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Assessment of Rainwater Harvesting Potential for Irrigation at Kabiruini in Nyeri, Kenya

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ABSTRACT

A rainwater harvesting reservoir failed to supply the requisite water and was subjected to a rain, runoff and irrigation assessment to reveal information about that system failure. Historical and actual daily rainfall was obtained in addition to actual runoff measured on the reservoir. Collected data was processed, analyzed and discussed to reveal causes of reservoir depletion which was the culmination of that failure by June 2009. The catchment of 120 ha was expected to harvest enough runoff to fill a reservoir of 25,000m^3. There was more runoff produced by the catchment than could be stored in the small reservoir which was leaking that water through its floor. There were large differences between the minimum and maximum potentials that no single value could be taken. So a dynamic water supply system was recommended.

Key words: *Assessment, Rainwater, Irrigation, Potentia*

1. INTRODUCTION

1.1. Background

In the hydrologic cycle, water evaporates from the earth's surface, forms clouds in the sky and returns to the same earth as rainfall (Tarboton, 2003; Perlman, 2012). The type of surface on which rain falls determines the amount of runoff flowing into rivers, ponds, lakes and oceans, tanks and dams. Water harvested into these reservoirs is then used in agriculture, aquaculture, sports, and transport. It can also be used for industrial and domestic purposes by those who have rights over it. Some of these reservoirs are contained within areas which some entities such as countries, communities, individuals and institutions claim rights of ownership. One of these ownership rights is to harvest rainwater as runoff for useful purposes (Wriedt et al., 2008). The focus of this study was to study the dynamics of runoff harvesting for the purpose of farm irrigation to explain the reservoir depletion which had occurred in Kabiruini dam. A quick remedy for reservoir depletion was not available since no data was available that pointed to the causes of that depletion. The significance of this was that the farm relied on an irrigation water quantity which could vary any time and disappear before crop maturity. It was also important to note that the amount of farmland to be prepared could only be assessed as minimum, average or maximum implying a lot of uncertainty in deciding the irrigation area to be prepared for a crop (Gitonga & Karanja, 2009)

This research was conducted at Kabiruini show ground where Jomo Kenyatta University of Agriculture and Technology has ownership rights to a demonstration farm. On this farm, there existed a reservoir which was full of soil and could as such not store enough water for irrigating the farm(Nissen-Petersen, 2003).Like many other water pans and dams, the trapped silt required to be removed occasionally in order to restore the original reservoir capacity or increase it.In this case,the university decided to remove the soil from the reservoir by scrapping in a process called de-silting which was completed in July 2006. After de-silting, the reservoir was expected to harvest and hold 25,000m^3 of water when full for the purposes of irrigation, fishing and recreation especially during the Nyeri agricultural show held every year from September 15th(Mueni et al., 2006)

To make sure the reservoir did not fill with soil quickly, a series of four concrete walls were constructed across the stream feeding the reservoir with water so that they hold the water and make it deposit its suspended soil. When the water level rose above the first concrete wall, it spilled over and flowed downstream to the next wall. This process continued over the other walls until the water reached the main reservoir. This main reservoir was an earth dam whose capacity was increased by de-silting. The reservoir system worked well in 2006 and 2007, but by August 2008 the water level in the main reservoir was unable to support fish farming, boat rides and irrigation. As a temporary measure, an alternative water pumping system for irrigating demonstration crops was started from further away in Muringato River. At the same time research began to bring out the possible causes of this reservoir depletion, possible measures of stopping depletion and possible ways of increasing the potential runoff use in irrigation.

This paper concentrated on assessment of rainwater harvesting potential for irrigation from where causes of reservoir depletion could be found.

1.1.1 Site location

The reservoir was located between the roads from Nyeri to Nanyuki, Nyeri to Nyahururu and Nyaribo to Kiganjo but was accessed through the show ground gate which was on the Nyaribo- Kiganjo road as in Figure1 .Coordinates of the reservoir were in zone 37M at 0274180mE 9956726mS on the leeward side of Mt Kenya.

