

# *Water Harvesting for Upgrading of Rainfed Agriculture*

Problem Analysis and Research Needs



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# Preface

The Stockholm International Water Institute (SIWI) has, as one of its objectives, to generate research in areas of international relevance with particular Swedish interest. One such area is upgrading of rainfed agriculture in tropical environments, an area of enormous relevance for global food security in the next few decades, given that the most rapid population growth and the lowest income countries are to a large degree located in the dry tropical and subtropical climate zones.

Swedish interest in this area dates back to the final selection of prizewinners from the nominations for the International Inventors' Award, launched by the Swedish Inventors Association in the late 1970's. One of the award sections being water, the prize was finally shared between a more traditional invention, a ventilated pit latrine in Zimbabwe, and a non-traditional project involving water harvesting for the upgrading of dryland agriculture in a drought stricken area in India with a starving population.

The interest was further developed at the Department for Water and Environmental Studies at Linköping University in a bilateral cooperation between Swedish scientists and two colleagues in India, Professor Sivanappan at Coimbatore Agricultural University and Dr Datye at Centre for Applied Systems Analysis in Development (CASAD) in Bombay, later including also Dr Anil Agarwal at the Centre for Science and Environment (CSE) in New Delhi.

In the early 1990's the interest broadened to include the research group on Natural Resources Management at the Department for System Ecology, Stockholm University within the project "From knowing to doing", supported by the Swedish Council for Planning and Coordination of Research (FRN) and the Swedish Council for Forestry and Agricultural Research (SJFR). This systems oriented research included a doctoral study on on-farm agrohydrological research analysing the causes behind the Sahelian yield crisis. In recent years, two additional doctoral studies have followed with focus on water harvesting for upgrading rainfed agriculture in East and West Africa respectively, this time supported by the Research Department of the Swedish International Development and Cooperation Agency (Sida/Sarec).

Later, a Round Table discussion in the Swedish Environmental Journal *Ambio* (March 1998) was organized as follow-up of a Special Session at the World Water Congress in Montreal, Canada in September 1997, addressing "Water scarcity as a key factor in food security". The outcome confirmed the need for serious efforts "to achieve substantial increases in food production within a finite amount of rainfall if we are to stand any chance to meet the food security challenge of today".

A workshop on water harvesting at the 1998 Stockholm Water Symposium, organized in cooperation with CSE, India, concluded that a crucial question for poverty eradication is how rainfed crops can be improved by supplementary irrigation based on water harvested from local rainwater or flash floods and stored in small tanks. It was noted that much is to be learnt from traditions in India and Sri Lanka as well as from more recent efforts in China and Japan. "Greening the village" by water harvesting may in fact involve an enormous potential and was projected to have very positive effects also on employment and income.

Parallel to the Swedish involvement in systems research for improved soil and water management, there is a growing understanding among water professionals that absolute water scarcity not necessarily is the factor limiting a doubling or even a quadrupling of food crop yields even in water scarce drylands. Rather, the major constraint is the erratic and unreliable character of tropical rainfall. This understanding is crucial, as it points at a very exciting window of opportunity to improve the livelihoods of rural communities, using innovative and appropriate water resource management techniques. Water harvesting is one of the most promising approaches in this respect.

In view of the involvement of Swedish scholars in analysing the potential of improving yields in dryland agriculture, the evident links to poverty eradication in drought prone regions, and the potential climate change implications in terms of soil-carbon sequestration in savannah agroecosystems, this area might be of strategic research interest for Sweden. SIWI therefore decided to synthesize the current level of understanding in the field of water harvesting for crop production- and to identify key research needs. MISTRA generously offered the necessary funds. The results are presented in this report.

The report is mainly divided into three parts. The first part presents the hydroclimatic constraints and challenges facing farmers, and gives a brief presentation of water harvesting and farmers coping strategies to manage water scarcity. In the second part of the report regional approaches from sub-Saharan Africa, India and China are presented. Based on the financial support available and the possibility to obtain information from literature, it was decided to base the India chapter on literature and the China chapter on a short study visit to Gansu and Hebei provinces. Most knowledge in the field of water harvesting, among the authors of the report, is from sub-Saharan Africa. Therefore the sub-Saharan Africa chapter gives a comprehensive description of water harvesting experiences with emphasis on floodwater harvesting and storage systems supplementary irrigation. The last part of the report reflects knowledge gaps that need to be filled, both regarding technical -, process - and systems research.

SIWI thanks the authors for their dedicated and inspired work. Special thanks go to Dr. Gunn Persson who graciously edited the report. SIWI also expresses its gratitude to MISTRA for the financial support.

