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REVIEW
Technologies for Harvest and Effective Use of Water in Rainfed Agricultural Areas

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Abstract
Agriculture in developing countries usually depends on rainfall. However, erratic rainfall makes agricultural production unstable. It is necessary to harvest water resources and to use them efficiently in order to stabilize crop yields. Methods of harvesting water resources are subject to topography. In lowlands, it is easy to collect water, because water flows in, but this is difficult in uplands, because water flows out. This article reviews methods of harvesting water resources and using them effectively in developing countries by reviewing papers from the last 20 years.

Discipline: Agricultural engineering
Additional key words: irrigation, mulch, tillage, water use efficiency

Introduction

Agriculture in developing countries usually depends on rainfall. However, erratic rainfall makes agricultural production unstable. Harvesting water resources and using them effectively can stabilize and increase crop yields. The large-scale development of water resources has become difficult because of lack of funds. Preservation of the environment and economically feasible technologies for the harvesting and efficient use of water resources in developing countries are thus required.

Methods of harvesting water resources are subject to topography. It is easy to collect surface water and to build reservoirs in lowlands, because surface water flows into such areas. Moreover, groundwater is usually shallow and easy to extract. Groundwater is a valuable resource because it is not influenced by evaporation and can be pumped easily with simple technologies. However, pumping too much water lowers the water level and limits the future supply. When dry weather continues for a long time, water shortages become a problem even in lowlands.

In uplands, groundwater is usually deep and it is difficult to extract. Methods of collecting surface runoff effectively are thus important. Once surface runoff is saved in a low-lying area, it is difficult to lift it again to reach farmlands. Boers & Ben-Asher reviewed technologies for collecting water, but their review was more than 20 years ago[11]. Then, methods to reduce infiltration, to enhance the ratio of runoff and to collect runoff in reservoirs were usual. Now, additional methods to retain moisture in soil are becoming popular.

This article reviews methods of harvesting water resources and using them effectively in lowlands and uplands in developing countries by reviewing papers from the last 20 years.

Collecting and using water resources effectively in lowlands

1. On-farm reservoir

Lowlands are generally used for paddy fields because water collects there easily. However, in some places rainfall is erratic, and both floods and droughts can occur. Methods to cope with such erratic rainfall are thus necessary.

An on-farm reservoir can be built to collect rain and to retain excess runoff. When rainfall is not enough to grow crops, the stored water is used for supplemental irrigation[25,39]. Jensen et al. calculated the amount of water required for rice in the most important period of its growth, the reproductive period, by simulating the daily water balance in farmland[28]. They found that the opti-

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mum storage was a ditch of 2 m deep with an area occupying 5% of the total rice fields. Panigrahi et al. made a similar estimation for Kharagpur, India[43]. They found that suitable storage to ensure enough water for profitable rice growth was an on-farm reservoir 2 m deep (with a 1:1 side slope) occupying 9% of the total rice fields.

2. Reuse of irrigation water

Because paddy rice needs more water than other crops, reuse of irrigation water is important. One method is to reuse runoff from upstream paddies in downstream paddies. Zulu et al. calculated the proportion of this reused water to be about 15% on the Niigata Plain, Japan[72]. Water lost by infiltration from paddy fields and canals can be captured for reuse by using a well or a horizontal drain[49].

3. Method of saving irrigation water

Some experiments to enhance the efficiency of water use (total yield/amount of irrigation) by saving irrigation water on the farm have been reported. Because infiltration of irrigated water during land preparation is large and is influenced by cracks in the soil, tillage practices can reduce infiltration[65]. Subsoil compaction in a paddy field with high water permeability reduced infiltration and increased rice yield and water use efficiency[52]. Wet-seeding of rice and cultivation in shallower than normal water during the rice growth period reduced the total use of irrigation water and increased water use efficiency[6,9,10]. Bouman & Tuong reported that water savings of 23% (±14%) under saturated soil conditions reduced yields by only 6% (±6%), but similar savings under dry soil conditions reduced yields by 10 to 40%[12]. They concluded that total rice production can be increased by using water saved in one location to irrigate another. Tabbal et al. and Tuong & Bhuiyan listed methods for saving water on-farm[58,61].

