Role and Potential of Small Storages for Rural Water Resources Development: the Case of Southern Malawi

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SUMMARY:

A study was undertaken in Chingale catchment, southern Malawi to assess small storage (ponds) roles and potential for rural water resources development to satisfy growing demand by aquaculture and irrigation. Combined with field measurement, survey, and remote sensing analysis, the SCS runoff method and GIS based spatial analysis was applied to identify water harvesting potential. The results are combined with socio-economic considerations to assess current ponds and site suitability for future development. Results show lack of guidance on ponds construction and ponds water management leads to poor performance of existing ones. More than half of current ponds were built on soils with high infiltration rate causing significant losses of water. The combined losses through evaporation and seepage amounts to more than 2500 mm per year. The ponds however help produce significant protein and cash income for local farmers. The catchment has a lot of potential to further develop ponds. Conducting Integrated Irrigation and Aquaculture (IIA) at small household ponds offers an approach for local people to increase income and improve nutrition situation.

1 INTRODUCTION:

Many parts of Sub-Sahara Africa (SSA) have abundant rainfall but lack of water infrastructure and associated technology for improved water management. Current water withdrawals for SSA for agriculture, domestic water supply and industry are estimated to be about 3.8% of the total annual renewable water resources (Africa Union, 2003). Rainfed farming covers 97% of the region’s cropland and produces most of the region’s food. The irrigation area is only 20% of the irrigation potential estimated by FAO and water still remains an untapped resource for the majority of SSA (Faurès & Santini, 2008).

Malawi is a relatively small country yet with a distinct climate because of the diverse landscapes (large lakes, high plateau of more than 1000 meter above mean sea water level, rugged relief rising over 2400 meter while southern lowveld as low as 60 meters above mean sea water level). Malawi has an extensive network of rivers and lakes with the water bodies covering more than 21% of the territory. However, the distribution is irregular and varies by seasons and years, 90% of the runoff in rivers and streams occurs between December and June, only 0.1% of the runoff is estimated to be captured for later use(Ferguson & Mulwafu, 2004). Malawi is one of the most densely populated countries in Southern Africa with rapid population growth. The country has a population around 16.7 million. Nearly 90 percent of the people live in rural areas. Agriculture is the backbone of the economy contributing 63.7 percent to the total income of the rural people, 36 percent of the GDP, 87 percent of the total employment and supplying more than 65 percent of the manufacturing sector's raw materials (*Malawi Poverty Reduction Strategy Paper*, 2002).

Water is the key influence factor for both aquaculture and agriculture. The irrigated crop yields are double or more of comparable rainfed yields in Africa. Irrigation development is considered as a cornerstone for agriculture development in Africa (You et al., 2010). Malawi has benefited from capture fisheries on Lakes Malawi, Malombe and Chilwa; the Shire River; and numerous smaller rivers, lakes and lagoons. Fish is an important component of the daily diet for urban and rural Malawians and it constitutes an estimated 28% of the total animal protein consumed in Malawi (Russell AJM, 2008). However, with the growth of population the per capita consumption of fish has declined significantly (Russell AJM, 2008). Increasing private investments on rural water resources development can help agriculture and aquaculture development. However, adoption rate of rain water-harvesting (RWH) techniques is low and very often the smallholder irrigation schemes are underperforming with a lack of maintenance (Mulwafu et al., 2003). Increasing the rate of adoption on rural water resources development is therefore critical for irrigation and aquaculture development in Malawi for economic development as well as poverty alleviation.

The government of Malawi has placed a high priority on irrigation and water resources management to ensure food and water security at household level, for example through water harvesting, improved catchment protection and management (Malawi, 2012). Many challenges exist in implementing such policies and encouraging investment in technology and infrastructure. The challenges include floods and droughts caused by erratic rainfall, water resources degradation caused by heavy deforestation, sedimentation of rivers and reservoirs, catchment encroachment, agrochemical pollution, improper effluent disposal and, in some areas, over exploitation.

