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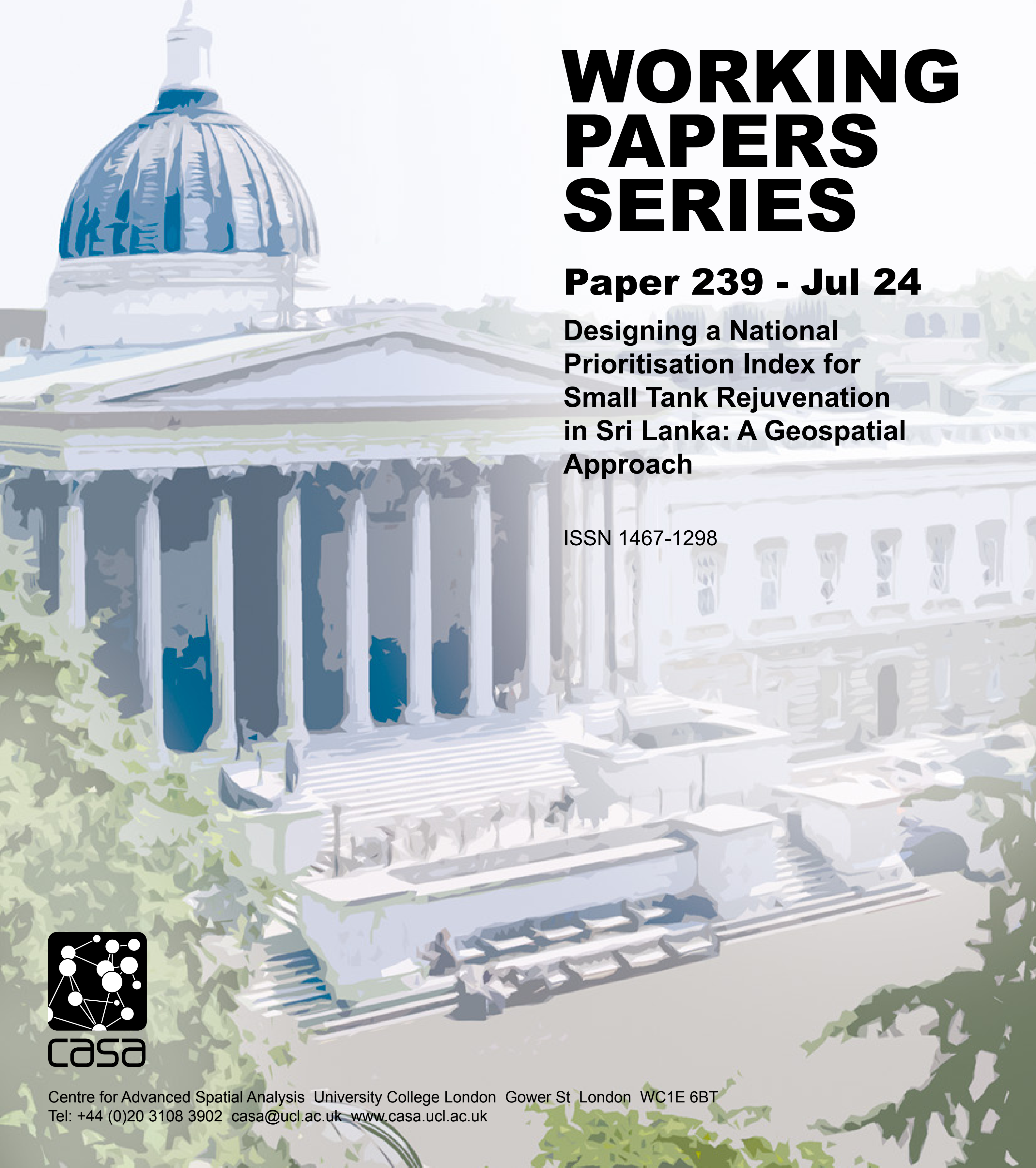

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Designing a National Prioritisation Index for Small Tank Rejuvenation in Sri Lanka: A Geospatial Approach

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Designing a National Prioritisation Index for Small Tank Rejuvenation in Sri Lanka: A Geospatial Approach

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Abstract

In Sri Lanka, climate change and recurrent droughts pose significant threats to agricultural communities. Village water storage tanks have been used in countries in Southeast Asia since the third millennium BC. According to the National Tanks Survey, Sri Lanka has some 23,000 small tanks of 80 hectares or less; however, 21 percent are currently non-functional due to decades of neglect. This study designs a National Prioritisation Index for the rejuvenation of small tanks, employing a geospatial approach to. Our research disaggregates district-level statistics at a 1 km resolution to map the demand from agricultural-dependent populations. We then construct several prioritisation indices that evaluate tanks from supply, demand, and utility for groundwater rejuvenation perspectives. Our findings highlight priority areas for tank rejuvenation concentrated in Kurunegala and Anuradhapura districts. The indices developed in this study provide a framework for targeting investments effectively, thereby optimising resource allocation for drought mitigation efforts. The approach can support enhancement of water security and resilience in vulnerable agricultural communities across Sri Lanka and in other parts of South-East Asia which are reliant on such infrastructure for water storage.

Statements and Declarations

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1. Introduction

Water storage is crucial for water security in countries with monsoon driven climates (Anand, Kakumanu, and Amarasinghe 2019). As a result, village water storage tanks have been used in countries in Southeast Asia like India and Sri Lanka since as far back as the third millennium BC (UNDP 2019) and are one of the oldest traditional water harvesting structures. They contribute to water security, particularly for agriculture dependent populations (Rodrigues et al. 2012) by creating a buffer to mitigate the impact of floods in the monsoon months and provide additional supply for crops during water shortages and droughts in the dry season (Anand, Kakumanu, and Amarasinghe 2019). Given increased rainfall variability associated with climate change (Bayissa et al. 2022; IPCC 2023), the role of water storage is becoming ever more important. There are three types of tank classification in Sri Lanka: minor, medium and large.

This paper focuses on small tanks of 80 hectares or less, which are classified as minor irrigation systems or minor irrigation works (Vidanage, Kotagama, and Dunusinghe 2022). According to the National Tanks Survey, Sri Lanka has some 23,000 small tanks[1] of 80 hectares or less. However, some 21 percent are currently estimated to be non-functional (either damaged or abandoned) due to decades of neglect with the gradual advent of canal and groundwater systems of irrigation. The Ministry of Agriculture and organisations like UNDP are now attempting to revive some of these neglected tanks (Vidanage, Kotagama, and Dunusinghe 2022) to reduce the risk of crop failures due to climate fluctuations.

However, with such a large number of tanks dotted around the country it is difficult to systematically identify where investment in rejuvenation should be targeted, and thus most efforts have been with smaller scale case studies to identify prioritisation criteria using qualitative analysis or analysis on small clusters of tanks. For example Kalaiarasi and Arul developed a Tank Rehabilitation Index (TRI) for prioritising tanks to rejuvenate based on 24 indicators reflecting the physical, hydrological and socio technical aspects, but it looked at only four tanks of a cluster in Kiliyar sub basin, Palar basin, Tamil Nadu, India (M. S and Arul 2022). Another study by Nagarajan managed to build an index for 89 tanks across two cascade systems in Addakkal, Hyderabad, India (Nagarajan 2013). Other studies have identified some of the reasons for why some rehabilitation projects either succeed or fail, highlighting management issues (Sirimanna and Prasada 2022), the utility that they serve/demand they face, and the local capacity to manage them (CBOs etc.) (Asian Development Bank 2006). In addition to providing water for agriculture, silt from tanks can also be used to improve agricultural land fertility (Anand, Kakumanu, and Amarasinghe 2019).

Whilst this information is extremely important, this study makes a rare attempt to build an index with a combination of available global, census and household survey datasets to take a wider lens across all the 23,000 small tanks in Sri Lanka, and come up with criteria to first assess tank demand from the

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[1] Though estimates vary between 18k (Aheeyar 2004) and 30k (Dharmasena 2004), the data received from the Ministry of Agriculture for analysis in this paper shows approximately 23,000 small tanks located across Sri Lanka.

agriculture dependent population, and finally identify a means to decide which tanks to rejuvenate first. The steps to get to this prioritisation index are substantially more computationally intensive than what has been attempted previously. The resulting methodology has potential application for other contexts, including even larger datasets across bigger countries in the region.

The paper seeks to address four research questions. Firstly, how do we identify the tanks in Sri Lanka that are most in need of rejuvenation? In other words, we first view the problem from a supply perspective. Secondly, we take a demand-based approach and ask how do we identify the areas of Sri Lanka that are most in need of small tank rejuvenation? Part of answering this question also means identifying where agricultural dependent populations live. Such data is not readily available from household datasets at any low level of spatial granularity, and therefore we had to design a method to compute this. Finally, once we had metrics for supply and demand indices computed, we asked one further question: how amdshould we prioritise tank rejuvenation in Sri Lanka considering both supply- and demand-side constraints, as well as those which may hold the highest potential for groundwater recharge? This final piece is considered as a subfilter of those tanks already identified for prioritisation based on supply and demand factors.