Harvesting and using water resources effectively in uplands

1. Method of collecting water

It is difficult to use groundwater in uplands because it is usually found deep below the soil surface. Therefore, it is necessary to harvest surface runoff as much as possible and to use it effectively.

Yoshinaga et al. calculated the relationship between reservoir capacity and catchment area in the southwestern islands of Japan[66,67]. Sur et al. calculated the amount of harvested runoff to be 1,200 to 2,800 m^3/ha in northern India[56]. A water balance calculation revealed that leakage from the reservoir in that study accounted for 61 to 81% of total water loss. It is therefore important to reduce leakage of stored water. Pepper & Burke used different soils as lining material in the reservoirs behind four dams and evaluated the effects. The technique was successful, and could reduce the cost of sealing earthen dams[44]. In experiments on reducing leakage from a reservoir, dispersed clay from sodic soils proved effective[4,45]. Magnesium oxide has also been used to prevent leakage[23]. A method to increase surface runoff by covering the catchment area with asphalt, fiberglass or concrete was also reported[16,33].

Techniques for collecting water in sloping uplands are commonly combined with measures to control soil erosion. Methods to reduce the flow rate of surface runoff and to increase infiltration into the soil are important. Zougmore et al. studied the effect of stone lines on soil moisture and sorghum yield[71]. Lines spaced 25 m apart reduced surface runoff by 23% when compared with no lines. Sorghum grain yields about 6 m uphill of the lines were 60% greater than those 19 m uphill of the lines. Abu-Zreig et al. dug trenches and filled them with river sand; the trenches maximized water collection, prevented soil erosion and did not interfere with agricultural operations[2]. Hudson reported methods for soil and water conservation in a semi-arid zone, such as changing the shape of the soil surface and the arrangements of rows and ridges[27]. Fig. 1 shows an example. Bruins et al. reported rainwater-harvesting in Africa[13].

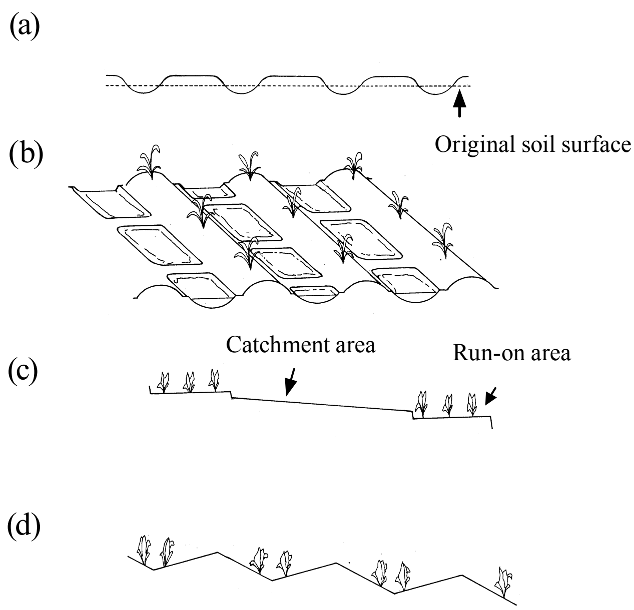


Fig. 1. Methods of changing the soil surface to increase retention of rainfall on crop land[27]
(a): Broad bed and furrow, (b): tied ridges,
(c): conservation bench terraces, and
(d): contour furrow or strip tillage.

2. Irrigation method

It is important to increase water use efficiency by minimizing water use and maximizing crop yields. Efficient irrigation methods include subsurface drip irrigation, which is application of water by drip or trickle equipment installed below the soil surface; deficit irrigation, which is application of less water than full irrigation in relation to wilting point and field capacity in the root zone; and supplemental irrigation, which is application of water only when rainfall is not enough for crop growth.

Camp reviewed more than 150 examples of subsurface drip irrigation[14]. The yields with subsurface drip irrigation were greater and the use of water was less than with furrow and sprinkle irrigation in more than 30 examples. However, because equipment and maintenance are more expensive than those of the other methods, only highly profitable crops are suitable for subsurface drip irrigation.