RWH is a technology to effectively collect water from surface runoff during rainy periods (Helmreich & Horn, 2009). With the increasing water demand and the water resources degradation in Malawi, RWH provides an effective way to make better use of limited water resources to develop agriculture and aquaculture. Small water storages such as farm ponds prove to work well in parts of Malawi. They can greatly improve water availability during dry spells, which helps to improve overall productivity from crops and fish (Kam et al., 2013). Integrated irrigation and aquaculture (IIA) can help increase productivity of water and lands to improve food security and increase household income (Moehl, 2001). IIA for small household ponds in Malawi seems to offer a new opportunity to improve living condition for the local farmers.

Upscaling of small storages however requires integrated approach by considering catchment input factors such as water, soil, vegetation, agricultural areas and settlements. The target density, sizes, and management of small storages are all important elements of a synthesized problem that a lot of factors have to be put into consideration. Providing an accurate spatial representation of the runoff generation potential is very important for developing a runoff harvesting plan for any catchment (de Winnaar, Jewitt, & Horan, 2007). Geographical information system (GIS) and remote sensing (RS) offer us an efficient new approach to deal with this item. RS can help us generate some necessary spatial databases required by GIS. GIS provides a framework for collecting, storing, analyzing, transforming and displaying spatial and non-spatial data for particular purposes(Padmavathy, Raj, Yogarajan, Thangavel, & Chandrasekhar, 1993). The representative spatial landscape characteristics such as soil, land use, rainfall data and slope information are important inputs to identifying runoff harvesting potential (de Winnaar et al., 2007).

Social factors present another layer of complexities in upscaling of small storages for effective rural water management. Mbilinyi et al., (2007) recommended more analysis on socio-economic factors to increase the usefulness after extensive RS/GIS analysis. Ramakrishnan et al., (2009) developed a decision tree based approach incorporating hydrological, hydro-geological and geotechnical criteria for selecting sites for different rain water harvesting techniques. These studies offer a good insight into the importance of integrating various factors in analyzing small storage development potential.

This paper describes our efforts in exploring small storages (ponds) upscaling potential in the Chingale catchment, Southern Malawi for integrated irrigation and aquaculture development. The objective is to: a) examining current status of ponds and their role in local people's livelihoods; b) assessing the potential for upscaling of ponds as a type of small storages for integrated irrigation and aquaculture development in Southern Malawi. The study is based on a two year field measurement, survey, and extensive hydrological analysis based on GIS platform. The potential of pond development is assessed and the respective limiting factors are discussed.

2 Study Area

Chingale catchment is in the southern district of Zomba (Fig.1) with an area of 258 km^2. The catchment borders with the Zomba Nature Reserve and Malosa Forest Reserve to the east. The catchment receives around 960 mm rainfall annually, ranging from 785 to 1210 mm (Kam et al., 2013). More than 90% of the total rainfall concentrates on the period from November to April. The relatively concentrated rainfall, accompanied with deforestation and soil degradation, generates high runoff volumes closely following the pulses of rainfall. The catchment is dominated with four types of soils, namely, loamy sand, sand, sandy clay loam, sandy loam. Sand consists more than 50% in all of them.