2. Data sources and Sampling

We used a range of different data sources to conduct the analysis. For population modelling we used the WorldPop estimates at a 1km resolution from 2020. This data comes in the form of a global raster with 352,520 pixels. Secondly, we take a Global Human Settlement Layer (GHSL) from the European Commission from 2023, which classifies land types at 1km into eight different categories (Annex 3). From these we extrapolate which categorisations are urban vs. rural. Third, we use a land cover polygon received from the Sri Lankan Land Use Policy Planning Department which has 38 categories of land use (see S1 text). We classify these into agricultural and non-agricultural lands. The Household Income and Expenditure Survey 2012 is used to extrapolate the poverty rate at district and DSD level and then for calculations at district level of population dependent on agriculture as either a primary or secondary occupation. Two other global datasets which are used in the calculation of tank supply needs are the GLoSEM database on soil erosion and the CHIRPS rainfall variability dataset, which gives the coefficient of variance for rainfall between 1983-2000 in the Maha season[2] at 100m resolution. For full details on the provenance of each data source see Table 1 in Annex 1.

Finally the tank data was drawn from three different databases. Our base data for the analysis was the national level database on the tanks themselves from the Ministry of Agriculture of Sri Lanka. This dataset contained a record of 23,163 tanks in Sri Lanka with their command area, water height, and water level. Another associated database from the Ministry of Agriculture was then spatially joined to this dataset to add data on the functionality status of each tank. This brought us down to 21 thousand tanks for which this information was available on the functionality status. We then needed additional information on the shape of each of these tanks (rather than just their GPS locations on the map). A survey by UNDP used satellite imagery to trace the outline of each of the tanks surveyed, but this was possible for 11,014 of the tanks in the country. A final constraint was that we were also seeking to gain siltation information from the tanks for computing the supply side index later in the methodology. However, only 6,938 of the tanks had such information in the survey. We used a machine learning

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[2] The Maha season falls during the "North-east monsoon" from September to March and is one of two seasons when the crops are sown and harvested http://www.statistics.gov.lk/Agriculture/StaticalInformation/PaddyStatistics#gsc.tab=0

technique (see section 3.2) to compute missing siltation information for the remainder, bringing back up the total to 11,014 tanks under analysis.

3. Methods

3.1. Design the conceptual framework

First of all, we sought to reach a conceptual understanding of the factors to consider when thinking about tank prioritisation. We grouped the factors to consider under three thematic categories as laid out in the research questions. The first were *supply* related factors which considered the current status of each of the tanks under study. It includes factors such as the level of siltation measured in the tank at the time of the survey and the risk of soil erosion (according to the global dataset Global Soil Erosion Modelling (GloSEM) from the European Soil Data Centre). We also used the functionality status as part of a regression to ensure that we were building an index that correlated with the factors that would be considered to contribute to non-functionality. Secondly, we considered *demand* related factors for tank rejuvenation. The UNDP survey revealed that 94% of the tanks that were included in the survey were used for some kind of agricultural practice, with 87% of them reportedly being used for irrigation by the community that were managing them (UNDP 2019). This led us to the importance of identifying the agriculture dependent population (ADP) for the tanks under study, in order to ascertain the level of demand they would face. This data was not readily available and the computation process is described in detail below; it required consideration of population counts as well as land use and household survey data on agricultural dependency at district level. Secondly, we considered rainfall variability as an important factor in determining the demand for tanks given that areas with a higher coefficient of variance of rainfall would be more likely to rely on the tanks for either drought or flood mitigation due to unexpected weather events. Thirdly, once the prioritised tanks on supply and demand factors had been identified, we added a final consideration on the utility of rejuvenation with respect to groundwater replenishment. To assess potential for contribution to groundwater replenishment, we considered the underlying aquifers on which each of the tanks were located. We assessed their respective pump yields in ranking their utility for rejuvenation from a groundwater replenishment perspective (Figure 1). More detail on each of these methods is now provided in the respective subsections.

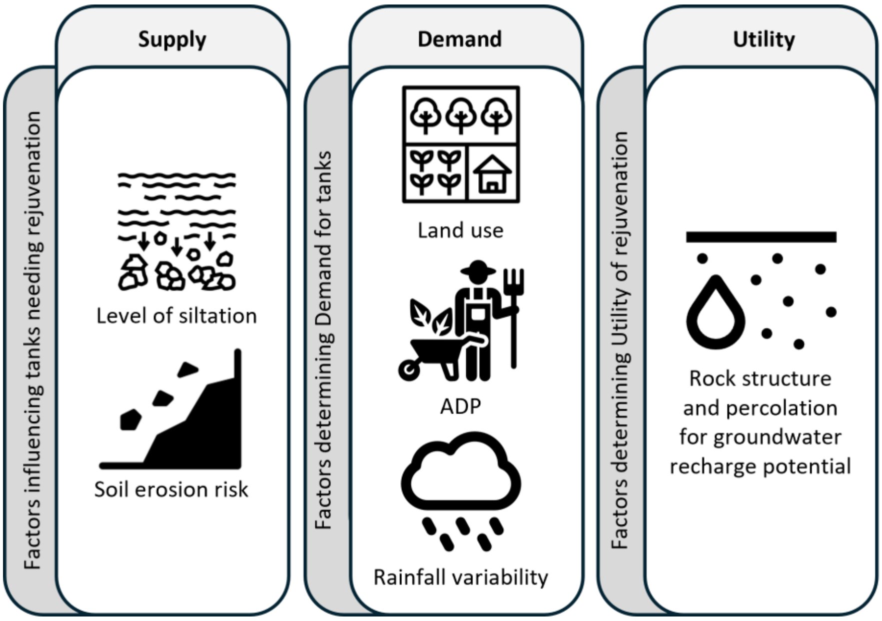

Figure 1 - Factors influencing supply, demand, and utility of small tanks rejuvenation.

All of the analysis described below was conducted in python. Scripts and corresponding public datasets are available on GitHub at https://github.com/fdlopane/SL-Tanks/.

3.2. Compute the Supply side index

Computing the need for tank rejuvenation without considering demand is the first part of the index creation. This considers data from the tank survey and associated information on the functionality status of the tanks, their level of siltation and the soil erosion risk. Those tanks which will be prioritised are those that have high siltation levels and a high soil erosion risk. Each of these factors was normalised and the product of the two was computed to provide the index value for each tank polygon in the dataset. Those with the highest scores in terms of both siltation and soil erosion are those which will rank highly on the join index and be prioritised for supply side considerations. The formula for this computation is as follows:

$$S_i = SS_i \cdot E_i \tag{1}$$

Where S_i is the Supply-side index of tank i, SS_i is the normalised siltation score of tank i, and E_i is the normalised soil erosion score at tank i location.

A weighted sum is then performed to generate index statistics' aggregation at DSD and district level. Though computing the index itself is straightforward, due to the missing data on siltation for some 3,000 of the 11,000 tank polygons, we used an ordered logistic model to compute the missing siltation values before creating the index. Note that the soil erosion risk index considers a Digital Elevation Model (DEM) in its computation. The estimates for each of the components of the index were derived from the survey data at the tank level and the soil erosion risk was estimated by spatially joining the GLoSEM database to the tank outlines.

3.3. Compute a Demand side index

Considering those tanks that are non-functioning will only provide a partial picture, as it is possible that some tanks are abandoned or in a state of disrepair simply because they are no longer needed by the surrounding population. Due to the rise of irrigation systems, some abandoned tanks may no longer be needed, or the surrounding population could no longer be engaged in agricultural activities. With this in mind, we consider demand side factors and seek to compute the agriculture dependent population for each tank using a combination of spatial datasets and the HIES household survey for calibration.

3.3.1. Compute the agriculture dependent population (ADP)

This step uses three data sources: the Sri Lanka Policy and Planning Department Land Use raster; a WorldPop population count raster; and the Household Income Expenditure Survey (HIES)[3] district level agricultural dependent population from 2016 (Figure 2).