Deficit irrigation is more favorable than full irrigation from the viewpoint of water use efficiency (total yield/amount of irrigation), though the yield is usually reduced[70]. Deficit irrigation is usually combined with supplemental irrigation. Table 1 shows examples of the studies on deficit and supplemental irrigation. Although the effects of deficit and supplemental irrigation are different at different crop growth stages and for different soil moisture conditions, it is essential to supply enough water to crops in the stages that are most sensitive to water stress and to reduce the amount of irrigation in the other stages. It is important to monitor soil moisture and to supply water according to the condition of the soil[18–22,29,38,40–42,57,60,68,69].

Table 1. Research on deficit irrigation

Authors	Crop	Country	Results	Reference No.
English et al. (1996)	Wheat Cotton Maize	USA USA Zimbabwe	Deficit of between 15% and 59% would be economically optimal.	18
Fabeiro et al. (2001)	Potato	Spain	The larger potatoes were obtained in the treatments which had not undergone deficit in the ripening period.	19
Fabeiro et al. (2003)	Sugar beet	Spain	The best treatment is to cause medium, moderate, and severe water restrictions during development, root swelling and ripening, respectively.	20
Fabeiro et al. (2003)	Garlic	Spain	The treatment with no deficit during the ripening stage had the highest productions.	21
Fox et al. (2003)	Sorghum	Burkina Faso	The yield at supplemental irrigation (60–90 mm per season) and fertilizer application (46.5 kg N ha^{-1}) is higher than normal practice by a factor of 3.	22
Kashyap et al. (2003)	Potato	India	The maximum allowable depletion ofavailable soil water, 45%, attains maximum water use efficiency.	29
Mugabe et al. (2000)	Wheat	Zimbabwe	Yield decreased by 7–12% at 3/4 of full irrigation.	38
Oweis et al. (2001)	Wheat	Syria	A multiple sowing-date strategy has reduced the peak farm water demand rate, but does not maximize total farm production.	40
Oweis et al. (2004)	Chickpea	Syria	2/3 of full irrigation gives the optimum water use efficiency.	41
Panda et al. (2003)	Wheat	India	The maximum allowable depletion ofavailable soil water, 45%, attains maximum water use efficiency.	42
Sweeney et al. (2003)	Soybean	USA	A single irrigation at different reproductive stages can influence early maturing soybean yield and quality.	57
Tavakkoli et al. (2004)	Wheat	Iran	Maximum water use efficiency would be achieved when 60 kg ha^{-1} of fertilizer application is combined with 1/3 of full supplemental irrigation.	60
Yuan et al. (2003)	Wheat, corn, potato	China	The economic analysis indicates that potato production is the best alternative for defict irrigation.	68
Zhang et al. (1999)	Wheat	China	The yield response curve to irrigation showed a plateau, indicating a great potential in saving irrigation water.	69

3. Soil management

Soil management can be used to increase infiltration of rainfall and to keep the root zone moist. Kijne emphasized the importance of soil tillage to increase infiltration[30]. Surface crust formation by rainfall reduces the permeability of the soil and increases surface runoff. Al-Qinna & Abu-Awwad reported that the application of water at 6.2 mm/h by means of trickle and sprinkler irrigation did not form a surface crust and increased soil moisture more than irrigation at 14.4, 24.4 and 28.8 mm/h[5]. Rockstrom & Valentin and Stroosnijder & Hoogmoed studied the influence of surface crusts on surface runoff in a water balance calculation. Disruption of the crust increased infiltration, but the crust soon regenerated[46,55]. The effect of tillage is influenced by soil features, topography, and crops. Some reports recommended no-tillage or the combination of tillage with the measures to prevent soil erosion, depending on soil features and farming systems[7,24,54,64]. Unger & Cassel reviewed the effects of tillage and concluded that more studies were needed because the effects are influenced by various factors, such as soil features and methods of tillage[62]. In addition to mechanical destruction of the crust, biological destruction by termites can be encouraged in the semi-arid and sub-humid tropics[34,35]. Moreover, because the termites collect and transport animal and plant material to their nests, their activity improves soil fertility.