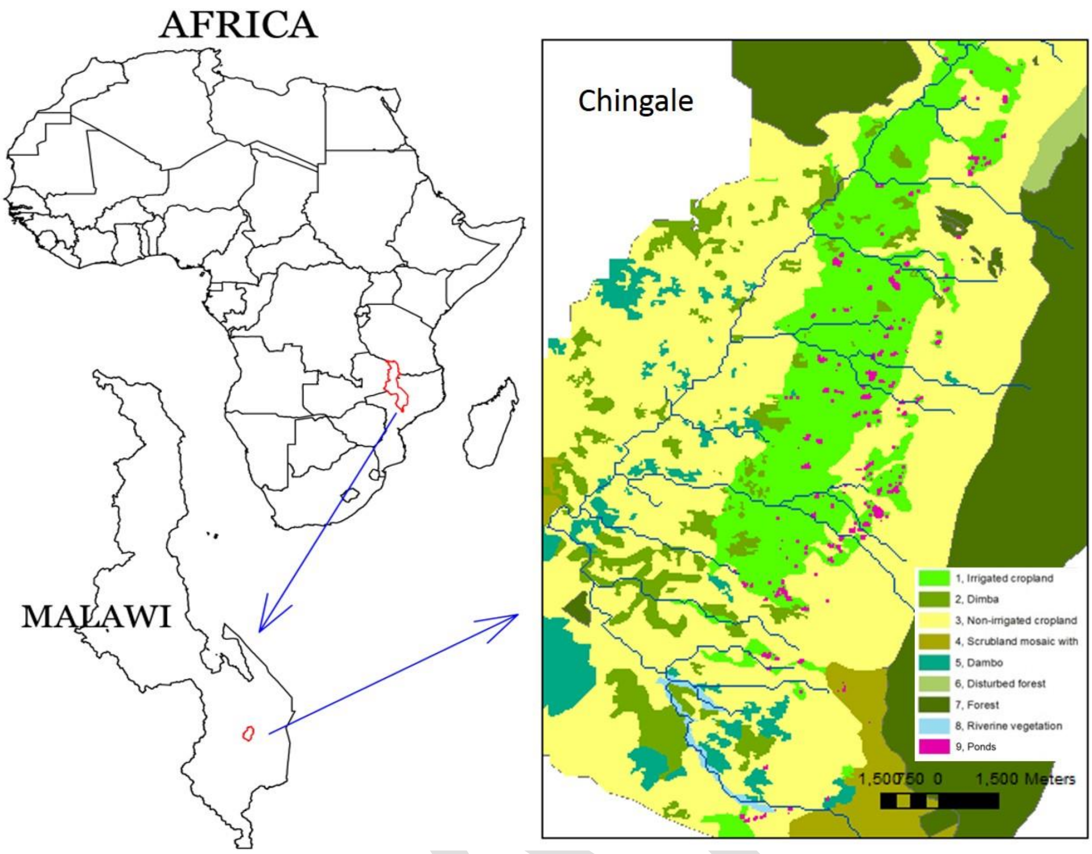

Fig 1 The Chingale Catchment and its location in Malawi, the right map shows land use of the area including ponds as extracted from GeoEye imagery.

The land use of the catchment was extracted from a GeoEye high resolution image of 15th September 2010. The cropland area of the catchment is estimated to be 13,000 ha owned by about 9,435 households. An irrigation belt runs in between the forest on the east and the Lisanjala River to the west. The total irrigated areas are 129 ha, about 10 percent of total cropland areas. A total number of 740 ponds were identified with an accumulative surface area of 16 ha which is about 223 m^2 each. Field survey reveals the average depth of the ponds is 1.5m.The spatial distribution of ponds are highly correlated with irrigated areas as shown in figure 1.

Agriculture is the main source of household food security in the catchment, while aquaculture provides vital nutritional value in the form of protein and further, limited cash income. Average family land holding size is 2.57 ha. Food shortage is usually experienced from August to February for about 40% of population. The main crops planted in Chingale are maize, groundnuts, cassava, vegetables, pigeon peas, rice, pumpkin and beans.

3 METHODOLOGY

3.1 DATA COLLECTION

Field measurements on stream flows, selected ponds (water inflow, water levels and outflow), rainfall and evaporation has been carried out. Daily rainfall data (from 1960 to 2012) are collected at Chancellor College. Samalani Primary School pan evaporation experiment provides us more reliable evaporation data for ponds water balance calculation.to identify problems in its agriculture and aquaculture activities, and to develop alternative means for improving the living standard of the local farmers. Four classes of field measures are presented as follows: (1) Water use situation (2) Soil property (3) Land use status (4) Agriculture and aquaculture development situation. In addition to landuse map with settlements, ponds, and irrigated areas as described in previous section, Shuttle Radar Topographic Mission (SRTM) is used for runoff and pond potential analysis.

A field survey mainly focus on ponds has been implemented at Chingale catchment. Questionnaires designed for local farmers and workshops with local government and NGOs provide us a clear acknowledge of social-economic factors on the ponds development and local agriculture development status.

3.2 Pond potential assessment framework

Input datasets were analyzed on a ArcGIS Version 10.1 environment. The key steps involve spatial runoff generation, pond water balance and suitability analysis. Figure 2 illustrates the key inputs and steps involved in the process.