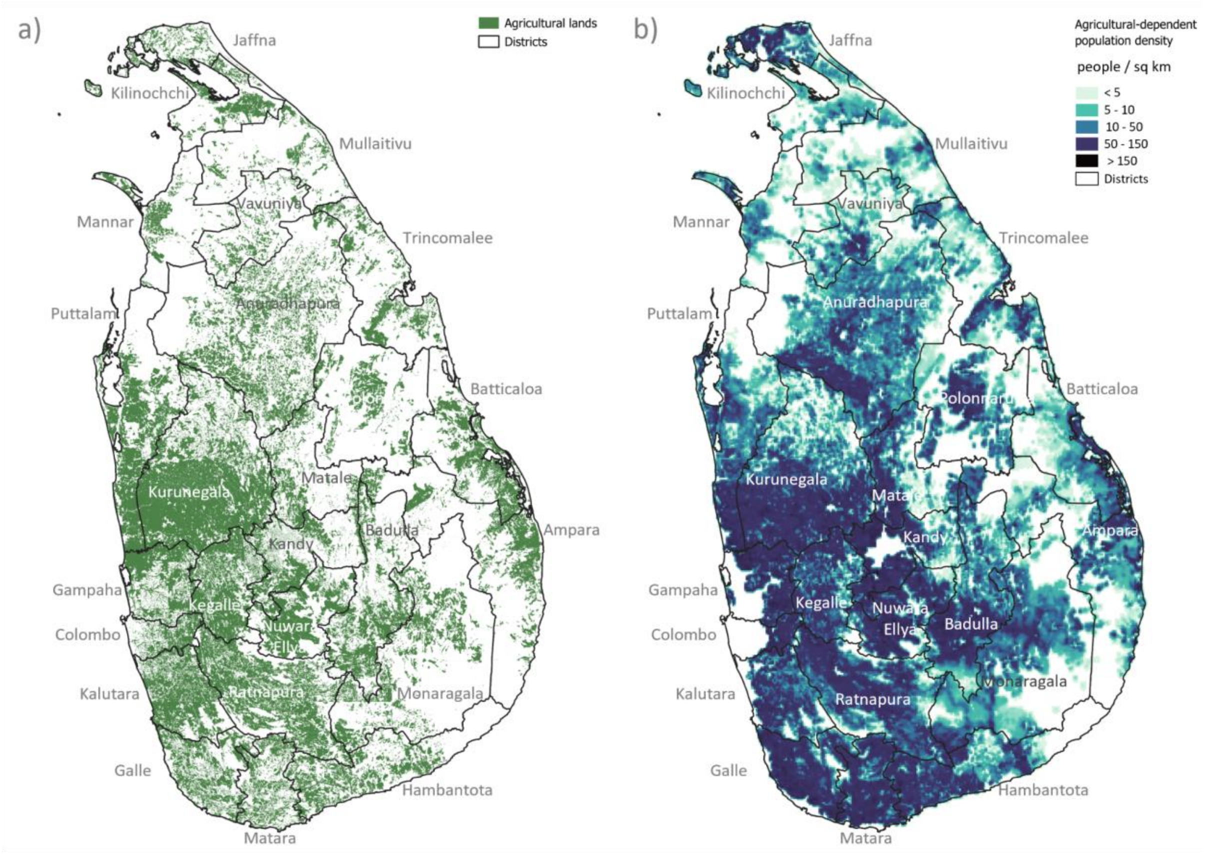

Figure 2 - a) Lands classified for agricultural use; b) Computed agricultural-dependent population.

To start with we use HIES survey data to estimate the agricultural dependent population we would expect at the district level. These HIES district level estimates are computed by a research team at the Water GP of the World Bank, and take into account population dependent on agriculture, not necessarily as the main occupation, but also considering secondary occupations. The estimate made use of an indicator called the "Agriculture Dependent Population" (AgDep) that provides a comprehensive measure of the proportion of the population within an administrative boundary that is dependent on agriculture as a primary source of income. The AgDep indicator combines two pieces of information: first, the number of household members aged 15 years and over who are employed

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[3] The Sri Lanka Household Income and Expenditure Survey (HIES) 2016 is a nationally representative survey conducted by the Department of Census and Statistics of Sri Lanka. This comprehensive survey collects detailed information on the income and expenditure patterns of households across the country, aimed at assessing living standards and informing economic and social policy decisions.

or working in the agriculture industry at the time of the survey interview, and second, the number of household members who have had income from agricultural activities, such as cultivating crops or livestock, as an employer or own account worker during the last year at the time of the interview. To create this indicator, the primary data source adopted in this analysis is Sri Lanka Household Income and Expenditure Surveys (HIES) of year 2016, which is a complex survey conducted on a nationally representative sample to characterise important aspects and living pattern of people in different segment of population at a national sector and district levels. Sri Lanka HIES 2016 covers all 25 districts in the country and a 20.7 million household population. The first piece of information is obtained from the household demographic characteristics section (question 15). A household is considered as an agriculture-dependent household if any household member is employed in the agricultural industry. The second piece of information is obtained from the household income section 5.2 and 5.3: a household is considered as an agriculture-dependent household if any of the household members cultivate paddy, other seasonal crops, or other agricultural activities such as non-seasonal crops cultivation and livestock raising, as an employer or own account worker for sale or household consumption during the last year at the time of the interview.

However, this first step is only to provide us with some validation data, in order to come up with a method of estimating ADP at a much more fine-grained resolution (100m). In order to produce a fine-grained estimate, we need to combine multiple raster datasets and conduct an estimation process (Figure 3). This starts with using the 1km resolution population count data from WorldPop. Though a 100m resolution World Pop file exists we found it to be inaccurate with visual comparison with satellite imagery revealing heavily displaced human settlements at that level. We therefore used the 1km resolution dataset and resampled it to 100m, converted it to points, and joined it with the Global Human Settlement Layer (GHSL) raster (see Annex 4). This enabled us to categorise the population as urban or rural depending on the grid cell on which they were located. We used the GHSL classification of urban and rural populations to mask out urban populations from the analysis. We then joined this to the District Secretary's Division (DSD - one administrative level below a district in Sri Lanka) and district identifiers, enabling us to calculate the proportion of each district and DSD population that is rural. In parallel, we took the land use layer from the Ministry of Lands (see Table 2 in Annex 2), which contains 38 land types and categorised s into agricultural or non-agricultural (note that this does not consider whether the land is irrigated or not). For each district we took the 100m rural population point layer generated earlier and summarised the total population within each of the agricultural land shapes that was generated. As a result, for each agricultural land polygon we have the rural population of the district that falls within it, and those that fall outside of it. This results in a count of the total rural population for each district that falls within agricultural lands.

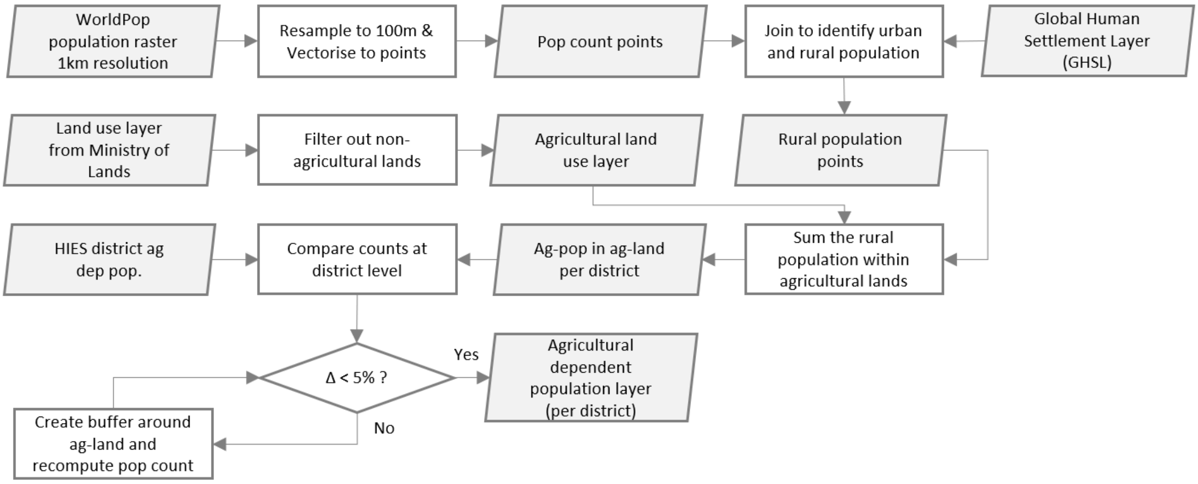

Figure 3 - Agricultural dependent population geocomputation workflow.

At this point we made a comparison between HIES household survey estimates on the agriculture dependent population at the district level and the computed estimates. Where the geospatially computed estimates of ADP are more than 5% lower than the HIES estimates, we then iteratively compute a buffer in 100m intervals around the agricultural lands to get to within 5% of the estimate. The aim is to get to all estimates at district level within +/-5% of the HIES estimates. As a final stage to get the ADP country-wide, we merge back together each of the respective district level shapefiles with their corresponding ADP estimates into a single layer. This single combined polygon on agriculture dependent population can then be used to break down the rural population at DSD level if smaller levels of disaggregation are sought.

