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Simple methods for soil moisture assessment in water harvesting projects

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Simple procedures based on the uncalibrated use of soil moisture blocks were developed to assess moisture contents of soils cultivated under experimental water harvesting in dry-land Sudan. This experimental system is based on a series of earth embankments and parallel channels which divert floodwater from a central watercourse to adjacent cultivated lands. The achievements of water harvesting remained below expectation due to recurrent breaching of earth works. However, the procedures utilised to assess moisture contents proved successful. These can also be designated as a monitoring instrument for preventing breach damage in water harvesting projects.

Keywords: Sudan; dry-lands; water harvesting; soil moisture monitoring

Introduction

In dry-lands, crop production is possible only when additional water is made available for cultivation. With declining investments in irrigation in developing countries, alternative methods, such as soil and water conservation, have become more important in recent decades (Turral, 1995). Water harvesting is one such technology and is based on the collection and concentration of surface runoff for cultivation before it reaches seasonal or perennial streams (Reij *et al.*, 1988). Water harvesting is practised in nearly all African dry-lands either in its indigenous form, or as technique introduced by international donor programmes (Van Dijk, 1995). Its scope as a low-cost alternative to irrigation is increasingly recognised in developing countries in other parts of the world (Napier *et al.*, 1994; Tabor, 1995; Gupta, 1995). Despite this growing interest, its success is still largely measured through standard economic evaluation procedures (Böjö, 1992) and through averaged rates of runoff, soil moisture, erosion, sedimentation, crop yield and productivity (Doolette & Magrath, 1990). The experiences from Sudan discussed here in contrast focus on the continuous methods of monitoring water harvesting performances in the field. The Soil Conservation, Land Use and Water Programming (SCLUWP) Administration, residing under the Ministry of Agriculture and National Resources and regionally represented by a department, implements water harvesting projects in, among others, the Border Area of eastern Sudan (Fig. 1).

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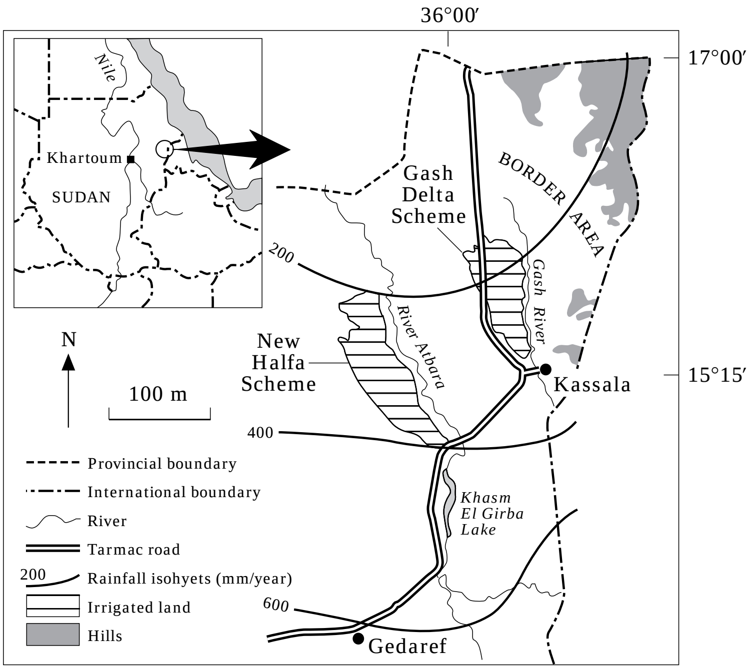

Figure 1. The Border Area.

The Border Area is a gently sloping pediplain located between 15°–17° N and 36°–37° E, at about 500 m above mean sea level. Annual rainfall is 150 and 400 mm at its northern and southern margins, respectively. This is unimodally distributed over May–November, with August usually the wettest month. Monthly mean maximum temperatures range from 33·7°C (Aug) to 41·7°C (May), with minimum temperatures from 16·0°C (Jan) to 25·2°C (Jun). Class-A pan evaporation monthly is between 90 mm (Dec) and 320 mm (Apr and May).