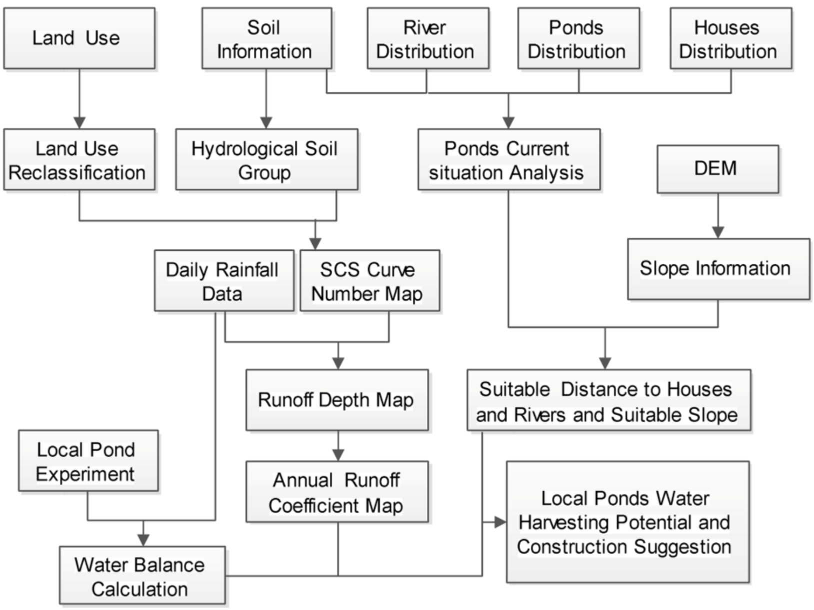

Fig 2 Methodology framework for pond potential and suitability analysis

Runoff Coefficient

The Soil Conservation Services (SCS) Runoff method has been widely applied to estimate the surface runoff (Munyao, Mannaerts, & Krol, 2010). This method considers several important properties of the watershed namely soil's permeability, land use and antecedent soil water conditions. The SCS Runoff method has been consistently usable results for runoff estimation in the past 30 years (Dhawale, 2013). In this study, we adopt it to calculate surface runoff. The SCS Runoff method with initial abstraction consideration is given in equations(Gupta, Deelstra, & Sharma, 1997; White, 1988):

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \tag{1}$$

$$S = \frac{25400}{CN} - 254 \tag{2}$$

Where,

Q is runoff, in millimeter; P is precipitation, in millimeter; S is potential maximum retention after runoff begins, in millimeter; CN is an index that represents the combination of hydrologic soil group, land use and land treatment situation. It varies from 0 to 100 where greater curve number represents a greater proportion of runoff after a given rainfall.

We reclassify the local land use mainly according to the Applied Hydrology (Chow, Maidment, & Mays, 1988) and Technical Release 55 (Watersheds, 1986) after field investigation. Application of SCS method need reclassify the soils into Hydrologic soil group (A/B/C/D). The standards mainly focus on infiltration rates and the textural soil composition(Munyao et al., 2010).

Table 1 Hydrologic Soil Group Classification

Soil Group ID	Hydrologic soil group	Area under each group(km^2)	Percentage under each group (%)
1	A	200.42	60.79
2	B	45.71	13.87
3	C	67.53	20.48
4	D	16.04	4.86
Total		329.70	100

HEC-GeoHMS are used to create the CN map after the soil group and land use identification have been finished. We chose 2003, 1962, 2007 (P=25%, P=50%, P=75%) the three years as typical years for different calculation conditions. Use rainfall data in 1962(P=50%) to calculate the runoff coefficient (RF_{coe}). Since the precipitation data are collected from single station and variations in antecedent runoff condition (ARC) cannot be distinguished. The annual runoff coefficient is based on runoff calculated using antecedent runoff conditions II ($ARC\text{II}$), which in the median value, motivate by the fact that the probability of occurrence of higher and lower values of the runoff coefficient would be equal (Pilgrim & Cordery, 1975). And it can also avoid complexities and a number of additional calculations. The annual runoff depth is summed by every runoff depth calculation result after each given rainfall.

$$\mathrm{RF}_{coe} = \frac{\text{Annual Total Runoff (mm)}}{\text{Annual Total Percipitation(mm)}} \tag{3}$$

3.3 PONDS WATER BALANCE ANALYSIS

A detailed spreadsheet based analysis of water balance analysis for selected ponds has been carried out to gain insight on water availability, use and losses of individual ponds (figure 3). The ability of the ponds to store water and the efficiency to turn this water for use during dry spell can therefore be considered with available runoff for better understanding of ponds rain water harvesting capacity and local ponds developing potential.