The use of mulch to reduce evaporation from the soil surface can increase the efficient use of soil moisture. In field experiments, green and dry straw mulches conserved about 15% more water than the no-mulch treatment in the top 500 mm of the soil profile and the yield of yellow sarson (*Brassica rapa*) increased by about 40%[37]. Sharma et al. conducted a similar experiment with wheat[51]. Bennie & Hensley concluded that the use of mulch achieved efficient use of rainwater in South Africa[8]. Mulch not only reduces evaporation from the soil surface, but also increases the activity of soil organisms. The population of earthworms underneath mulch was higher than in the absence of mulch, and soil moisture also increased[3]. Mando reported that the combination of mulch and termite activity increased permeability

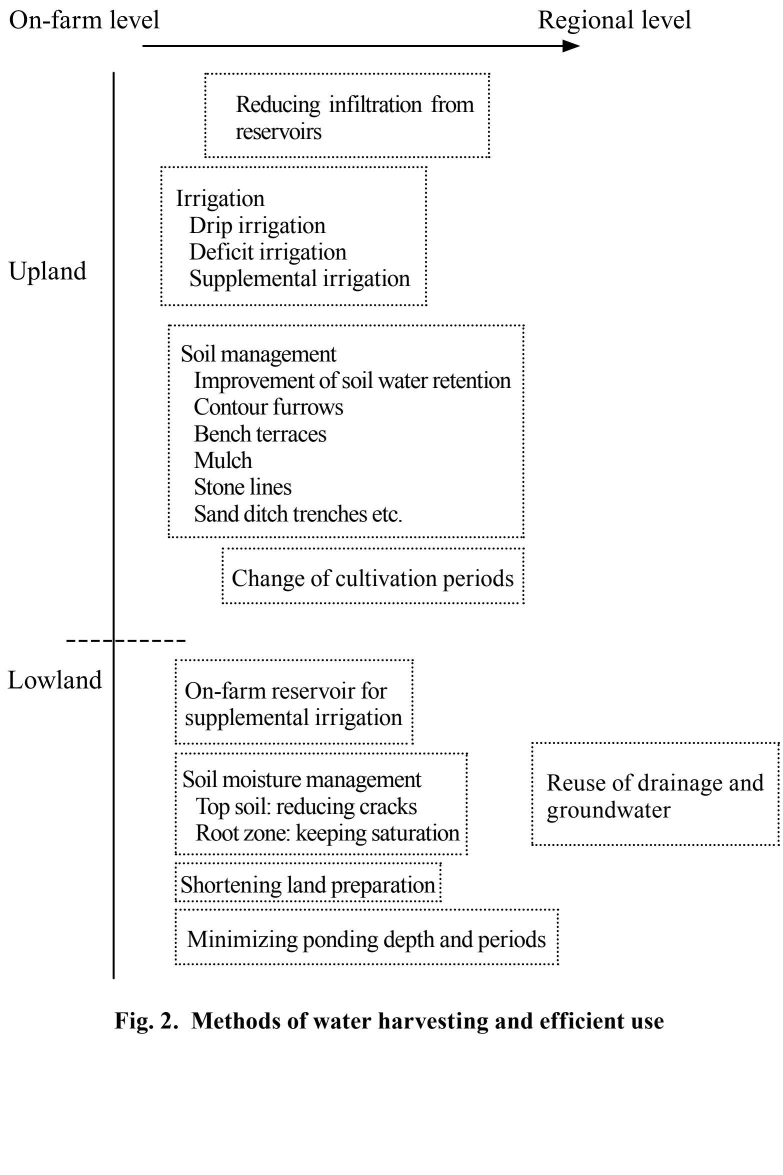


Fig. 2. Methods of water harvesting and efficient use

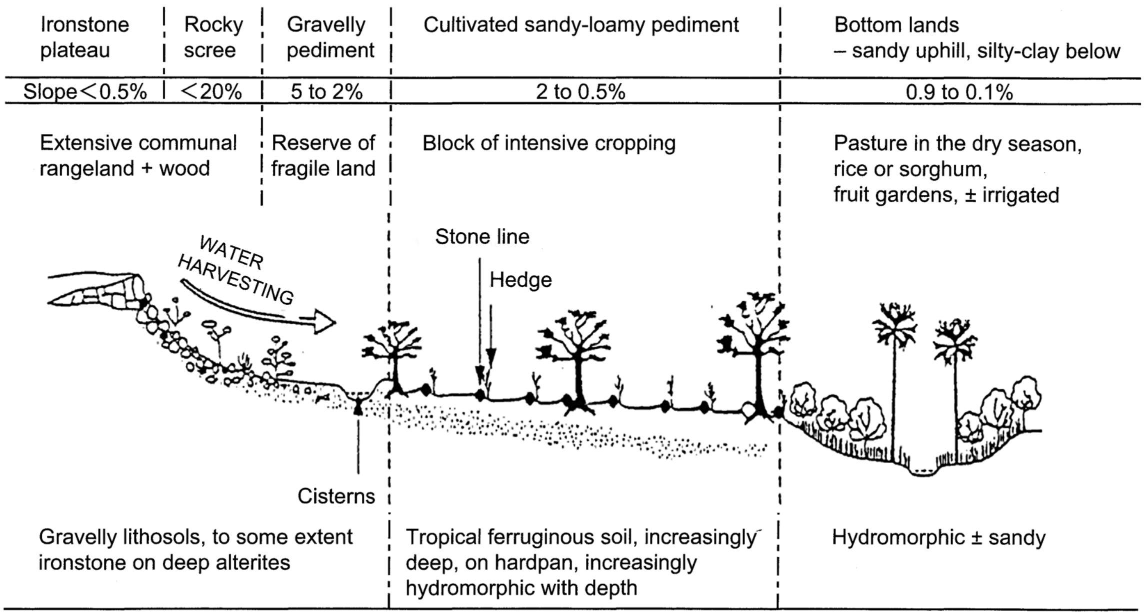
and soil water storage[36].

The effects of mulch and tillage have been compared. Crop yields were higher with mulch treatment than with tillage management[26,48,50]. Smith et al. and Unger et al. also reported that mulch-based farming gave better soil and water conservation than a tillage-based system[53,63].

Soil moisture can be increased through optimum combinations of tillage, mulch, crop rotation, and reshaping of ridges and furrows[1,15,17,31,32,59].

Conclusion

This article reviewed methods of harvesting water resources and using them effectively in developing countries (Fig. 2). From now, it is important to combine these methods and to consider management of a basin. Fig. 3 shows an example of improved use of water resources in a basin[47]. To harvest and use water resources more effectively, it will be necessary to accumulate the results of more field experiments.