The region is flanked by foothills of the Ethiopian Highlands. These are drained by large watercourses, while smaller streams spring from the isolated rock outcrops and sparsely vegetated plains. Geologically, the parent material is Tertiary Basement Complex rock and Quarternary Clays of the Plain. The major soil types are Eutric Fluvisols, Eutric Regosols, Vertic Cambisols, and Vertic, Haplic and Calcic Luvisols. These soils of mainly loamy texture have a high surface-sealing and crusting capacity which enhances runoff. Floodwater generated at the valley bottom and rainwater generated at its interfluves is used by the semi-nomadic Beja for subsistence cultivation of sorghum and millet. They rely on indigenous water harvesting techniques for this purpose, locally called *teras* (Van Dijk & Ahmed, 1993).

In 1987, SCLUWP introduced a new technique for water harvesting to make better use of the region's hydraulic potential and expand its cultivated area. This technique was first developed in a pilot scheme in the northern delta Headadeib, located 20 km NE of the regional capital Kassala. SCLUWP received financial and technical support for the project from the Netherlands' government and The Ford Foundation between 1987 and 1991. The new technique (Cosijn & Van Dijk, 1989; Van Dijk, 1991, 1995) utilises floodwater of *khor* (watercourse) Headadeib which is captured in the adjacent foothills. The catchment size amounts to 875 ha of which 710 ha (81%) is on rock outcrop and 165 ha (19%) on almost bare pediment slopes. Given an estimated runoff coefficient of 0·6 and measured highest frequency of occurrence of rainfall intensity being 5–10 mm h^{-1}, about 7–15 m^3s^{-1} can be expected to arrive as floodwater

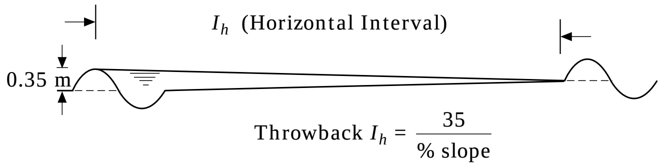

Figure 2. The principle of water harvesting.

according to the standard rational formula (Hudson, 1971). This water is available for the irrigation of 75 ha of cultivated land inside the pilot scheme area.

The cultivated area is covered by 0·35-m high earth embankments and parallel channels which divert floodwater from *khor* Headadeib to adjacent land. The embankments and channels are built in series on a gently sloping plane (less than 0·9%) on the near terrain contour with a 1:1000 fall towards the watershed crest. This causes harvested floodwater not only to spread laterally away from the watercourse, but also forces it in the direction of the slope until it meets the crest and next upstream embankment. A total of 14 embankments were built at Headadeib. These are 3 m wide and raised at 40–70-m intervals, according to local terrain gradients and the following equation (see also Fig. 2):

$$I_{\mathrm{h}} = 35/s \qquad \text{(Eqn 1)}$$

where I_{h} = horizontal interval, or distance measured from the embankment crest to the foot of the next upstream embankment (m) and s = percent slope.

Earth embankments were originally designed to have runner grass protection at the sections crossing the central watercourse. In practice, no grass cover was established and semi-permeable structures of rock and brushwood wattle were installed to simultaneously provide protection against erosion and allow sufficient floodwater to reach downstream zones.

The project's short-term goals included, among others, the development of a system to make crop production less dependent on seasonalities in rainfall and runoff by manipulating runoff to penetrate soils between the watercourse and its elevated crest boundaries (Kraayenhagen, 1987). Therefore, with respect to monitoring of water harvesting performances, focal attention was given to an assessment of temporal and spatial patterns of soil moisture content. In this vein, the new technique was considered to function better when it demonstrated: (i) an increased capacity to store soil moisture, as gauged by analysing moisture content over time; and (ii) a more uniform spreading of harvested runoff over cultivated lands, as gauged by analysing moisture content over space, i.e. along the terrain slope between subsequent embankments.