Stockholm 30 June 2001

Director Ulf Ehlin

# Executive summary

## ***Food production deficiencies in semi-arid regions***

For sub-Saharan Africa and Southern Asia alone there is an estimated *hidden annual food gap of almost 400 million tons by the year 2020*. According to a global IFPRI (International Food Policy Research Institute) study report, this is the food required above the total sum of projected domestic production and imports, to meet the energy needs of the population. Hunger and poverty are thus predicted to remain a major problem especially in these two regions, both subject to "undernutrition climatology". In these regions, a large proportion of the arable land is located in water scarce areas subject to recurrent dry spells. Water stress caused by such short and recurrent periods of drought during crop growth is a major cause of yield reduction. In the past, misleading "blue water" analyses (focusing only on perennial river flow and accessible ground water) and drought assessments (focusing only on annual cumulative rainfall) have been used as arguments to rule out semi-arid tropical savannah agroecosystems as potential bread baskets. There are several problems with such conventional analyses. The majority of the land users in these areas depend on rainfall for their livelihoods (i.e. green water), not on irrigation based on blue water. In drought prone drylands there are problems both due to rainfall deficiencies (primarily due to poor temporal distribution of rainfall and high evaporation losses), soil problems as well as plant problems, the latter originating from dry spell damages and nutrient deficiency.

The green revolution clearly showed that well regulated crop water access is crucial for stable long-term yield increase. Not only because yield growth is directly related to plant water uptake, but also because secured crop water supply reduces risks for crop failure, thereby increasing farmers' incentives to invest in farm inputs, such as fertilizers, hybrid seed and pest management. Even though irrigation plays a very important role in supplying foods, the potential for increasing water withdrawals for irrigation is considered quite limited. Despite the higher risks of crop yield fluctuations in rainfed agriculture in drought prone areas, it is a safe assumption that the bulk of world food will also in a foreseeable future originate from rainfed agriculture. A significant gain in crop production in rainfed agriculture will therefore have to come from small scale harvesting of water in combination with protective irrigation. Remarkable successes have in fact been witnessed in poverty stricken and drought prone areas in India. Research suggests that there is a *large window of opportunity* in terms of potential gains in crop yields that needs to be analysed. This report provides an analysis of the problematique and an identification of fundamental research needs.

## **Part 1. The problem**

### ***Rain does not infiltrate properly***

Our focus is on semi-arid and dry sub-humid areas where water undoubtedly is a major environmental constraint. In East and South Africa, on-farm grain yields of maize amount merely to some 1 ton/ha, as compared to yields on research stations in the same region that are in the order of 5 ton/ha. With a length of growing season of 75-179 days in these areas, the cumulative potential evapotranspiration for the growing season is 600-900 mm. Rainfall is often lower than this and highly erratic. Severe crop reductions due to dry spells typically occur 1-2 out of 5 years. A dry spell occurs as short periods of water stress, often only a couple of weeks long, during crop growth. In fact, droughts and dry spells constitute a more common cause for crop failure than absolute water scarcity in terms of low cumulative annual rainfall. The reason is poor rainfall partitioning in the sense that the rainfall does not infiltrate

properly due to a combination of human induced land degradation and high intensity rainfall events. The result is *soil water scarcity in the root zone*. But, in addition, there are remarkable evaporation losses from dryland agriculture where soil evaporation on average accounts for 30-50 % of the rainfall. This is very high in comparison with many farming systems in the world and is partly due to low leaf area of sparsely cropped systems. At the same time, surface runoff may be as much as 10-25 % of the rainfall and groundwater recharge sometimes as much as 10-30 %. The result is that the biomass-producing transpiration constitutes a mere 15-30 %, sometimes only some 5 % of the rainfall. The implication is that at present, on average for semi-arid rainfed farming systems in sub-Saharan Africa, 70-85 % of the rainfall is not used in agricultural biomass production.

### ***The water in the root zone is not fully used***

For tropical cereals, the on-farm water requirement, in form of evapotranspiration or total amount of evaporated water, per unit of crops produced ranges between 1,500 and 3,000 m<sup>3</sup>/ton grain and can occasionally amount to more than 5,000 m<sup>3</sup>/ton. Even though such water use efficiency estimates are important (e.g. as a means of identifying opportunities to produce more crop per drop), the farmer seldom recognizes the task as to maximize water use efficiency as a primary goal, but rather to assure a stable supply of water to the crop throughout the crop season.

In the report an analytical tool is offered for assessing how much the yields can realistically be increased within a given rainfall depth. The analysis of maize based on synthesized averages suggests that there is a large scope for improving yield levels within the available rainfall. Improving plant water uptake capacity will depend largely on the availability of plant nutrients and organic matter in the root zone. There is therefore a close link between plant water and soil nutrient availability.

### ***Water harvesting is an ancient technique***

Basically, four biophysical determinants contribute in reducing yields: hydroclimatic deficiencies, soil deficiencies, plant damage-related deficiencies and nutrient deficiencies. Hydroclimatic deficiency sets the boundary conditions of potential yields. Adding extra water is one way to compensate for soil water deficiency and to reduce the risk for plant damage during dry spells. The source of such water may be water harvesting, defined as the collection of water for productive use. It is used as an umbrella term for a range of methods of collecting and conserving rainwater and runoff water.