To estimate the ADP served by each tank, we generated a 1 kilometre buffer around each tank, and overlapped each command area with the agricultural dependent population layer to get a final count of served population by each tank.

3.3.2. Add in covariance of rainfall and generate combined demand side index

To then get the demand side index we need to consider the covariance of rainfall, as the ADP will be in greater need of the tank in areas where rainfall variability is higher. To get this estimate for each tank, we spatially join the CHIRPS data on rainfall variability (Coefficient of Variance) 1983-2020 Maha Season to the tank polygons with the information on ADP above and normalise the values between 0 and 1. The higher the variability the greater the demand. Then to get the combined demand index value we multiply the normalised rainfall variability by the normalised ADP to get a final score for each tank where the higher the score the higher the demand.

$$D_i = ADP_i \cdot R_i \tag{2}$$

Where D_i is the Demand-side index of tank i, ADP_i is the agricultural dependent population served by tank i, and R_i is the normalised rainfall variability at tank i location. A weighted sum is then performed to generate index statistics aggregation at DSD and district level.

3.4. Generate a combined prioritisation index weighting tank prioritisation by agriculture dependent population

Here we take the supply side index generated in section 3.2 and weight the score given by the agriculture dependent population mapped to each tank. Note that we would occasionally encounter populations that fell within the catchment area of more than one tank. In such cases, we decided these populations could be mapped to both tanks, given that they had the choice to go to either one. This means that the numerical estimate of ADP is inflated beyond the population of the area, due to the overlap in populations dependent on multiple tanks.

$$SD_i = S_i \cdot D_i \tag{3}$$

Where SD_i is the Supply-Demand index of tank i, S_i is the Supply index score of tank i, and D_i is the Demand-side index score of tank i.A weighted sum is then performed to generate index statistics aggregation at DSD and district level.

3.5. Separate the analysis by areas where tank rejuvenation is likely to lead to higher groundwater recharge

There is some initial evidence that tanks could contribute to groundwater recharge: VanMeter et al. (2016) assessed the role of tanks as rainwater harvesters in agricultural landscapes within semi-arid regions of Tamil Nadu in southern India and found that shallow groundwater recharge increased by more than 40%. Another recent study (Brauns et al., 2022) in three catchments in the crystalline basement of the Cauvery Basin within Karnataka State of southern India looked at the impact of cascade of tanks on recharge to aquifers using groundwater chemistry and water-level data. They concluded that recharge contributions from tanks to groundwater are small and dependent on local geology and land-use practices. Brauns et al. (2022) cautioned that careful planning and monitoring of groundwater levels and quality are necessary as chances of groundwater contamination from agricultural chemicals and other sources (e.g., urban pollutants) are high. VanMeter et al. (2016) concluded that while recharge potential from rainwater harvesting in tanks could be seen as a 'nature-based solution' to water scarcity, it may lead to negative environmental consequences by dramatically reducing (up to 75%) natural runoff. Though the full impacts of tank rejuvenation on groundwater recharge in the Sri Lankan context are under-researched, we have included this element to the analysis as a theoretical exercise for when more information becomes available that re-inform the index structure.

There are six main aquifers in Sri Lanka with an additional aquifer found throughout the weathered basement (Figure 4). Geology and hydrogeology of these aquifer systems vary considerably across the country, which in turn affects the utility of tanks upon which they are situated. A final layer of this analysis is to consider the pumping yield of each of the respective aquifers in the prioritisation of tanks for rejuvenation.

Well-yield data from Sri Lanka's National Water Supply and Drainage Board (NWSDB) show that the highest yield aquifers are shallow alluvial (920 L/min), followed by deep confined aquifers (up to 585 L/min), next are shallow karstic aquifers found in the Jaffna peninsula which have considerable productivity (yield 400 L/min), shallow sandy aquifers have a yield of 225 L/min. Those with lower yields are basement regolith aquifers (150 L/min), regolit or fractured aquifers (75 L/min) and laterite (Cabook) aquifers (70 L/min)(Joseph et al. 2022). Despite being low in productivity, focused groundwater recharge via leakage from tank cascades is highly likely in regolith or fractured aquifers in the north and southeast of the country.

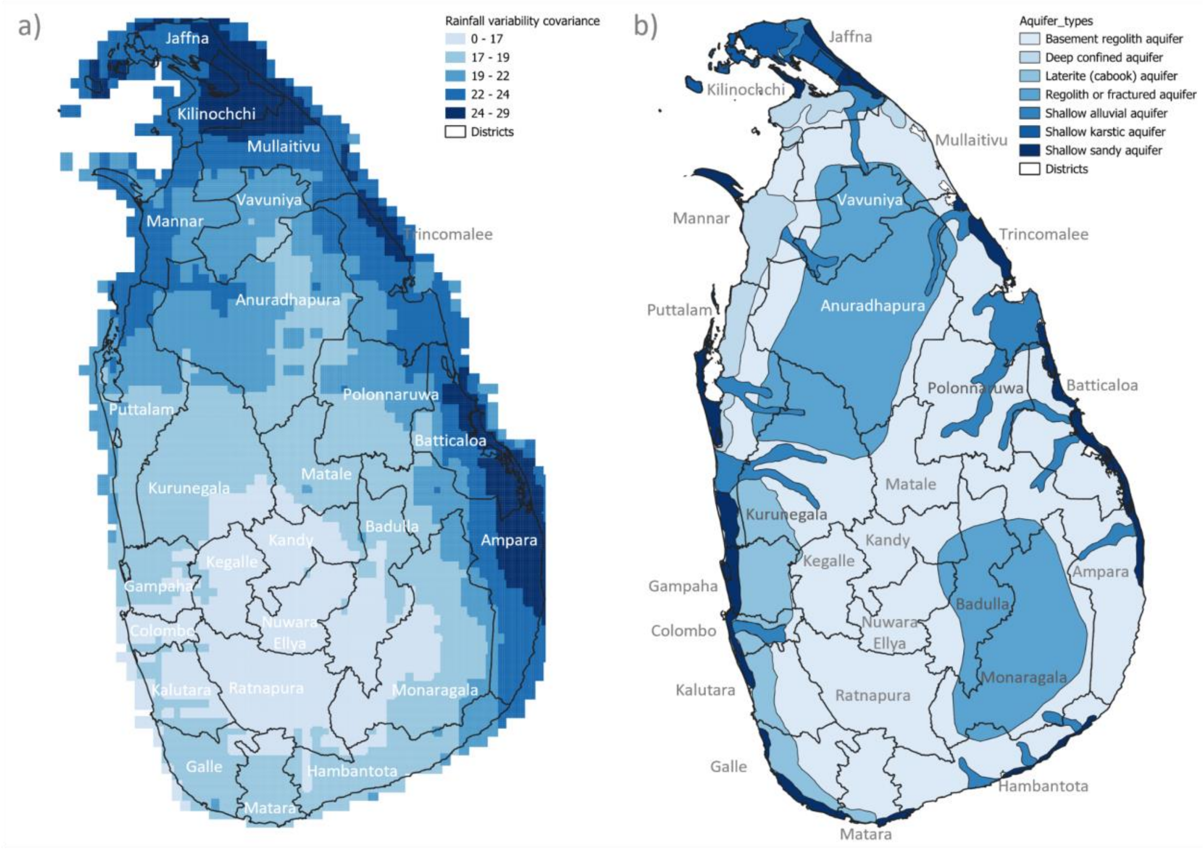

Figure 4 - a) Rainfall variability covariance in Sri Lanka; b) Geographic distribution of various aquifers in Sri Lanka[4]*.*

3.6. The combined index with groundwater recharge potential

With the tank demand, tank supply and tank utility indices all separately calculated, we then create a combined composite index. First of all we rank the tanks depending on the supply-demand index score with the highest scoring being those that are most likely to require rejuvenation based on both sets of characteristics.

For the top 10% scoring tanks according to this ranking, we apply the groundwater recharge index so that we can sub-prioritise the tanks that score highly on supply and demand characteristics to consider groundwater recharge potential.

$$C_i = SD_i \cdot GWR_i \tag{4}$$

Where C_i is the Combined Supply-Demand index taking into account groundwater recharge potential of tank i, SD_i is the Supply-Demand index of tank i, and GWR_i is the groundwater recharge potential score of tank i location. A weighted sum is then performed to generate index statistics aggregation at DSD and district level.

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[4] Aquifer map compiled and digitised from several sources including Dissanayake and Chandrajith, 2018; Dissanayake and Weerasooriya, 1985; Karuratne, 2007; Panabokke, 2007; Panabokke and Perera, 2005.

