic discontinuities. In a previous study, fractures and lineaments formed due to tectonic activities were considered around Wariyapola resulted in high yielding wells with high fracture density (Jayasena, 1989; Jayasena, 1993).

Materials and Methods

Fracture traces, lineaments and boundaries of reservoirs and DOB were initially demarcated using aerial photographs, however, subsequently re-plotted them on to a Google Earth map with necessary corrections to rectify the distortion. After the rectification, the GPS based well locations (338) were regenerated to obtain accurate measurements. Structural geologic control of well yields within the DOB was examined with respect to the axes of major antiforms and synforms, faults and shear zones. The ArcGIS package has been used to analyze relations between these features. “Add path” was used for linear features while “Add polygon’ was used for aerial boundaries. The generated “KML” files were converted into a “shapefile” using the “ArcToolbox” option.

Three buffer zones with 200 m interval up to 600 m around MMR’s and tributaries were created, merged and dissolved using ArcGIS. The input features based on geometric intersection were computed as overlap for all layers before written to the output. The intersect tool was used to separate yields from each buffer zone before calculating respective lower and upper quartiles. The interquartile range (IQR) of well yields with respect to distance away from the MMR’s and tributaries were tabulated and box plots were prepared.

Results and Discussion

GIS-Based Study On DOB

ArcGIS, Google Earth and three-dimensional images gave contrasting results for the basin area (2728.37 km^2), basin perimeter (280.29 km) and the mainstream length (approximately 137 km). The mainstream was designated into the sixth order (Strahler, 1957) which, originates from 850 m above MSL and runs adjacent to Kurunegala before discharging its waters to the sea at Chilaw lagoon. The slope of the mainstream varies between 1.1% to 1.7%.

Fracture Distribution

Fracture traces of the DOB have been transferred onto ArcGIS from the Google Earth for frequency analysis. The highest percentage of 7.1 is observed in the 330^0 - 340^0 direction, whereas, the lowest percentage of 3.7 follows in the EW direction (Fig. 3). A large number of field scale joints in different rocks within the Wariyapola area, however, indicated prominent E-W direction (Jayasena, 1989). Moreover, many of these joint traces are not commonly observed on the aerial photographs and/or Google Earth images, except at few places within the central part of the Wariyapola area, which may suggest that they are not wide enough to be observed as linear fractures. The fracture trace density (based on length/km^2) is high in the southern flank of the DOB. However, only a few fractures are observed on the western lowlands due to the denudation produced surficial materials (Fig. 3).

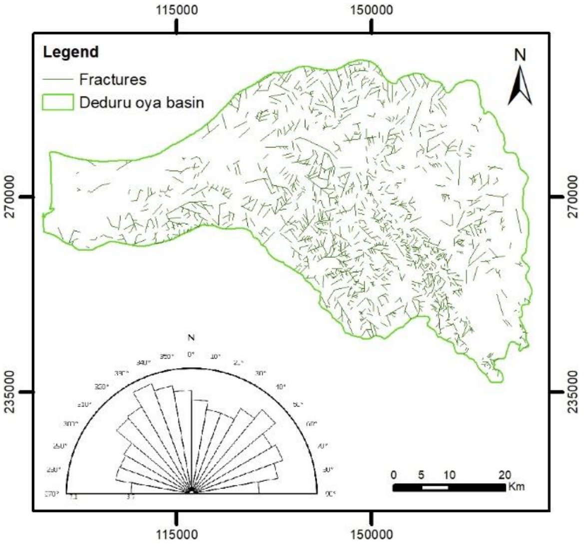

Fig. 3 Google Earth-based fracture trace/lineament distribution and the respective frequency diagram (Rose diagram) of the DOB.