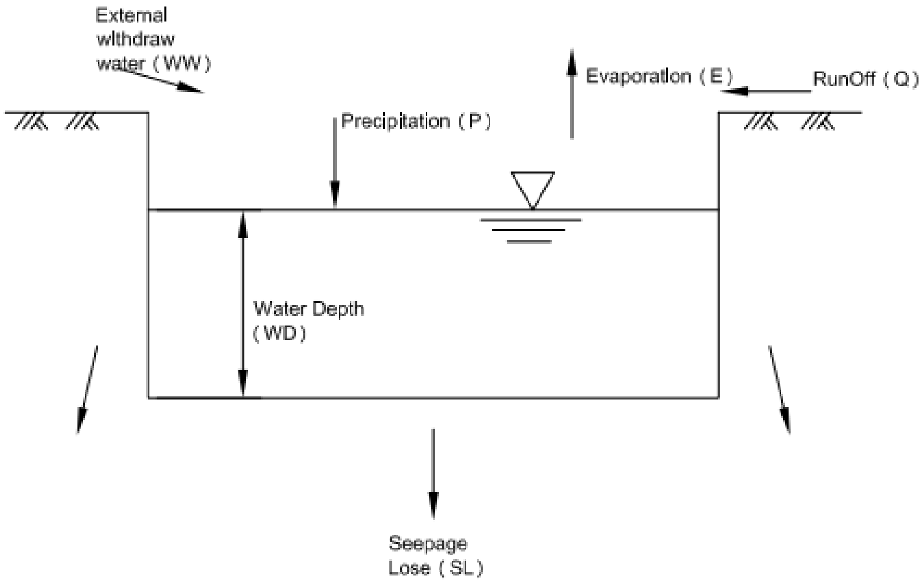

Fig 3 Pond water balance model

Since the local ponds are very shallow (ground water supply is limited) and the lack of ground water table data, we ignore the ground water supple in this study; We consider lateral seepage and deep percolation together as seepage lose.

So the water balance equation is

$$Q + P + WW - SL - E = \Delta WD \tag{4}$$

Where ΔWD is the change in pond water depth, in millimeter; P is precipitation, in millimeter; Q is runoff, in millimeter; WW is external withdraw water from other water resource, in millimeter; SL is seepage lose, which conclude lateral seepage and deep percolation, in millimeter; E is evaporation, in millimeter.

Several ponds water level observation has been conducted at Chingale catchment. We adopt the pond level data observed at the pond owned by Mr.Kanyemas in the central of the catchment. The latitude is 15°14′6.97″S and the longitude is 35°14′43.79″E. It is located at sand and the soil depth is more than 150mm. The runoff coefficient here is 14.3%. The distance from the pond to the nearest river is 193 meters and the distance from the pond to the nearest house is 20 meters.

Considering about the pond observation data is from March 2011 to February 2012, the same period precipitation data collected by Chancellor College are used in this research. The total precipitation of the 12 months is 1133.5 mm, it is higher than the average annual precipitation 960 mm. Malawi has a hot summer rainfall season from November to April. During our research time, the sum rainfall from November to April is 1080 mm, it consists 95.2% of the annual precipitation. This is an intensive water-consuming time of the local ponds.

4 RESULTS

4.1 PONDS CURRENT SITUATION ANALYSIS

The ownership of ponds is usually with the family, with only a few belongs to community. All the ponds surveyed are hand dug on people’s own land, which means the cost is mainly in the form of own labor. People don’t perceive water use as conflicts with their neighbors, partly due to autonomy in pond management. Few use the water in their ponds for domestic use. Majority of the ponds are for aquaculture purpose. Security and access are therefore the overwhelming factors in determining the locations of ponds. Figure 4 shows that half of the ponds appear within 50 meters to rivers and 100 meters to houses. Building ponds aside by the rivers will make it easier to withdraw water from rivers at dry season. There appears however not enough consideration of other physical and technological factors such as soils and slope.