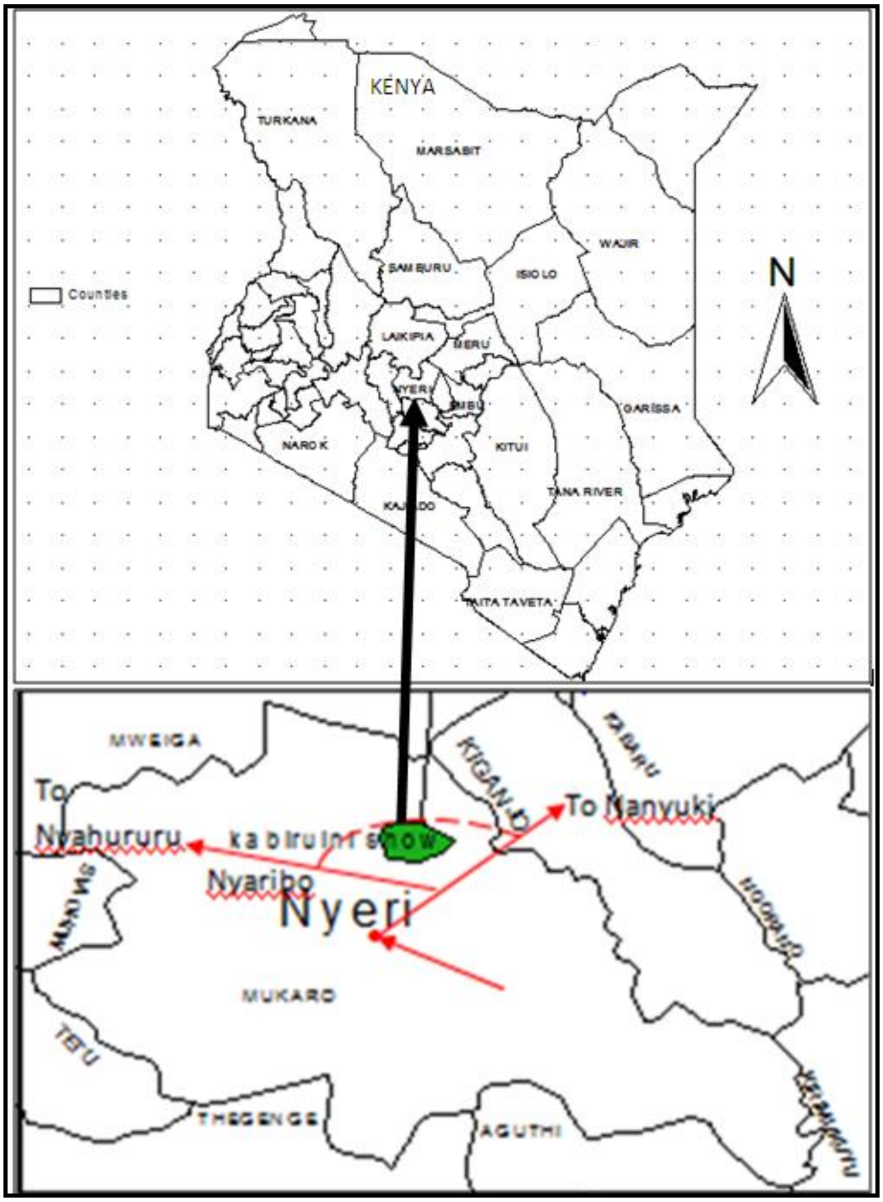

Figure 1: Location of Kabiruini Catchment in Nyeri Showground

1.2 Problem Statement

The research problem was lack of information relating rainfall, potential runoff harvesting and irrigation. Before 2006, the kabiruini reservoir problem was having inadequate storage capacity for the water uses envisaged by the university, but this was solved by de-silting. Then reservoir depletion occurred just after two years of de-silting implying that the reservoir had other issues pertaining to the runoff harvest and its usage in irrigation. These issues pertaining to runoff harvesting and irrigation were addressed by assessing the quantity of runoff that the catchment provided and the potential area that could be irrigated by that runoff without depleting the reservoir. This information was then used to simulate or model a rainfall-runoff –irrigation system that avoided reservoir depletion. That information was sought from the data concerning catchment, reservoir and farmland characteristics.