Poor soils : Deficient in N and P, sometimes Km Ca, Mg and trace elements; pH 5 to 6.5.
Fragile soils : Slacking crust, poor infiltration, plough pans, poor in organic matter.
Restoration of soil fertility : Tillage + spot manuring + N, P, K supplements + control of runoff + sorghum or strong-rooting legumes.

Improvements

Uncultivated water harvesting area

- Storage of runoff
  - 1/2-moons, microcatchment
  - Cisterns for cattle, and for irrigating a garden
  - Hill lake in a favourable location
- No-grazing area (5-year contract)
  - Forage trees along the subsoiling line
  - Grass behind the stone lines
  - Protection against fires
- Grazing organized by the community herder

Rainfed crops

- Slowing runoff
  - Hedges + trees along edges
  - Stone lines
  - Lines of *Andropogon* grass, every 10 to 25 m
- Creating a bocage against the wind
- Dense, early sowing, tied mounds to enhance water storage
- Irrigated gardens behind the cisterns
- Cattle passage corridors
- Rotation of cattle paddocks
- Manure/compost pits near dwellings
- Supplementary fertilization as required by crops

Irrigated crops + Off-season fruits gardens

- Spreading flood water
- Trapping fertile sediment
  - Filtering dikes
  - Bunds build of sods/rice fields
  - Small village reservoir
- Recharging groundwater to increase security in periods of drought.
- Avoiding large trees, which draw too much on groundwater
- Maintaining a forage zone to act as a filter

Fig. 3. Examples of improved use of water[47]
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