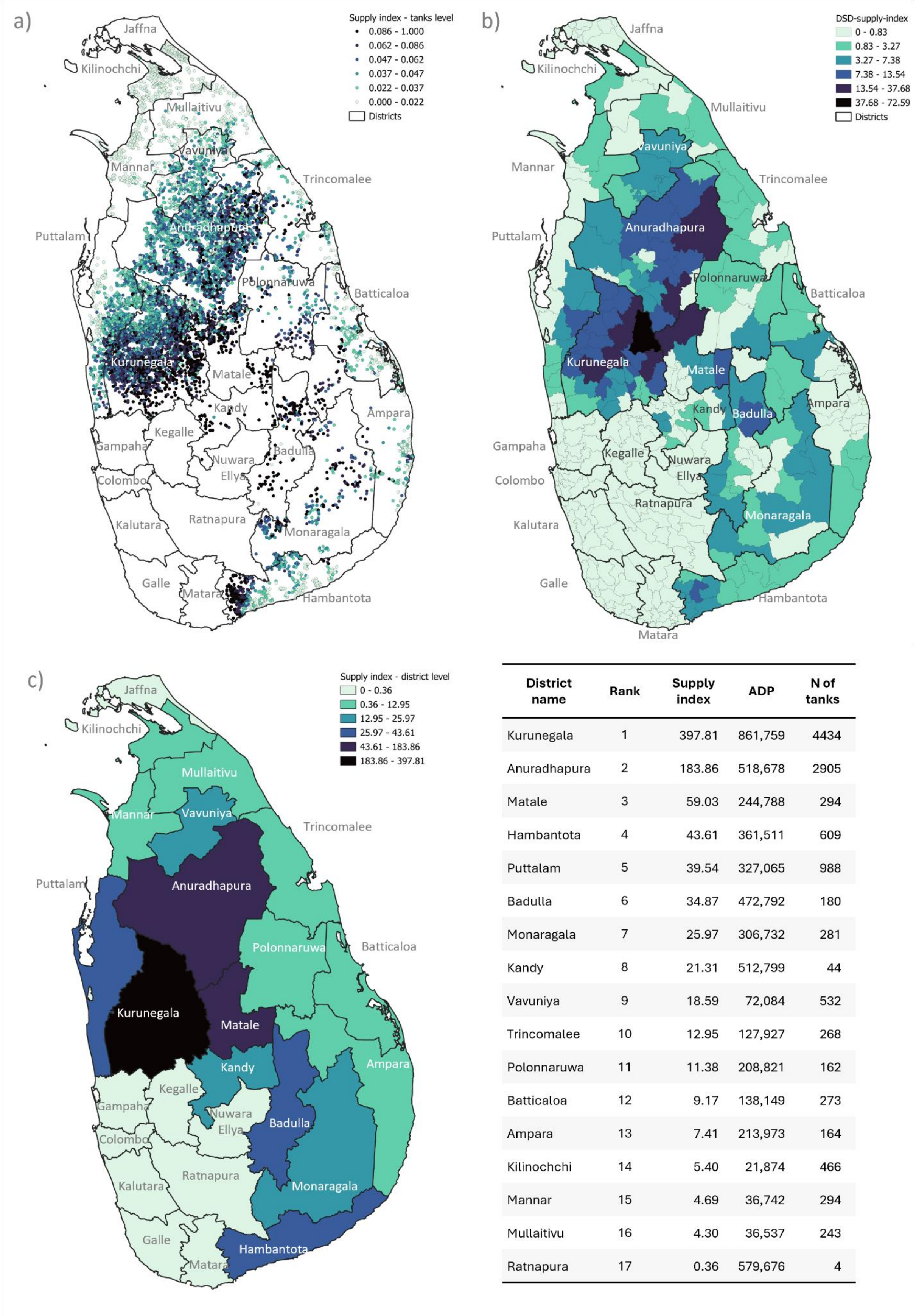
4. Results

Examining the visualisation of both supply (Figure 5) and demand (Figure 6) side indices, tanks in Kurunegala and Anuradhapura rank highest, partly because there is a large concentration of tanks in these two regions (4,434 in Kurunegala and 2,905 in Anuradhapura, with the remainder of the sample having under 1000 in each district). Their siltation and soil erosion rankings also cause them to rise in the rankings for those in need of rejuvenation. Kurnegala has the second highest supply index score in the country, while Anuradhapura is sixth out of sixteen. Matale and Hambantota are next in priority according to their supply index scores, but have comparatively small numbers of tanks (294 and 609 respectively), implying that a larger proportion of the tanks in those districts are in need of greater attention for rehabilitation.

When we compare district and DSD level maps, we see the level of variation within the priority districts. This is particularly notable in Hambantota on the combined supply-demand-GWR index where the targeted tanks are all in DSDs to the west of the district. Within both Anduradhapura and Kurunegala we also see DSDs of much greater focus.

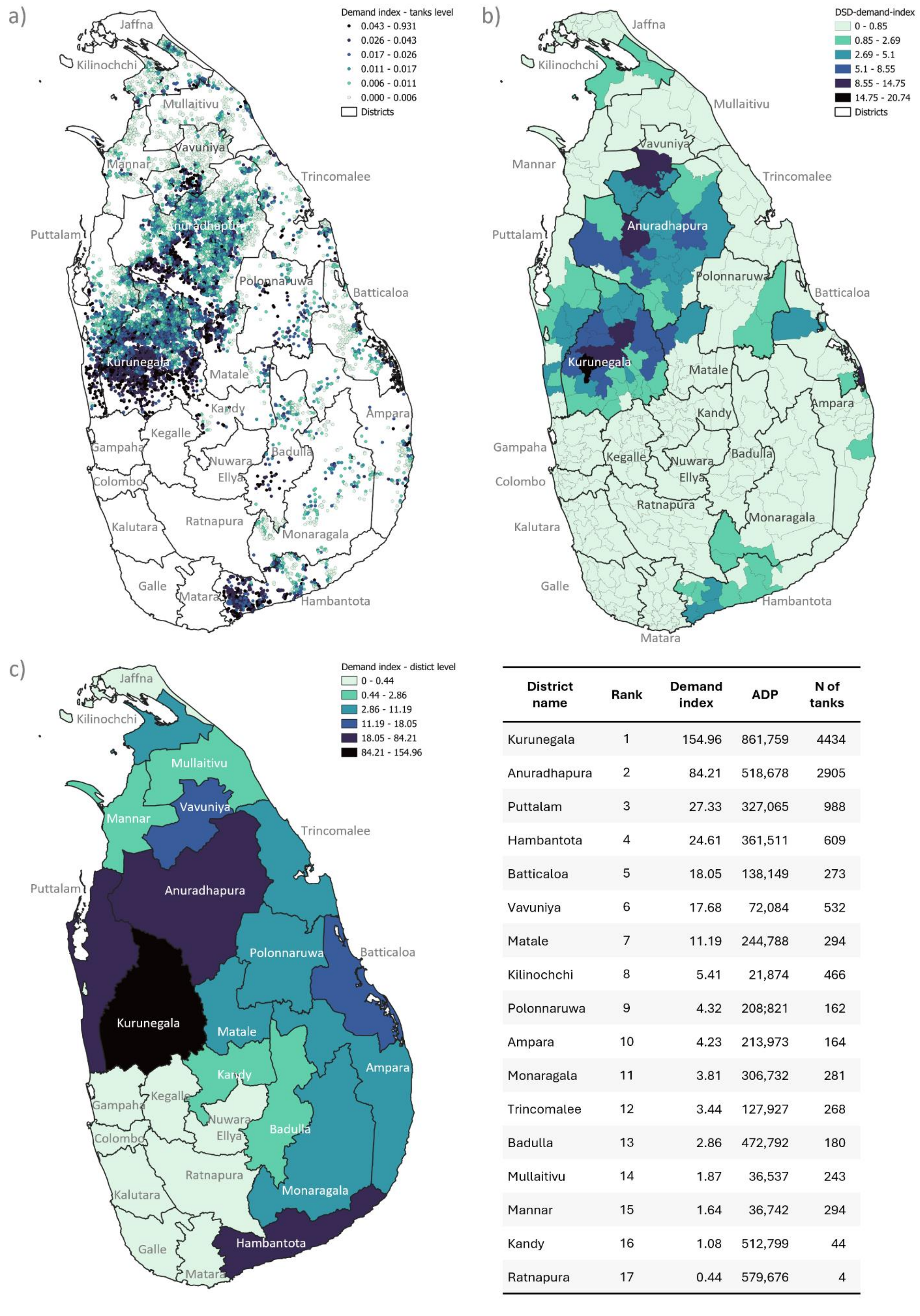
The demand index also shows highest scores for Anuradhapura and Kurunegala. The results at DSD level are partially driven by the agriculture dependent population which is highest in Kurunegala and Ratnapura with Anuradhapura coming third. Due to the small number of tanks in Ratnapura however, this district does not feature in the list of tanks to be prioritised for tank demand. Puttalam and Hambantota also rank highly for demand targeting.