The Kabiruini reservoir within the Nyeri agricultural show ground was to demonstrate good water management by providing irrigation water to both JKUAT farm and its neighbors. Failure to demonstrate that leadership in irrigation water management was a real challenge which could not be explained by the simple answer of being a victim of climate change. It required plausible information on the rainfall-runoff-irrigation relationship that did not deplete the reservoir.

Starting with rainfall, year 2006, when the silt was removed in order to increase reservoir capacity, had the highest rainfall which filled the excavated reservoir to overflowing creating an impression that the reservoir could harvest and store all the required runoff to irrigate the land. Rainfall drastically reduced in the following years to a level where fishing and boat rides were stopped because of the reservoir depletion by June1, 2009 just when irrigation for crops to show visitors was to start (Kenya Meteorological Department, 2006).

Since design and construction data was not available, the catchment characteristics which increase or decrease potential runoff harvest were measured. Most of the reasons for reservoir depletion were expected to be catchment characteristics, available storage in the reservoir and unlimited use of stored runoff. Therefore performance of the reservoir depended on the irrigation area, storage capacity and the catchment characteristics.

The objective of this research was to assess the potential of Kabiruini reservoir for rainwater harvesting and irrigation avoiding reservoir depletion

2. METHODOLOGY

2.1 Methods of Assessing Rainwater Harvesting Potential for Irrigation

Assessment of rainwater harvesting potential aimed at coming up with values which informed about causes of depletion which occurred in 2009 in Kabiruini reservoir. Parameters that would lead in the direction of reasons of depletion were measured. These parameters were analyzed not only in as far as they affected the rainfall, runoff or irrigation potential but also how they affected one another. The potential or capacity for future rainwater supply for irrigation was sought for in analysis of datasets such as rainfall which converted to rainwater or runoff that was used for irrigation.

2.2. Assessing Rainfall Potential

Rainfall for years 1970 to 2009 from Nyeri prison rain station number 9036223, was used to assess the potential of filling the reservoir with water by converting to runoff. The daily rainfall received on site was assessed in Microsoft excel for potential to provide required crop water on daily basis and annually. Then the annual rainfall total was analyzed for minimum, mean, standard deviation and maximum over a 36 year period. In addition to these statistical measures, a linear regression was used to predict rainfall for 2010 which was checked against an actual annual rainfall measured on the reservoir. Daily rainfall was arranged in columns such that each year covered a maximum of 366 rows. Each day's rainfall was analyzed in order to assess its potential contribution to irrigation potential.

2.3 Assessing Potential Rainwater Harvesting Site

Rainwater harvesting is influenced by site characteristics such as slope, land use/cover, hydrologic soil group and rainfall. Slope was determined by a combination of spirit leveling, tacheometry and spot heights extracted from google earth imagery which were interpolated into contours at one meter vertical interval. Catchment boundary was then marked following the shapes of the contours. Land use was mainly agricultural and the land covers mapped within the catchment were crops, forest and grass. Soils were sampled randomly and analyzed to classify them into the four hydrologic soil groups A, B, C and D (Munyao, 2010)

2.4 Assessing Runoff Potential

To assess the runoff potential from the rainfall the soil conservation service curve number (SCS-CN) model was adopted. As a model for daily rainfall to runoff conversion, it was applied to the tabulated daily rainfall described above with minimum modification. The modification included the "if then" analysis that was used to discriminate rainfalls that could produce runoff and those that could not. Since the daily rainfall was already in columns of 366 days, an equation was added to the table to select the year whose runoff was required and deliver the daily rainfall for that year into the column where the SCS-CN model could be applied. The model was copy pasted down the column to calculate each day's runoff and an annual total was summed at the bottom of the column.