Analysis of Tube Well Data

Analysis of 338 domestic water supply tube wells in the DOB gives the following results. The minimum and the maximum depths are 7.5 and 140.15 m, respectively. The average depth is about 53 m with a standard deviation of 18.3 m. The lower and upper quartiles vary from 39 to 63 m. The minimum and maximum yields are 0 and 1200 liters/minute. The average well yield is about 95 liters/minute with the standard deviation of 165.3 liters/minute. The lower and the upper quartiles vary from 11.7 to 100 liters/minute. The lower yields may result due to wells drilled away from the tectonic fractures and joints. Further, it could also be due to incomplete or improper drilling and construction failures subjected to reducing well efficiency. The recharging area includes headwater regions with elevated central highlands on the south-eastern side of the DOB. The distributary drainage system with a thick pile of alluvial deposits in the discharging zones located in the western lowlands of the Deduru Oya floodplain could support for high yielding wells (Fig. 4).

Structural Geologic Control of Yield in the DOB

The axes of major antiforms and synforms have a general NW-SE trend. The analysis shows that the wells drilled near the axes of synforms generally have lower yields. In contrast, wells located close to the axes of antiforms have higher yields (>30 liters/minute). Most of the faults are concentrated in the eastern part of the DOB covering the central highlands of Sri Lanka with traces aligned in the NNE-SSW direction.

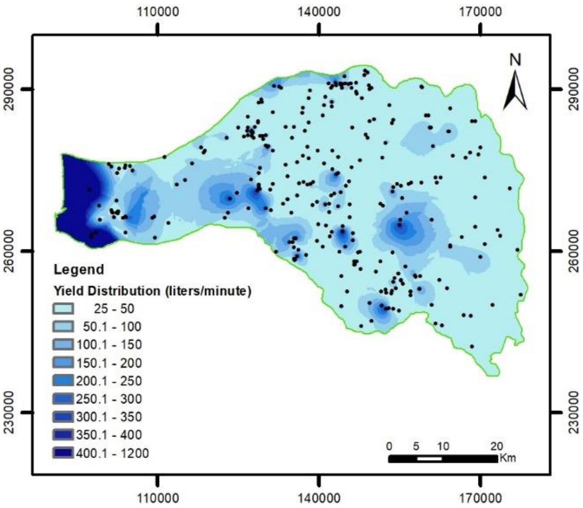

Fig. 4 Distribution of tube wells and respective yield variations in the DOB.

These faults could be generated due to neotectonic movements parallel to the proposed arcuate axis of upliftment in the central island (Vitanage, 1972; Silva et al., 1983). The shear zones which run in the NW-SE directions contribute more to high yielding tube wells (Fig. 5). In this analysis clusters of high yielding wells associated with the MMRs are eliminated.

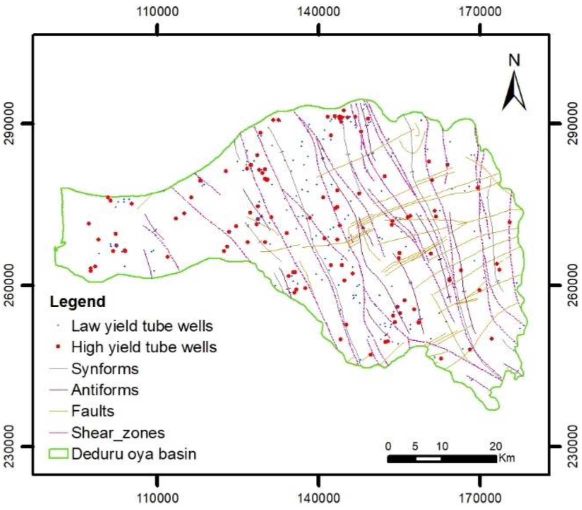

Fig. 5 Distribution of structural geologic features and tube wells in the DOB.