When supply and demand indices are combined (Figure 7), Matale and Hambantota also become prioritised though the top two districts remain consistent. Groundwater recharge potential consideration (Figure 8) does little to change the ranking between the districts, though again, within the DSDs level maps it becomes evident where in each priority district the most attention should be focused. Although the areas where groundwater recharge would be most effective are largely not in the priority districts, this was added as a sub-selection of the supply-demand targeted districts and hence by construction did not change the results greatly. It is worth noting that areas with higher numbers of tanks in general have lower pump yields in terms of aquifer recharge potential. The districts with some of the highest variance in rainfall do not see themselves at the top of many of the indices (Kilinochchi, Batticaloa and Ampara) perhaps because their tank numbers and agriculture dependent populations are relatively small.



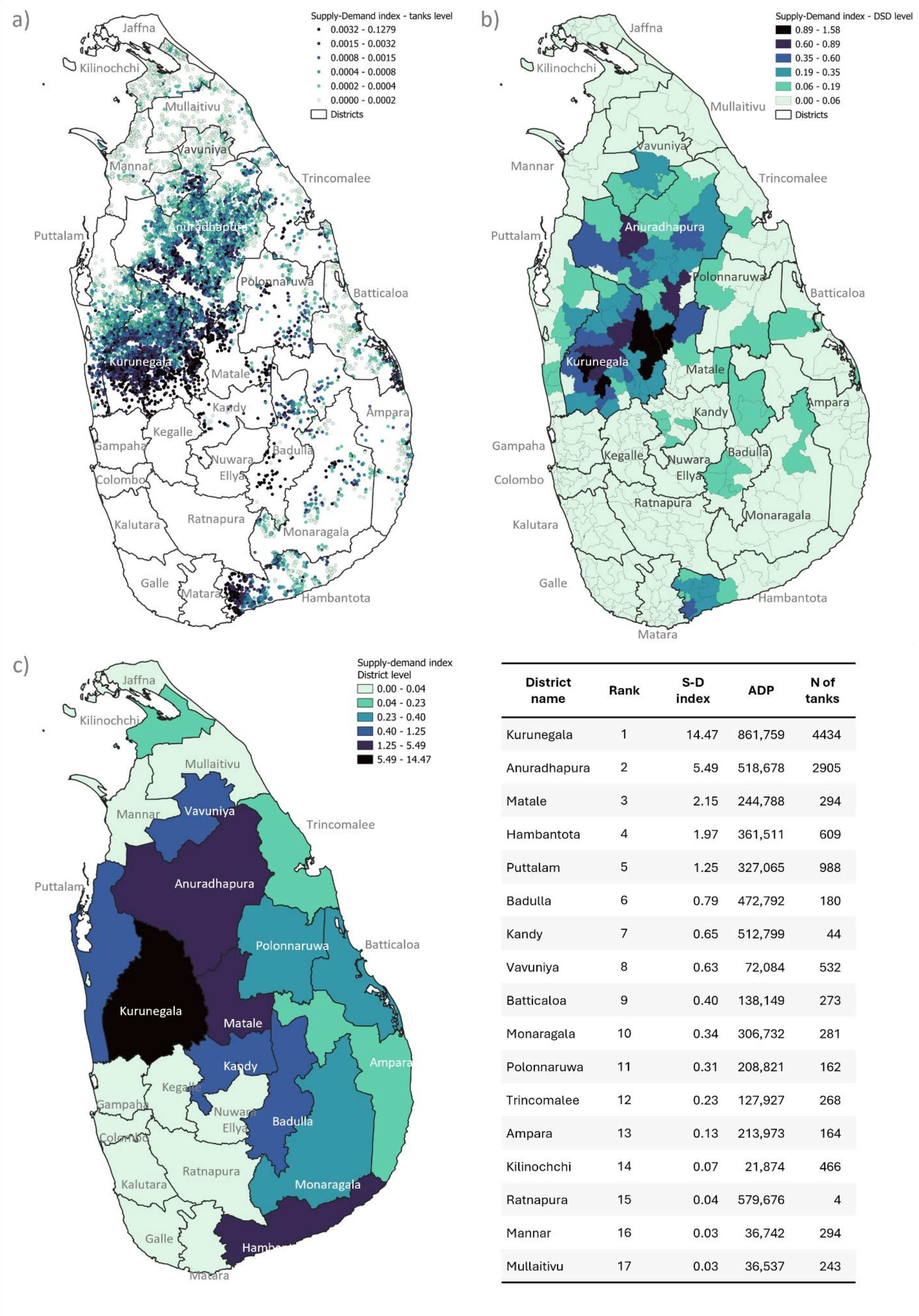
District name	Rank	Supply index	ADP	N of tanks
Kurunegala	1	397.81	861,759	4434
Anuradhapura	2	183.86	518,678	2905
Matale	3	59.03	244,788	294
Hambantota	4	43.61	361,511	609
Puttalam	5	39.54	327,065	988
Badulla	6	34.87	472,792	180
Monaragala	7	25.97	306,732	281
Kandy	8	21.31	512,799	44
Vavuniya	9	18.59	72,084	532
Trincomalee	10	12.95	127,927	268
Polonnaruwa	11	11.38	208,821	162
Batticaloa	12	9.17	138,149	273
Ampara	13	7.41	213,973	164
Kilinochchi	14	5.40	21,874	466
Mannar	15	4.69	36,742	294
Mullaitivu	16	4.30	36,537	243
Ratnapura	17	0.36	579,676	4

Figure 5 - Supply index at: a) tanks level; b) DSD level; c) District level.



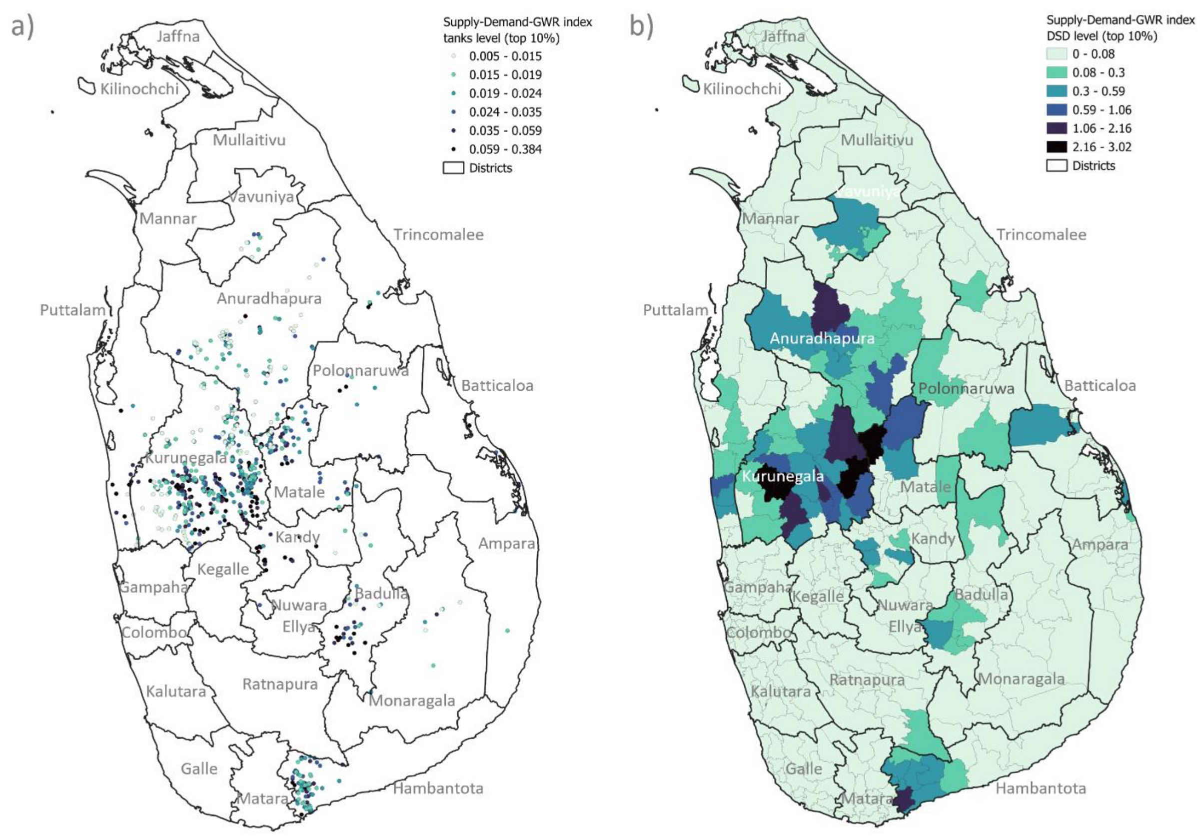
District name	Rank	Demand index	ADP	N of tanks
Kurunegala	1	154.96	861,759	4434
Anuradhapura	2	84.21	518,678	2905
Puttalam	3	27.33	327,065	988
Hambantota	4	24.61	361,511	609
Batticaloa	5	18.05	138,149	273
Vavuniya	6	17.68	72,084	532
Matale	7	11.19	244,788	294
Kilinochchi	8	5.41	21,874	466
Polonnaruwa	9	4.32	208;821	162
Ampara	10	4.23	213,973	164
Monaragala	11	3.81	306,732	281
Trincomalee	12	3.44	127,927	268
Badulla	13	2.86	472,792	180
Mullaitivu	14	1.87	36,537	243
Mannar	15	1.64	36,742	294
Kandy	16	1.08	512,799	44
Ratnapura	17	0.44	579,676	4