The effects of catchment characteristics were expressed as curve numbers selected from the table and modified to maximum soil water retention S by equation2 as equation1 calculated the runoff Q coming from the rainfall P. An average curve number CN and maximum soil water retention S was obtained from each separate area of land cover and hydrologic soil group. The average S was used in the model application in addition to the catchment area in hectares, producing runoff in cubic meters (USDA, 2004)

SCS-CN model

$$\boldsymbol{Q} = \frac{(\boldsymbol{P}-\mathbf{0.2}\boldsymbol{xS})^2}{(\boldsymbol{P}+\mathbf{0.8}\boldsymbol{xS})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Equation 1}$$

$$\boldsymbol{S} = \frac{\mathbf{25400}}{\boldsymbol{CN}} - \mathbf{254} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Equation 2}$$

In addition to the runoff calculated from the SCS-CN model, there was runoff simultaneously measured with rainfall on the reservoir. The actual runoff was used to check the predicted runoff potential in order to be sure that the model for runoff calculation was within a reasonable accuracy. It was also used to assess the retention capacity of the reservoir in terms of seepage. Whereas rainfall was measured with a rain gauge, the actual runoff was measured by reading the water depth in the reservoir on a tide gauge. Water depth measured daily was converted to volume of runoff according to the shape of the reservoir and according equations 3 and 4. Daily runoff was then accumulated to annual runoff for each year which was used for prediction and statistical analysis.

$$\boldsymbol{V} = \boldsymbol{Lb}\frac{\boldsymbol{h_n^3}}{\boldsymbol{h^2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Equation 3}$$

$$\boldsymbol{V} = \frac{(\boldsymbol{b_1}+\boldsymbol{b_2})}{\mathbf{2}}\boldsymbol{Lh} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Equation 4}$$

Where b is width of reservoir, L is length; h is depth while V is volume.