Soil moisture content can be assessed by various direct or indirect techniques which differ in scale of implementation, sophistication of data collected, ranges of soil suction covered, and implementation potential for given soil types (Payne, 1988; Briscoe *et al.*, 1992; Shih & Jordan, 1993). Among the simplest is one based on electric resistance as an index of soil water. This technique also has several other advantages. First, it is relatively cheap in the context of budget size for internationally supported projects in developing countries. Second, it can easily be combined with low-cost devices for field navigation and recovery of instruments. In the Border Area, runoff farms of both the indigenous and 'project' type are not visibly demarcated. Land use is opportunistic, depending on the timely arrival of rainfall and runoff. Farms are geographically dispersed to spread risk, while within each farm various sections between the valley bottom and interfluves are cultivated seasonally (Van Dijk, 1995). Rural infrastructure therefore is largely absent, which turns orientation in the field without navigation aids into a complex task. Easy recovery of instruments is important because the region is crossed by transhumant nomadic peoples. This compels one to hide equipment meticulously to avoid loss by vandalism. High rates of sedimentation and dense plant stands due to poor thinning standards further suggest the use of methods which allow easy recovery of equipment in the field.

Materials and methods

Electric resistance was measured by coaxial electrodes embedded in small prefabricated units of gypsum called soil moisture or Bouyoucos blocks (Schwab *et al.*, 1981). These can be placed at desired levels and assume a moisture content in equilibrium with the surrounding soil. The electrodes are connected to a portable meter whose readings have a known relation to block resistance (ohm) and soil suction (bar). Its main applications are in monitoring crop water balances in humid environments and water-scheduling under conventional irrigation. Readings must then be calibrated to obtain moisture content in absolute terms (volume percent by weight) using direct weighing or other methods (Stenitzer, 1993). However, for evaluating achievements in water harvesting in Sudan where runoff cannot be controlled and support equipment is limited, trials can be set up such that changes in moisture content are analysed in relative terms and uncalibrated readings can suffice.

Three types of trials were made in the pilot scheme (Van Dijk, 1991) of which the one aimed at the analysis of temporal and spatial patterns of moisture content is discussed here. The effectiveness of water harvesting in terms of its ability to capture runoff and distribute this over cultivated lands was evaluated by measuring soil moisture in representative sections upstream (third–fourth embankment), midway (seventh–eighth embankment) and downstream (twelfth–thirteenth embankment) (see Fig. 3). In each section, soil moisture blocks were placed in vertical bore holes along imaginary reference lines at the main rooting depth of sorghum and millet of 30 cm. Three lines running perpendicular to the embankments in the direction of the slope were used in the upstream, and four in the midway and downstream sections. One block per line was installed at the up-slope and one at the down-slope location between subsequent embankments. The spacing between lines was set at 50 m, and per line, between blocks, at 20–30 m. The latter distance depends on the area between embankments and hence on local gradients of slope (see Eqn 1). Navigation in the field and recovery of blocks was improved by erecting coded angle-iron benchmarks on the embankments. Their identifying marks indicate the compass bearing of reference lines, as well as the spacing between individual blocks. In addition, scrap metal was buried at all measuring locations to allow easy recovery by means of a metal detector.

The optimum range for plant growth, 0·2–0·6 bar soil suction (pF 2·3–2·8) relates to uncalibrated meter readings of 95–75 for the equipment used at Headadeib (Eijkelkamp, n.d.). If calibrated, this would correspond to 30–34% volumetric moisture content for the locally prevalent loamy-textured soils. Meter readings were taken by trained staff of SCLUWP every other day during three wet seasons 1988–1990. These covered 22 August to 15 October 1988, 14 August to 9 October 1989, and 11 September to 10 October 1991. The total costs of monitoring equipment (soil moisture blocks, portable meter, compass, metal detector, pieces of scrap metal, angle-iron benchmarks) amounted to US $850, with running costs of US $75 per year for maintenance and repair. These costs are low, given the pilot scheme's total annual costs of US $60,000 (Van Dijk, 1995) and the equipment's capacity to assess moisture contents quantitatively.