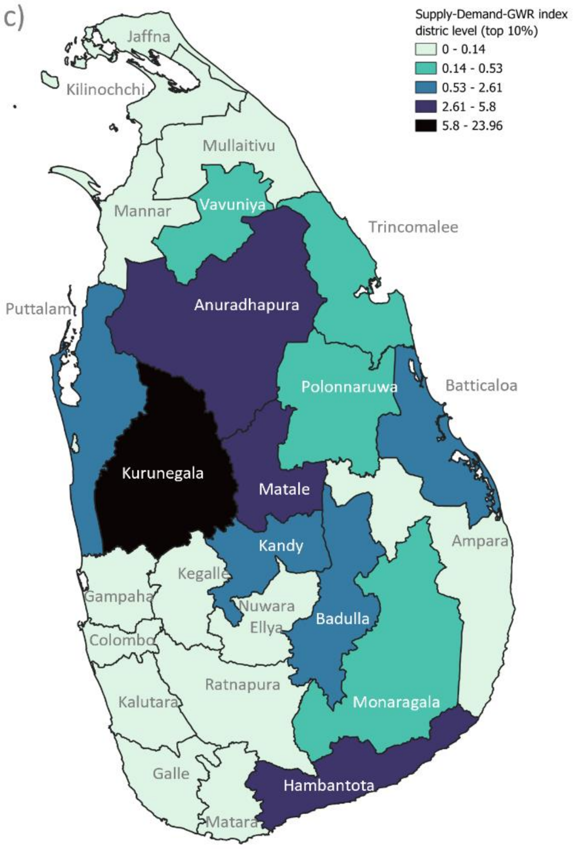
Figure 6 - Demand index at: a) tanks level; b) DSD level; c) District level.



District name	Rank	S-D index	ADP	N of tanks
Kurunegala	1	14.47	861,759	4434
Anuradhapura	2	5.49	518,678	2905
Matale	3	2.15	244,788	294
Hambantota	4	1.97	361,511	609
Puttalam	5	1.25	327,065	988
Badulla	6	0.79	472,792	180
Kandy	7	0.65	512,799	44
Vavuniya	8	0.63	72,084	532
Batticaloa	9	0.40	138,149	273
Monaragala	10	0.34	306,732	281
Polonnaruwa	11	0.31	208,821	162
Trincomalee	12	0.23	127,927	268
Ampara	13	0.13	213,973	164
Kilinochchi	14	0.07	21,874	466
Ratnapura	15	0.04	579,676	4
Mannar	16	0.03	36,742	294
Mullaitivu	17	0.03	36,537	243

Figure 7 - Combined supply-demand index at: a) tanks level; b) DSD level; c) District level.





District name	Rank	SD-GWR Index	ADP	N of tanks
Kurunegala	1	23.96	861,759	4434
Anuradhapura	2	5.80	518,678	2905
Matale	3	4.64	244,788	294
Hambantota	4	3.91	361,511	609
Puttalam	5	2.61	327,065	988
Kandy	6	1.85	512,799	44
Badulla	7	1.59	472,792	180
Batticaloa	8	1.10	138,149	273
Vavuniya	9	0.53	72,084	532
Polonnaruwa	10	0.38	208,821	162
Monaragala	11	0.25	306,732	281
Trincomalee	12	0.24	127,927	268
Ampara	13	0.14	213,973	164
Ratnapura	14	0.12	579,676	4
Kilinochchi	15	0.00	21,874	466
Mannar	16	0.00	36,742	294
Mullaitivu	17	0.00	36,537	243

Figure 8 - Combined supply-demand with groundwater recharge potential prioritisation at: a) tanks level; b) DSD level; c) District level.

5. Discussion

This paper has outlined a novel approach for identifying village water storage tanks in Sri Lanka that are most in need of restoration, considering supply side constraints, demand side pressures as well as their potential for offering a tertiary support to recharging the groundwater sources on which they sit. The estimates of agriculture dependent population for computation of tank demand at 1km resolution show their concentration in the Southwest of the country. For tank demand and supply, the highest scoring tanks and DSDs for prioritisation consistently appear in Anuradhapura and Kurunegala districts, but these more granular estimates enable us to identify where - in those districts - the greatest benefit for rejuvenation would be. With respect to groundwater recharge, most high yield aquifers are not in districts scoring highly on supply and demand indices. The analysis therefore took the groundwater recharge potential on the subset of top scoring tanks on the other two indices. Hambantota is the district which sees the fourth highest ranking at district level when considering all three factors. We would like to highlight that the potential for tanks to contribute to groundwater recharge is understudied and requires further investigation for this final metric to be fully utilised.

This study is the first known study to attempt a systematic large-scale prioritisation of such tanks in the region, with previous studies having been largely small-scale and/or qualitative in nature (M. S and Arul 2022; Nagarajan 2013; Sirimanna and Prasada 2022; Asian Development Bank 2006; Anand, Kakumanu, and Amarasinghe 2019). Water storage is crucial for water security in countries with monsoon driven climates (Anand, Kakumanu, and Amarasinghe 2019). They contribute to water security, particularly for agriculture dependent populations by creating a buffer to mitigate the impacts of floods in monsoon months and providing additional water supply for crops during water shortages and droughts in the dry season (Rodrigues et al. 2012). The method presented here for calculating high resolution estimates of agriculture dependent population is novel and holds potential to be applied to other countries around the world, with the replicable code provided. The indices themselves present an innovative perspective in their consideration of multiple characteristics that contribute to both supply and demand for tanks including rainfall variability and levels of siltation and soil erosion. The fine-grained estimates can be useful at the tank level but also their availability for aggregation at the DSD and district level can offer a useful tool for policy makers.

Though the study offers useful methods and results, there are also some limitations that largely relate to data limitations in terms of quality and availability. Firstly, the study does not consider the way in which tanks are connected to one another in cascades due to a lack of available data on the connections. Further research could either collect data on the ground on connections between tanks (which could be challenging due to the scale of the study), or potentially seek to detect cascades by using AI assisted image processing of high-resolution satellite imagery. The consequence of not having information on cascades is that this analysis will be biased towards rejuvenating tanks around which more people are living in the demand index. This may obscure the possibility that in a cascade of tanks, those higher up in the cascade may need rejuvenation and are having knock-on impacts on those further down, even if they see less direct human interaction. We provide the supply and demand side indices separately as well as combined in this analysis, so it is possible to distinguish the need for prioritisation on e.g. tanks that are in disrepair, even if they do not immediately serve a large population nearby. Secondly, for the estimation of the agriculture dependent population, we assumed that agriculture dependent populations would live close to agricultural lands, in the same way as we assume that users of tanks live close to tanks. Furthermore, due to the lack of information on the command area of each tank, we assumed a 1km buffer around each one. Empirical information on the command areas for each tank may in turn change the agriculture dependent populations we assume to be reliant on them in each administrative unit. And although the calculation of agriculture dependent population at the administrative unit level reflects the population, calculations of ADP at the tank level do not consider overlaps where a single user may be within the catchment of two or more tanks. Finally, the overall quality of the input data may be questionable as shown by the degree of pre-processing that was needed to combine information from across multiple sources before analysis begun. Siltation estimates were imputed for a portion of the sample as described in the methods section. The main contribution of the study is to provide the framework for analysis when input data is available, but it is nonetheless a large-scale effort with available information.

6. Conclusions

This paper has outlined an approach for prioritisation of village water storage tank restoration from a database of 11,000 considering supply, demand and utility factors. This is crucial, as these tanks are likely to be in higher demand in the coming decades, due to increasing climate variability. Some novelty aspects include the provision of fine-grained estimations of both agriculture dependent populations and tank prioritisation criteria, together with scale of the case study. It has also created a code base and methodology that can be replicated in similar contexts, such as in India where similar village tank systems have been in operation for thousands of years, and the scale for application is even greater. The paper also intends to be a useful policy tool by offering estimates at more aggregated DSD and district levels that highlight where different types of targeting could take place. Although the resulting estimates could benefit from improved data availability, particularly around tank cascades, this paper aims to also motivate the collection and collation of such information for applied usage.