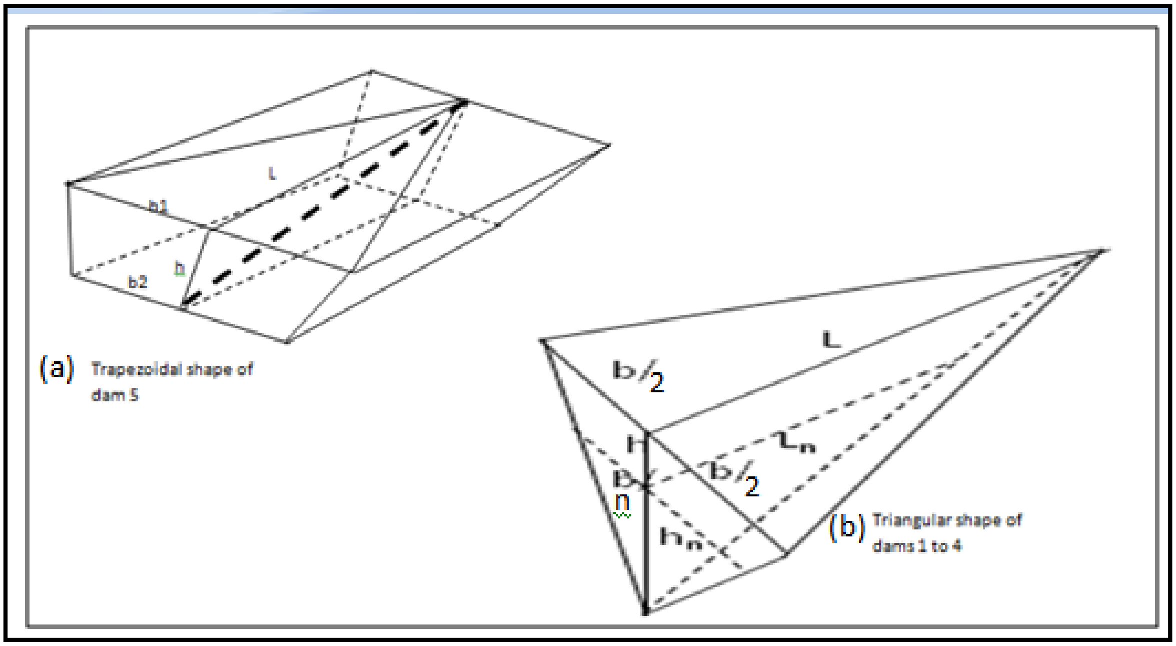

Figure 2: Approximate dam wall cross sections used to calculate actual runoff in the reservoir

When water depth h changed to hn in Figure 2, the width b and length L also changed to bn and Ln according to geometric similarity. That way the dynamic volumes of reservoir as influenced by actual rainfall for corresponding days were captured, put on a chart and used to analyze the reservoir capacity to sustain harvested runoff until the next cropping season.

2.5. Assessing Potential Reservoir Capacity

The Kabiruini reservoir consisted of an earth dam5 which was the main reservoir preceded by four concrete weir dams 1 to 4 which held water although their main purpose was to allow runoff to settle and deposit the suspended materials to lengthen the lifespan of dam5. A table was prepared in Microsoft excel to calculate the volume of each of the five dams which were then accumulated to form total reservoir water volume for each day. Annual runoff was accumulated at the bottom of the column containing daily reservoir runoff. It was possible to display on a graphical chart the daily variation of water volume residing in the reservoir so that by the end of the year whatever was remaining could be used to plan the first irrigated crop of the year. Like a bank account operation, this chart displayed whether at the end of the year there was something carried forward and if there were some expenses to be stopped (Gathenya et al., 2010).Irrigation can be assessed as a full irrigation where the entire crop water requirement is supplied from a reservoir or it can be taken as supplemental irrigation where water from the reservoir fills requirement gaps left by inadequate rainfall. This paper intended to use the latter because the show ground farms were mainly open to the sky and would receive rain when it fell implying that both stored runoff and rainfall were sources of water for the crops. It is customary to use the mean annual runoff as the potential supply for an irrigation project but due to the risk of wasting funds of land preparation when runoff harvest is below the mean, this paper took the potential to irrigate as ranging from minimum to maximum area with actual potential being according to the variable reservoir storage (Ahmed & Oweis, 2012).

3. RESULTS AND DISCUSSION

3.1 Assessment of Rainwater Harvesting Potential for Irrigation

In this paper rainfall, runoff and irrigation were considered as a system that continued from one to the other so that rainfall affected both runoff harvest and irrigation potential. The catchment characteristics contributed to rainwater harvesting potential per land cover by the curve numbers and proportion of area shown in Figure3. The land inclined towards the reservoir at a mean slope of 3% from the catchment boundary and therefore irrigation water should be pumped. The water could be pumped into farm tanks on high ground and allowed to flow by gravity or it could be pumped directly into the sprinklers or drips.

3.2. Assessment of Rainfall Potential

The mean rainfall which could be taken as the potential of Kabiruini was 836mm with a standard deviation of 263mm. A range of 1004 mm was encountered and when compared to predicted 907mm for 2010 it showed a big risk of predicting, preparing land and getting no rain at all. The actual rainfall measured on site in 2010 was 638mm which was 269mm below the predicted 907mm. That difference was one standard deviation below which further showed that rainfall was unreliable for crop production and required irrigation. Crop water requirement can be determined by many methods