Results

Data on measured rainfall and floodwater discharge in the pilot scheme area are given in Table 1. Total annual rainfall in 1988 was 335 mm, of which the bulk was evenly distributed over August (229 mm), and the first half of September (32 mm). Total rainfall reached 188 mm in 1989, characterised by two peaks in August (50 mm) and September (47 mm), and a relatively dry spell in between. In 1990, total rainfall was only 97 mm. This fell mainly outside the growing season in early May (not shown in Table 1) and again in mid-September (43 mm). Rainfall and discharges in the main watercourse at Headadeib show largely corresponding patterns over time, except in

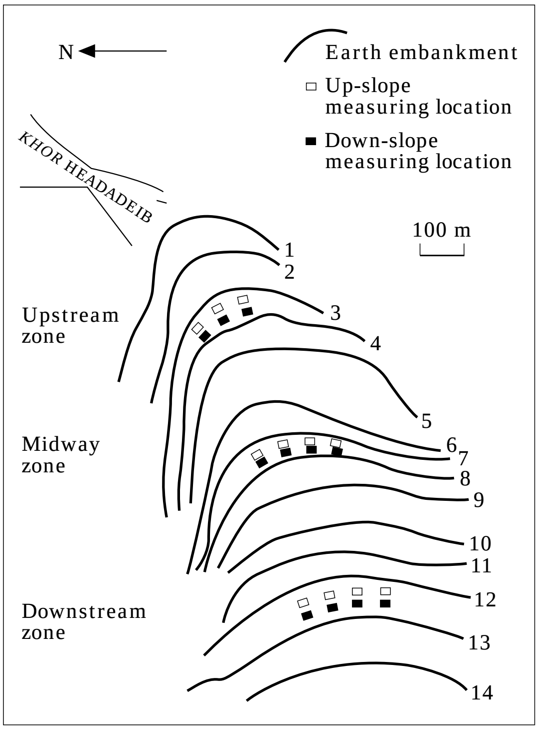

Figure 3. The system of earth embankments in the pilot scheme northern delta Headadeib and trial lay-out.

Table 1. *Rainfall (mm) and floodwater runoff (m^3) in the Headadeib pilot scheme area, 1988–1990 (from Van Dijk, 1991, p. 20, 23)*

	August		September		October		Annual total	
	rainfall	runoff	rainfall	runoff	rainfall	runoff	rainfall	runoff
1988	229	49,700*	32	5458	3	NA	335	55,165
1989	50	9700†	47	270	16	NA	188	12,456
1990	6	NA	43	NA	2	5590	97	13,929

*80% of which was received before 14 August.
†98% of which was received before 14 August.

1990. In this year, September received the greatest amount of rainfall, but October generated the greatest amount of runoff. Moisture content in meter readings is presented in Fig. 4, per monitoring zone (upstream, midway, downstream), per measuring location (up- and down-slope), and for the monitoring years (1988–1990). For each year, available data is given over the number of days since the earliest monitoring day in the series of three years, August 14.

First, a number of general observations can be made. (i) The wet seasons and related series of monitoring days differ in character over the period displayed in the time-window. The 1988 and 1989 measurements are earlier in the season and more numerous (both N = 28), while those of 1990 are later and smaller in number (N = 5). (ii) Patterns of meter readings show similarities by zones and locations, but to a lesser extent by years. The downstream zone is deviant in this respect with steadily declining levels of soil moisture in 1988, and also generally lower levels in 1989. (iii) Optimum levels for plant growth (meter readings 75–95) were reached for all zones early in 1988, and incidentally also in 1989 for the upstream and midway sections.

Second, the achievements of the new water harvesting technique can be evaluated as follows. (i) The temporal patterns of moisture content illustrate that seasonality in water availability for plant growth was not off-set in any one year. In 1988, moisture contents gradually decreased after the wet season, and a clear bimodal distribution persisted in 1989. The limited number of data for 1990 indicate that soil moisture remained at minimum levels in this year. (ii) The spatial patterns of moisture content between embankment pairs differ by monitoring zone. Given the new principle of water harvesting (see Fig. 2), down-slope locations were expected to generate higher meter readings than up-slope ones. In addition, the smaller the gradient in readings between the two, the more evenly runoff was assumed to have been distributed between the embankments. Higher readings down-slope were indeed found in all monitoring zones, except downstream. This can be explained by malfunctions in the system of earth embankments. In 1988, 49% of the total length of the twelfth and thirteenth embankment was breached. In consequence, spurious readings resulted from water draining freely from upstream locations. After repair, annual damage to these earth works was reduced to only 3% in 1989. In the very dry year 1990, up-slope readings were again spurious, but this time as a result of localised high-intensity rainfall instead of runoff thrown back up slope (Van Dijk, 1991). Smaller gradients between up-slope and down-slope readings were found in the scheme's midway and upstream monitoring zones for all years, according to expectation.