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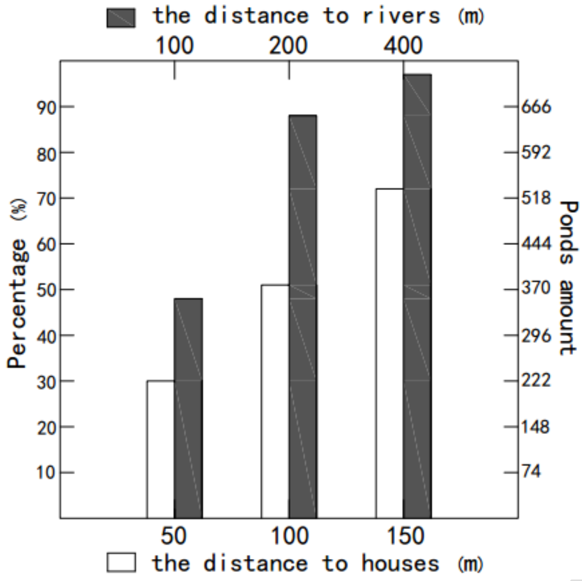

Fig 4 Ponds Distribution Diagram

Among the four main groups of soils found in Chingale, clay loam, which consists 18% of all areas, is relatively better for pond construction that they can better retain water and reduce seepage. However, only 182 of the ponds (24.5%) are built on the sandy clay loam. A total of 399 (53.8%) were built on sandy soil, which means high rate of water losses are expected for these ponds.

Significant losses of water is confirmed by field mesurement. Figure 5 and table 3 illustrates the evaporation from open water bodies versus rainfall and the total seepage losses. The total losses of 2.6 meter is much higher than average pond depth of 1.5 meter, which points to the one of the greatest drawbacks of small storages.

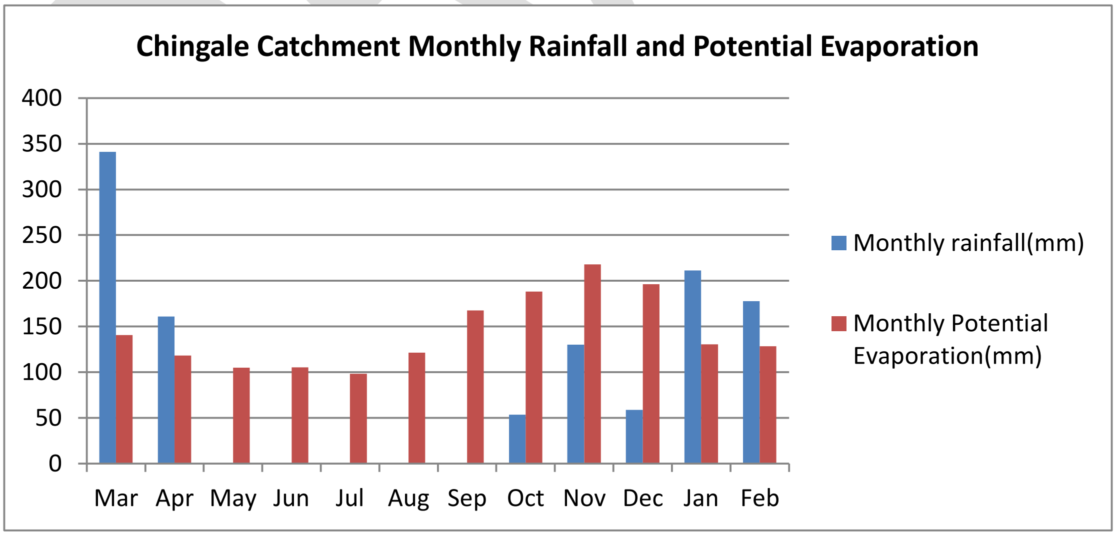

Fig 5 Chingale Catchment Monthly Rainfall and Potential Evaporation

Table 3 Water losses from the selected pond (mm)

	Annual	**Daily**	**Percentage**

Total losses	2590.00	7.10	
Evaporation	1718 14	4.71	66.34
Seepage	871.86	2.39	33.66

4.2 PONDS WATER HARVESTING POTENTIAL ANALYSIS

The GIS spatial analysis helps generate runoff coefficient map and other input parameters as shown in figure 6. The runoff coefficient is much higher in the transit areas from the mountainous forest to the valley. The irrigated areas and the ponds are generally falling in the high runoff areas.