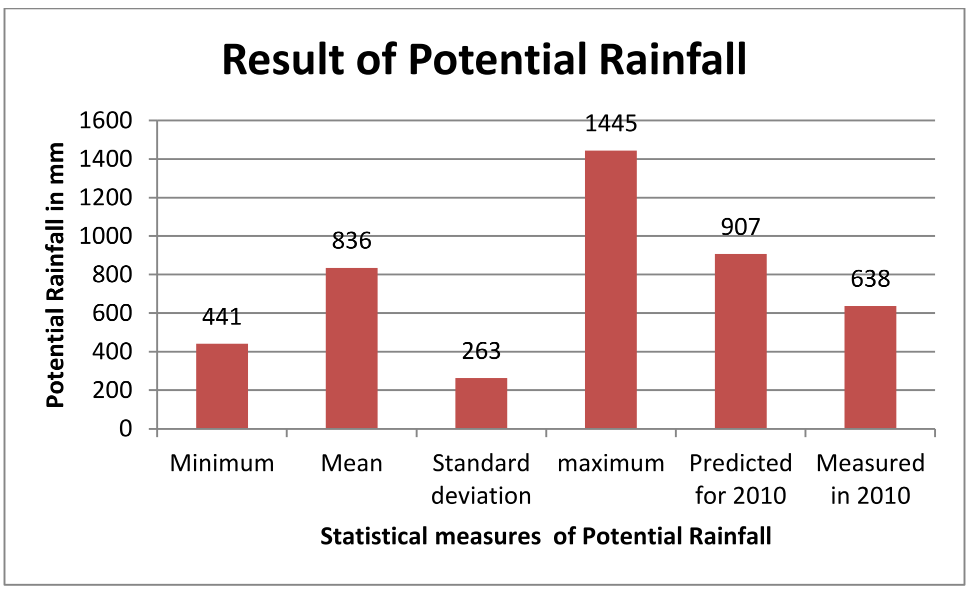

Figure 3: Result of Rainfall Potential

including estimation as done by Kay and Hatcho, 1992, where it ranges from 400 to 650mm for vegetables and cereals in a season less than 120 days. Based on this estimate, the rainfall received in 2010 was not capable of crop growth for one season.

3.3. Assessment of Potential Rainwater Harvesting Site

Catchment characteristics assessed facilitated selection of curve numbers CN, calculation of maximum soil water retention S and areas of different land covers. In addition, hydrologic soil groups B covering the lower area and C covering the upper area were identified. The result of land covers intersected with hydrologic soil groups facilitated selection of the curve numbers used in Figure 4. A mean curve number for the whole catchment was calculated as 74 and maximum soil water retention was 89.

3.4. Assessment of Runoff Potential

Potential runoff was predicted for 2010 as 52910 m^3 from linear regression of thirty six years between 1970 and 2009. Mean annual runoff was 38308 m^3 which was one and a half times the 25000m3 envisaged during the de-silting of the reservoir. So the catchment could on average produce more runoff than the expected but the variation among the years was very big ranging from no runoff to 111327m^3 which was five times of the expected reservoir capacity. Volume variation of this nature could have caused the reservoir depletion if farmers used whatever water was there expecting a harvest that never was because of drought as in 2009. Actual runoff harvested and measured in the reservoir was 36859 m^3 as opposed to the predicted volume of 52910 m^3 but there was water loss amounting to 18980m^3. Taking potential runoff as the mean annual runoff with a standard deviation of 30835m^3 really increased the risk for the farmer whose irrigation was designed for mean annual runoff. So starting a cropping season with a known amount of water in the reservoir whose value was not to change mid-season reduced the risk by hundred percent.