Discussion

The achievements of water harvesting in the Headadeib pilot scheme as monitored by uncalibrated soil moisture blocks have remained below expectation. The natural seasonalities in water supply were not offset by stable levels of soil moisture. Also, in some areas, the harvested floodwater was not uniformly distributed over the cultivated land. Breaching of each works was an important contributing factor to this poor level of performance (Van Dijk, 1995). Damage assessment is therefore another vital area for continuous monitoring in water harvesting projects. At Headadeib, breaching was usually preceded by floodwater locally overtopping embankments. These spills can be pin-pointed by the same procedures discussed for soil moisture monitoring, thereby allowing ample time to take measures to reduce breach hazard. The approach of studying indigenous water harvesting now widely propagated (Critchley *et al.*, 1994) may also benefit from these simple continuous measuring procedures.

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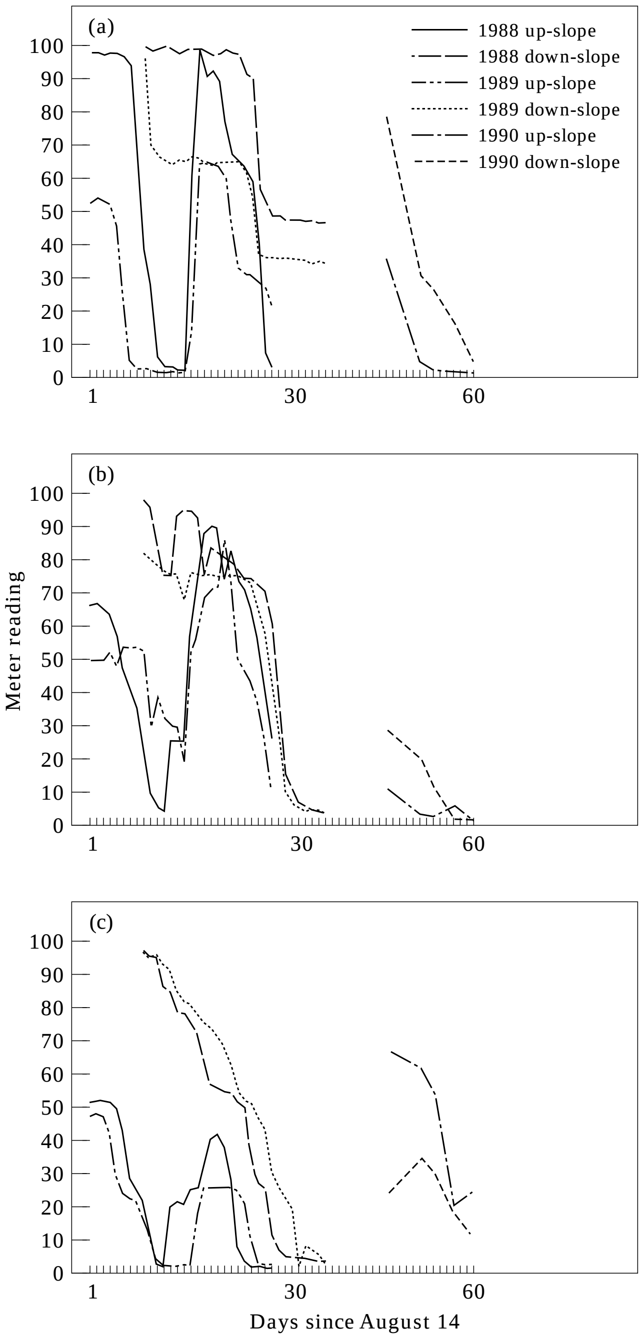

Figure 4. Soil moisture content in the (a) upstream monitoring zone (third–fourth embankment) (b) midway monitoring zone (seventh–eighth embankment) and (c) downstream monitoring zone (twelfth–thirteenth embankment), by measuring location and year (in mean meter readings).

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