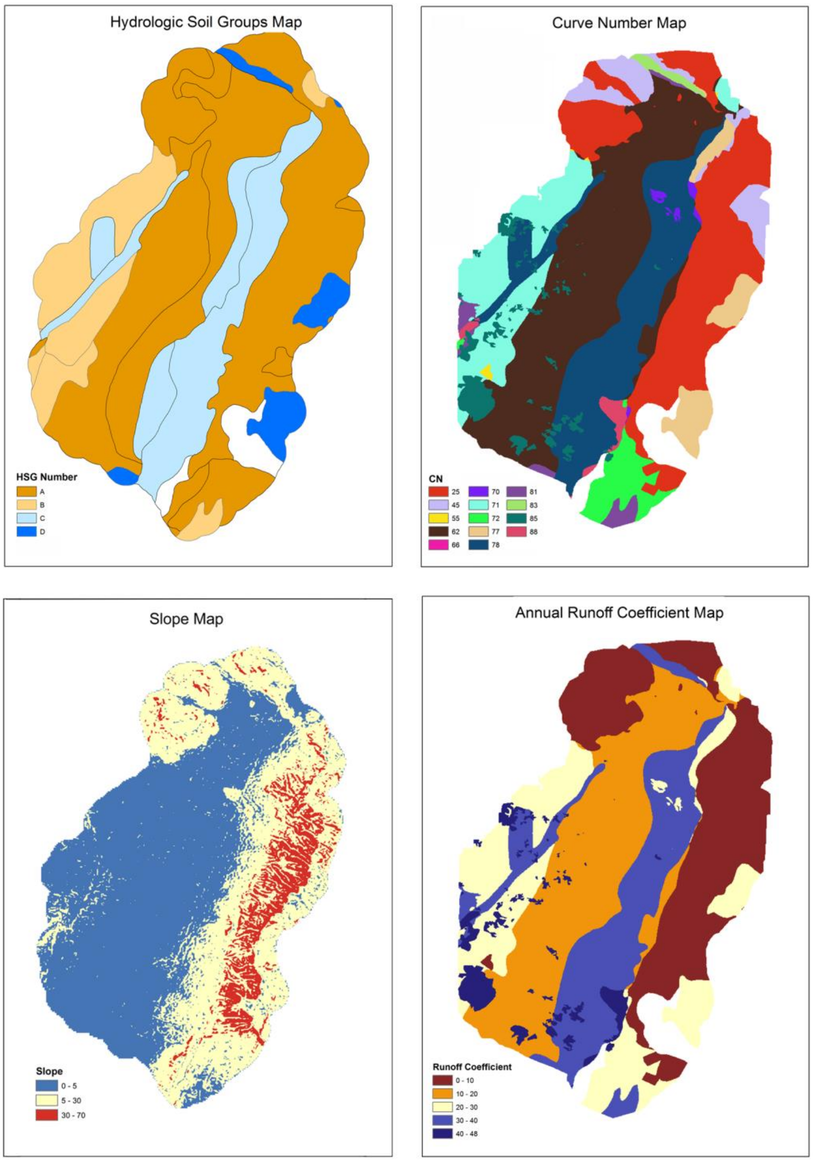

Fig 6 Hydrologic soil groups map, curve number map, slope map and annual runoff coefficient map of the Chingale catchment.

Table 2 Annual Runoff Coefficient

Runoff Coefficient ID	Runoff Coefficient	Area (km^2)	Percentage (%)
1	0%-10%	90.67	27.5
2	10%-20%	94.95	28.8
3	20%-30%	62.31	18.9
4	30%-40%	66.93	20.3
5	40%-50%	14.84	4.5
Total		329.70	100

The pond water storage capacity is only a small fraction of total runoff generated. Use 1962 rainfall data to estimate the whole area runoff volume. The annual runoff volume is 53086310 m^3. There are 741 ponds in Chingale with a total surface area of 165,600 m^2. The average depth of local ponds is 1.5m. The total water storage capacity is therefore 248,400 m^3, only 0.5% of local runoff volume which is estimated to be 53 million m^3 for a normal year.