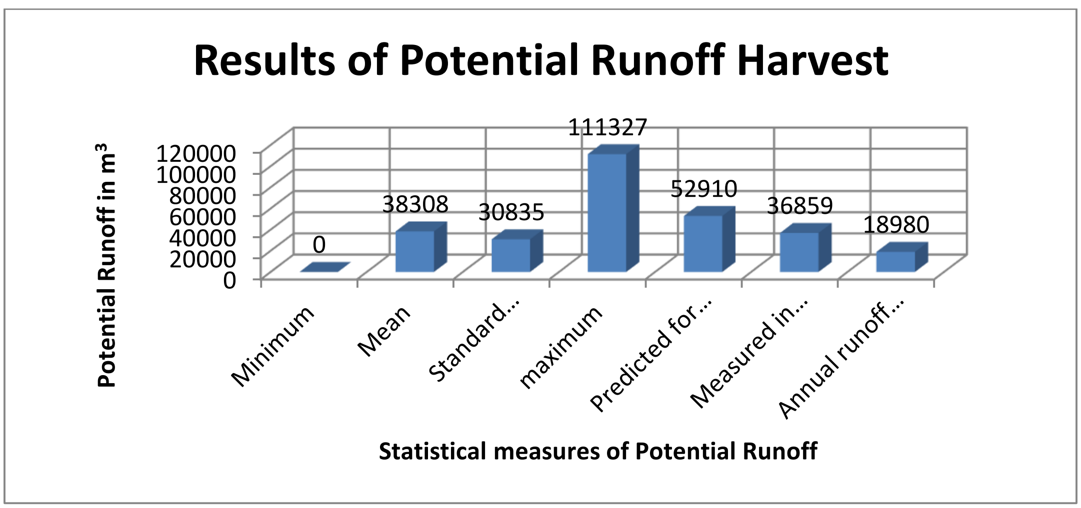

Figure 4: Result of Potential runoff Harvest

3.5. Assessment of Potential Reservoir Capacity

Reservoir capacity was calculated from contours and was 23302m^3 which was about 2000m^3 less than the expectation at de silting time. However, what could be available to the farmer was variable according to the amount harvested and stored at beginning of each season. Moreover the reservoir was leaking and this was attributed to the fractured rock outcrops left uncovered after de silting. From the image in Figure5, rocks could be interpreted and vegetation growing in the crevices left between the fractured rocks. So the idea of designing an irrigation project with a mean annual runoff as the potential left the farmer with many decisions in dynamically changing the irrigation area as the reservoir volume changed.

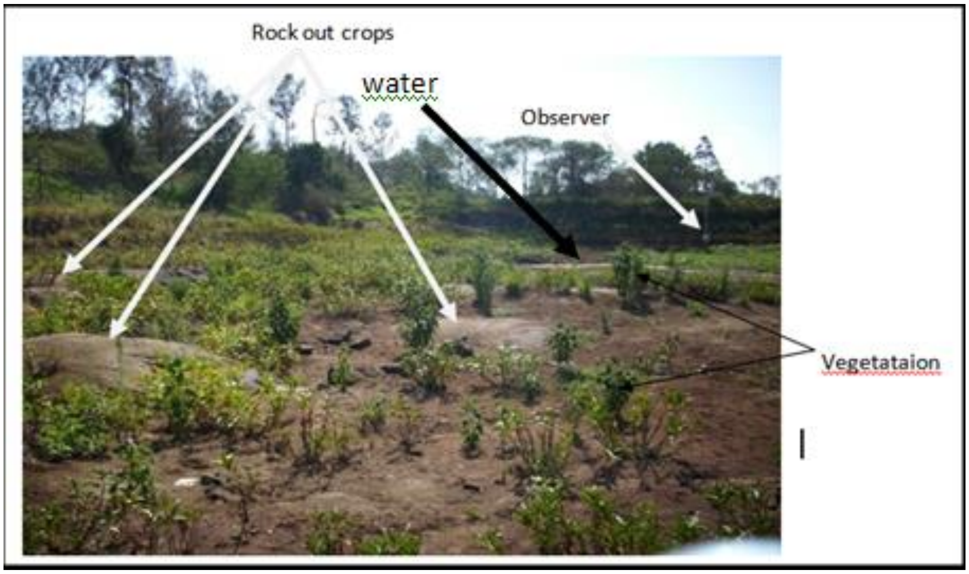

Figure 5: The reservoir floor showing rock out crops that could be leakage outlets

3.6. Assessment of Irrigation Potential

As a system the irrigation potential was taken as being supplied water from runoff but supplemented with any rainfall received. Irrigation potential from runoff harvested was on average 6 Ha with a standard deviation of 5Ha. Runoff could potentially irrigate 17 Ha or zero based on maximum and minimum potential with rainfall supplementing that potential by about 8 to 38 Ha. Potential irrigation meant the capability of this system comprising the rainfall, runoff, reservoir, scheduling and pumping or gravity flow. Since the results were to help the farmer select the irrigation area to supply available water to and rain could fall any time before, during or after irrigation then a very meticulous labor force was required to implement the assessment of irrigation potential with such high variation from zero to 38 Ha. Figure 6 shows the contribution of runoff and rainfall to the irrigation potential of Kabiruini.