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Supplementary materials

Annex 1

Table 1 - Table of data sources

Data Source	Description	Resolution/no. Observations	Source
WorldPop population count at 1km resolution 2020	Population count	1km resolution 352,520 pixels	WorldPop https://hub.worldpop.org/geodata/summary?id=35698
GHSL - Global Human Settlement Layer 2023	Land type (urban/rural)	1km	European Commission https://ghsl.jrc.ec.europa.eu/download.php
Land Use	Land cover by agricultural production	Polygon shapefile with 38 categories of land use	Sri Lankan Land Use Policy Planning department
HIES 2016	Population with occupation in agriculture, Poverty rate	District level	http://www.statistics.gov.lk/IncomeAndExpenditure/StaticalInformation
ESDAC GLoSEM Database 2022	High resolution cropland global soil erosion	100m resolution	https://esdac.jrc.ec.europa.eu/content/glosem
CHIRPS	Rainfall variability (Coefficient of Variance) 1983-2020 Maha Season[5]	-	https://www.chc.ucsb.edu/data/chirps
National Tank database	Tank command area, water height, water level	23,163	Ministry of Agriculture, Sri Lanka
Nimal tank database	Tank functionality status	-	Prof Nimal

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[5] The Maha season falls during the "North-east monsoon" from September to March and is one of two seasons when the crops are sown and harvested http://www.statistics.gov.lk/Agriculture/StaticalInformation/PaddyStatistics#gsc.tab=0

UNDP tanks database	Tank ownership, functionality, condition, utilisation, condition, renovation history and beneficiary	21,745	UNDP

Annex 2

Table 2 - Agricultural land classification

Land Use type	**Agricultural land classification/other**
Chena	Ag land
Coconut	Ag land
Home Garden	Non-ag land
Other (Mango, etc)	Ag land
Paddy	Ag land
Other plantations	Ag land
Rubber	Ag land
Tea	Ag land
Uncultivated lands	Ag land
Barren Land	Bare Land
Scrubland	Bare Land
Airport	Built up
Buildup Area	Built up
Runaway	Built up
Tunnel	Built up

Forest	Forest Land
Forest – Protected	Forest Land
Grass	Forest Land
Mangroo	Forest Land
Palmyra	Forest Land
Inland-Island	Island
Sea-Island	Island
Salter	Other
Prawn	Prawn
Quarry	Rocks
Rock	Rocks
Sand	Sandy areas
Tank	Water source - Tank
Well	Water source - Well
Bay	Waterbodies
Chanel	Waterbodies
Lagoon	Waterbodies
Lake	Waterbodies
Pond	Waterbodies
Reservoir	Waterbodies
Stream	Waterbodies

Lewaya	Wetland
Marshland	Wetland

Annex 3

Groundwater recharge classifications

There are six main aquifers in Sri Lanka with an additional aquifer found throughout the weathered basement (Figure 4). Geology and hydrogeology of these aquifer systems vary considerably across the country (Table 3). Shallow karstic aquifer composed of Miocene limestone with sandstone sequences is found in Jaffna peninsula that is of considerable productivity (yield 400 L/min) and has been extensively used over the years (Panabokke and Perera, 2005; Indika et al., 2022). Shallow sandy aquifer is found around the highly populated coastal parts of the island and these sandy aquifers are an important water resource in the country that provide adequate water supplies for agriculture and domestic uses (Dissanayake and Chandrajith, 2018). Shallow alluvial aquifer is found in different parts of the country and is of highest productivity in terms of yield (920 L/min). Deep confined aquifer is found in the north of the country and composed of limestone and sandstone (Panabokke and Perera, 2005). Laterite aquifer is found in the southwest of Sri Lanka that is composed of laterite (also known as Cabook formation). Shallow regolith aquifers are found along the inland valley systems in the dry climate zone, i.e., north central, northwestern, and southern provinces of Sri Lanka are of low yield but important water supply for domestic and irrigation for local communities. Lastly, the basement regolith aquifer is not widely recognized aquifer type but can be found within the weathered and fractured crystalline basement. The occurrence and groundwater flow within this basement aquifer are controlled by the degree of weathering and depth (Dissanayake and Chandrajith, 2018).

Among these aquifers, the shallow regolith aquifer type has close links to cascading irrigation tanks. It is recognized that the shallow regolith aquifer benefits from the presence of several small tank cascades that are situated within inland valleys. The average thickness of the regolith is not more than 10m, and the traditional hand-dug wells have been abstracting groundwater from this basement regolith aquifer for domestic water supplies in villages for more than 2000 years since the ancient Rajarata landscape (Panabokke and Perera, 2005). Groundwater recharge and sustainability of this shallow regolith aquifer is critically dependent on the health of these irrigation tanks. From hydrogeological standpoint, one can argue that rejuvenating these tanks will bring co-benefit to local populations and these regolith aquifers through enhancing groundwater recharge.

Table 3 - Aquifers and their generalised geology and hydrogeological characteristics, yield, recharge potential and risks. risks.

Aquifer name	**Geology**	**Aquifer materials**	**Aquifer characteristics**	**Pumping yield (L/min)**	**Recharge capacity**	**Leakage from tank**	**Risks to groundwater**

Shallow alluvial aquifer	Holocene	Unconsolidated sand and gravel	Unconfined; hydraulically connected to rivers	920	Recharge annually from rainfall and river water	Highly likely if present	Vulnerable to saltwater intrusion; drawdown risk is low
Shallow karstic aquifer (Jaffna peninsula)	Miocene limestone	Limestone with sandstone sequences	Confined and karstic in nature	400	Recharge annually from rainwater	Potentially highly likely if present	Vulnerable to pollution and over-exploitation
Shallow sandy aquifer	Sands of Quaternary age	Freshwater lenses in sand layers or dunes	Unconfined; highly productive	225	Recharge annually from rainwater in the *maha* season a	Highly likely if present	Highly vulnerable to saltwater intrusion
Deep confined aquifer	Sedimentary geology	Limestone and sandstone	Confined; isolated hydrological basins	585	Recharge annually from rainfall	Low to medium potential	Leaching of salts from cultivated lands
Laterite (Cabook) aquifer	Laterite formation or Cabook formation	Deeply weathered saprolite and sap rock	Mostly unconfined and shallow	70	Recharge annually from rainwater	Highly likely if present	Over-exploitation and contamination
Regolith or fractured aquifer	Precambrian crystalline basement hard rock	Weathered regolith and deep fractures	Unconfined to confined; Isolated pockets of groundwater	75	Seasonal recharge from rainfall and tanks	Highly potential for recharge from tank cascades	Geogenic Contaminants (trace metals, fluoride)
Basement regolith aquifer	Precambrian crystalline basement hard rock	Sporadically weathered regolith	Mostly unconfined and shallow	150	Seasonal recharge from rainfall and tanks	Potential for recharge from tank cascades	Low development potential

Annex 4

GHSL Settlement classifications

In this paper, we mask out populations classified as urban, dense urban, semi-dense urban and peri urban. That is we remove populations located in grid cells type 30, 23, 22 and 21 from consideration in agriculture dependent population calculations.

Table 4 - Global Human Settlement Layer – Settlement Model Grid (GHS-SMOD) Classification Rules (Schiavina, Melchiorri and Pesaresi, 2023).

Code	Class	Population Density (km^2)	Definition
30	Urban Centre	>1,500	Contiguous grid cells (4-connectivity) that has at least 50,000 inhabitants in the high-density cluster.
23	Dense urban cluster	>1,500	Contiguous grid cells (4-connectivity) that has at least 5,000 inhabitants and less than 50,000.
22	Semi-dense urban cluster	300 – 1,500	Contiguous grid cells (8-connectivity) that has at least 5,000 inhabitants in the cluster and is at least 3km away from other urban clusters.
21	Suburban or peri-urban	300 – 1,500	All other cells that belong to an urban cluster that do not meet the criteria for Urban centre, Dense, or Semi-dense urban cluster.
13	Rural cluster	<300	Contiguous grid cells (8-connectivity) that has at least 500 and less than 5,000 inhabitants in the cluster.
12	Low density rural	50 – 300	A cell with more than 50 inhabitants that is not part of an urban or rural cluster.
11	Very low density rural	<50	A cell with less than 50 inhabitants that is not part of an urban or rural cluster.
10	Water	-	Cells where more than 0.5 share covered by permanent surface water that are not populated nor built.