Analysis of Well Yield Variations Within the Buffer Zones

ArcGIS package was used to redraw the buffer zones with an interval of 200 m up to 600 m away from the MMRs (Fig. 6) and tributaries (Fig. 7). After eliminating dry wells, box plots were prepared for each case with respect to well yields recorded within 200, 200-400 and 400-600 m intervals (Fig. 8). The respective lower and upper quartiles with the Inter Quartile Ranges are presented in Table 1. The results undoubtedly exhibit the decreasing yields away from the MMR. It is clear that such yield variations were supported by the local recharging of the MMRs thus those zones could be potentially promising areas for groundwater mining. However, wells drilled in the alluvial plains of the tributaries after filtering those controlled by the MMRs and eliminating dry wells indicate different yield variations. The results indicate that the wells located 400-600 m away from the tributaries with steeper hydraulic gradients provide an appreciable amount of groundwater whereas with gentle hydraulic gradients towards the tributaries resultant with lower yields (Fig. 9). However, based on the common notion, well yields closer to a tributary should be higher than that away from it. Since the analysis even eliminates the manmade reservoir (MMR), the output should be attributed to the differences associated with geologic formations. The wells drilled in the alluvial formations closer to the tributary may have appreciable amounts of clayey matter which inhibit the groundwater inflow. However, within 400-600 m, the network of fractures in the bedrocks facilitate recharge to the wells through the tributaries where groundwater flow with ease. In addition, groundwater flowing through such rock fractures may improve the well efficiency supporting for high yielding wells. Overall analysis indicates that the well yields generally decrease beyond 600 m. Further scrutiny on a case by case is expected in order to provide a concrete recommendation.

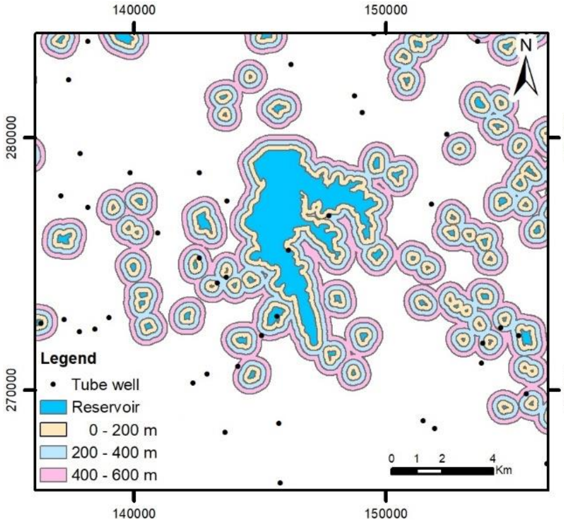

Fig. 6 The generated buffer zones with an interval of 200 m up to 600 m away from the MMRs.

Table 1 Yield variations within the respective buffer zones away from the MMRs and the tributaries.

	MMRs			Tributaries		
	Distance (m)			Distance (m)		
	0 to 200	200 to 400	400 to 600	0 to 200	200 to 400	400 to 600
Upper quartile (liters/minute)	470	165	55.0	36.8	67.5	142.5

Lower quartile (liters/minute)	18.0	15.8	12.8	7.0	12.8	6.5

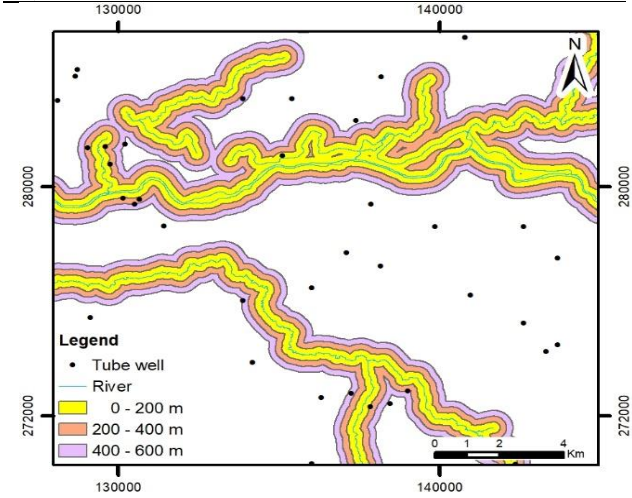

Fig. 7 The generated buffer zones with an interval of 200 m up to 600 m away from the tributaries (reservoirs have been eliminated in the analysis).