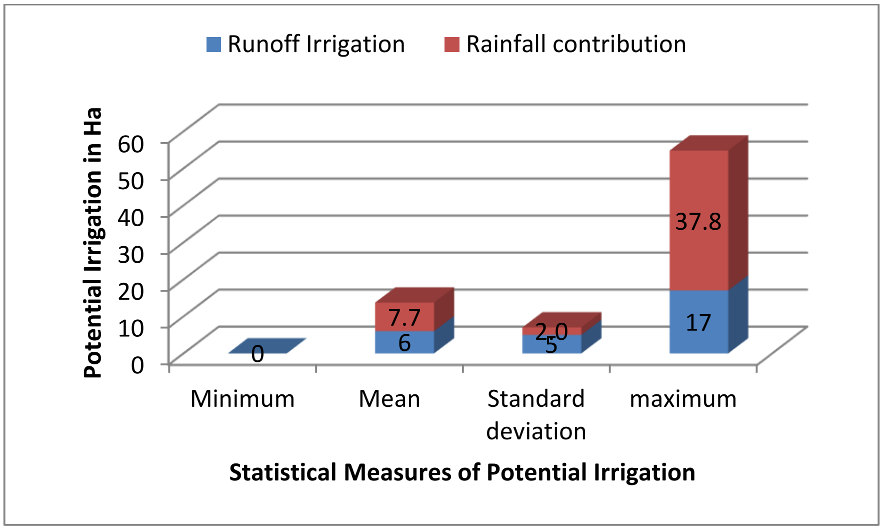

Figure 6: Result of Potential Irrigation

4. DISCUSSION

From the assessment of rainfall it was found to be inadequate for supporting a crop most of the seasons and therefore crops required supplemental irrigation. The supplemental irrigation water required to be measured accurately so that only what could not be supplied by rainfall was given. Potential rainfall also produced potential runoff depending on the quantity of rainfall received. Many rainfall events did not produce any runoff but contributed towards crop growth. As such those rainfall events contributed to the potential irrigation and not runoff. The rainfall events which contributed substantial runoff to the reservoir were above 35mm of rain and were very few in a year being about one per cent of all the rainfall events.

Runoff harvested collected in the reservoir which was much smaller than the mean annual runoff could provide. Most of the harvested runoff was therefore lost through the reservoir spillway or seepage through the reservoir floor. For the harvested runoff to be properly used, it required storage that was not varied by seepage. It should not be supplied to an area that was bigger than the available runoff could supply because such a situation would deplete the reservoir before the crops matured and waste all the resources put into the farm preparation. Precision agriculture would be required to stretch the available water to irrigate a bigger area than could be irrigated.

Potential irrigation could vary by upto 30Ha which if not well planned could be a big waste of resources used to prepare land and then water fails to be available

5. CONCLUSION

Although the potential rainfall was below crop water requirements, the potential runoff harvested was higher than the reservoir could contain, allowing wastage through the spill way. In addition to the reservoir being small, the floor was leaking harvested water away, making it more difficult to achieve higher irrigation potential. Even when leakage and reservoir capacity are addressed, precise apportionment of available runoff with consideration of irrigation area and land preparation would require a system to address.

RECOMMENDATIONS

It was recommended that the reservoir be enlarged to at least accommodate the mean annual runoff, then following a geotechnical study get the floor sealed. Further research should be done to relate the rainfall, runoff and irrigation area in a dynamic irrigation system that adjusts itself to available water resources simultaneously.

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