Suitability analysis for potential pond construction was based on runoff coefficient, land use, soil type, slope and socio factors as determined in previous sections. The protected areas and the areas where slope higher than 5% are removed. The remaining area is divided into 7 categories based on soil type, land use and runoff coefficient (Table 4).

Table 4 Chingale Catchment Land Classification

Category	Land Use	Soil Type	Runoff Coefficient (%)
A	Cultivated land	Sand	14.3
B	Cultivated land	Sandy loam	30.5
C	Scrubland mosaic with crops	Sandy clay loam	48.1
D	Cultivated land	Loamy sand	22.3
E	Cultivated land	Sandy loam	22.3
F	Dambo	Uncertain	41.7
G	Cultivated land	Sandy clay loam	30.5

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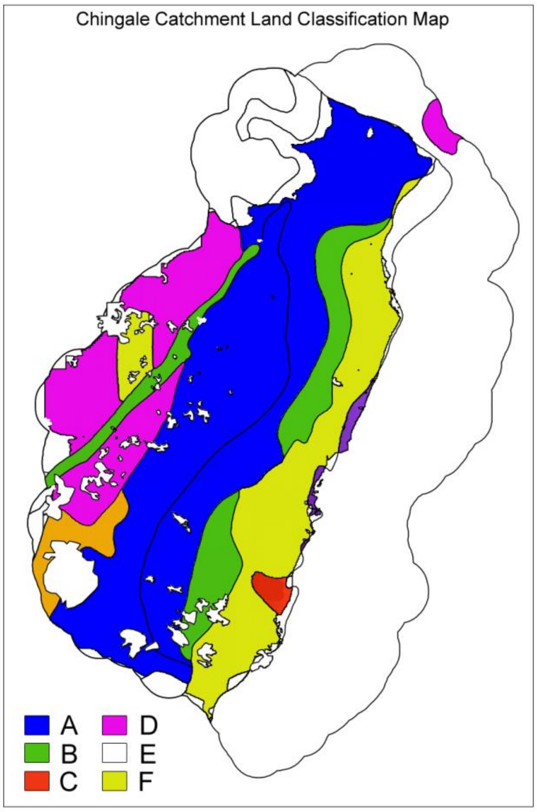

Fig 7 Chingale catchment land classification map

5 Discussions And Conclusions

Lack of investment and technical know-how is seriously hampering rural water resources development for poverty reduction efforts in Malawi. Small farm ponds, being already part of livelihoods strategy familiarized by many Malawians, play an important role in aquaculture development. Developing integrated irrigation and aquaculture pond systems offers a new approach to benefit both agriculture for a higher productivity and aquaculture for a better animal protein supply. The cost of such investment is highly decentralized with little to no extern assistance required by the cash-strapped farmers.

Ensuring minimum water losses and maximizing supply is key to successful pond development. In Chingale catchment, due to the soil property and the hot climate, both the evaporation and the infiltration rate are high which leads to excessive losses from ponds, which severely reduce available water in case of prolonged dry spell. However, ponds, as small storage facilities, are flexible options with low costs. The water balance analysis shows that the local ponds potential is still very high, although the current locations and design is less optimal.

The analysis also shows that the sizes of ponds can be diversified with a range of big, normal and small ponds to complement each other. In order to reserve enough water to maintain normal aquaculture activity and irrigation at dry season, most of the existing ponds need to be upgraded and more ponds should be built. Deeper ponds are needed to endure the high evaporation and rare rainfall supply in the summer if the ponds have no access to withdraw water from other sources. The direct runoff fro pond catchment rarely meets pond water demand. Diversions from temporary and perennial rivers are required for many of the small ponds. Engineering measures to reduce pond seepage and deep percolation is another possible solution. However, more studies should be carried out looking for cost-effective local engineering innovations.

The application of GIS, RS in ponds water harvesting potential analysis shows their effectiveness in mapping, investigation and modeling. Socio-economic elements however are often more important enabling factors. The runoff potential turns out not to be a key influence factor for ponds development. Combination of hydrological and socio-economic analysis through GIS spatial platform enables more in depth understanding with better consideration of practical constraints facing famers.

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