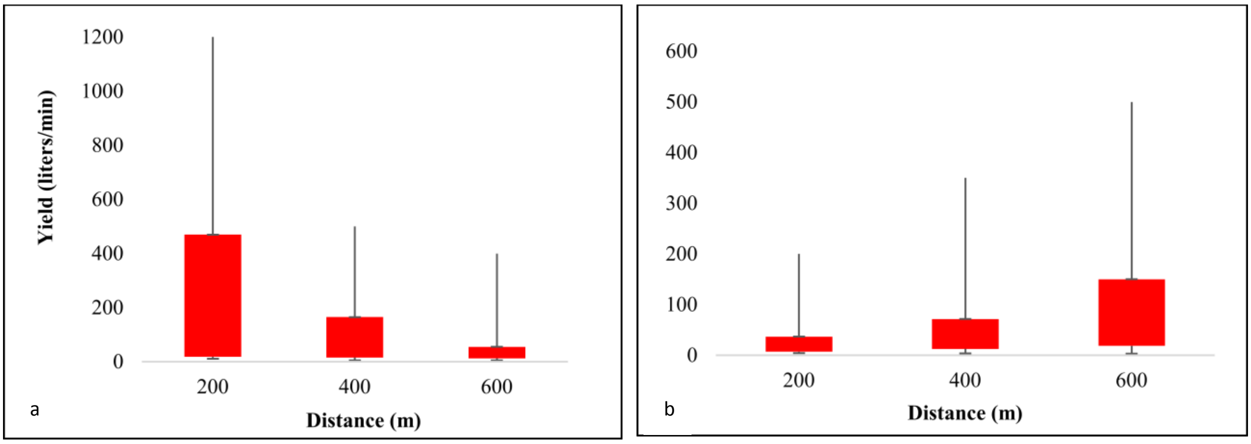

Fig. 8 Box plots showing the yield variation at 200 m intervals up to 600 m away from (a). the MMRs and (b). the Tributaries.

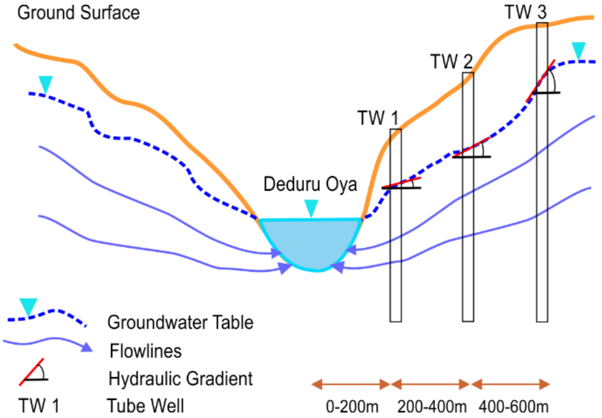

Fig. 9 Schematic diagram showing the cross-section of Deduru Oya with the possible water table and flow line distributions. Hydraulic gradients at 200 m intervals along with TW distribution are also given

Conclusion

It is recommended that E-W fractures or lineaments from the fractured rock regime should be avoided when locating wells to extract a large quantity of groundwater. Wells constructed near NW trending shear zones, along the axes of antiforms and at locations where fractures are interconnected could provide higher yields. Wells having higher recharging potential close to the MMRs clearly exhibit potential for groundwater mining. Well yields within the 600 m peripheral area of the tributaries exhibit a gradual increase; higher yields to the wells located away from the tributaries with steep hydraulic gradients whereas lower yields to the wells closer to the tributaries with gentle hydraulic gradients. Beyond 600 m, the yields are generally low except for localized pockets. The regional recharging areas mainly include headwaters in the elevated Central Highlands on the Southeastern segment of the DOB. The distributary drainage system with a thick pile of alluvial deposits in the discharging zones of the Deduru Oya floodplain could support for high yielding wells. Further analysis including modeling with the R software is planning.

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