The first use of water harvesting techniques is believed to have originated in Iraq over 5000 years ago, in the so-called Fertile Crescent, which is believed to be the very cradle of agriculture. In both India and China, the technique was in use more than 4000 years ago. There are two major forms: *in situ rainwater harvesting*, collecting the rainfall on the surface where it falls, and *external water harvesting*, collecting runoff originating from rainfall over a surface elsewhere. In order to enable supply of harvested surface runoff flow according to human needs over time, storage is inevitable, which can be done in various types of surface and sub-surface storage systems.

For the application of the harvested water there is a differentiation between supplemental or protective irrigation which is linked to a storage component and involves application of water to the crop a few times during the crop season, and runoff farming which involves direct diversion of overland surface water flow onto the field. The method of application differs according to the monetary investments linked to it. Runoff collection may involve land alterations, soil compaction etc., to increase the runoff from the area.



**Box 1. The potential role of water harvesting**

*A task of fundamental existential importance is to assess the potential role of water harvesting for improved on-farm crop yields, i.e. investigate to what extent farmer's actual yields are constrained by water scarcity possible to mitigate through improved and appropriate management, in order to move the resource poor farmer's reality closer towards what can be produced.*

**Focus has to be put on the farmer's reality**

In smallholder farms, in the semi-arid tropics, droughts and dry spells result on average in yield reductions four or five seasons in ten. Any effort of improving land productivity must take into account the entrepreneurial risks perceived by the farmers trying to make their living from such systems.

It is not surprising that a farmer will not invest in fertilizers, improved varieties or pest management where he risks crop failures say two to four years out of ten. However, recent research suggests that the prospect of doubling or even quadrupling yields is realistic even within the context of high risk for meteorological droughts. Such large yield increases cannot be achieved with water management alone, but has to be linked with simultaneous soil fertility management, pest management, crop rotations, capacity building among farmers, and extension services.

Development of protective irrigation has to involve not only the engineering measures but also a proper evaluation of the social factors surrounding a system. It has to fit within the production-system as a whole, the workload involved and the number of family members. No farmer will invest in his land or crop should the risks involved in doing so be too high. Every household is ultimately left to fend for itself, making tailored farm-level solutions for risk minimisation an important entry point in efforts of improving rural livelihoods.

**Part 2. Regional approaches****Sub-Saharan Africa - rapidly growing interest**

In this region, over 90 % of the farmers depend on rainfed agriculture. In modern time, the interest in water harvesting grew out of the meteorological droughts in the 70's and 80's and the opportunities documented in the successful experiences from the Negev desert in Israel. However, for decades the focus was primarily set on erosion control, aiming at reducing soil losses. Swedish support to the agricultural sector is no exception in its concentration on soil conservation measures. Still today desertification (presently interpreted as severe land degradation) is given more international interest than the enhancement of crop production in water-scarce regions. Within-field systems of water harvesting were classified as soil and water conservation. The infiltration enhancement that went with soil conservation measures was more or less a side effect. Actually in most cases the runoff collected, was efficiently disposed of through cut-off drains and dissemination of graded contour structures. Runoff was perceived as an enemy - interestingly enough not primarily to Man or the crop, but to the soil. Slowly, the focus is now being shifted toward land productivity enhancement. A century of soil conservation has had fantastic results in controlling soil erosion in many, especially steep sloped, tropical areas. But, soils have been stabilized while yields are at status quo or even declining. Thanks to the well-conserved land in many tropical farming systems, runoff management techniques that see runoff as a friend and not a foe in crop production, can probably produce quick results.

Systems for within-field runoff collection and redistribution are basically of two kinds: those sacrificing part of the crop field to harvest runoff and bringing it to the plants (strip cultivation, micro catchments, pitting, demi-lunes, infiltration trenches) and those avoiding runoff by maximising infiltration (conservation tillage, moist retention/terracing). Runoff farming is based on several techniques, covering runoff collection from roads or compacted surfaces, catching runoff within bunds from land adjacent to the field, or by catching spate flow from rivulets and large gullies.

In this region, water harvesting for crop production is nothing new - there are numerous indigenous and more modern *techniques practised*. The most common are in situ water conservation and runoff farming, while floodwater harvesting and especially storage systems are less common. *The question is why they are not adopted on a larger scale.*

The gap in the understanding of adoption criteria is very wide and should include issues like biophysical preconditions for system function, socio-economic preconditions, market issues, land tenure issues, and the critical issue of human capacity. Another question is what external services farmers must expect when developing their production systems. There has been a tendency over the past 10-20 years in development efforts to be reluctant in relying on external knowledge and investments in rural development. Water harvesting is an excellent test case in trying to find the dependency balance between externally trained expertise and indigenous expertise. How to blend indigenous knowledge and the need for expertise is a huge challenge for rural development in sub-Saharan Africa, which specifically affects water harvesting development.

### ***India - revival of ancient technique***

In this region, 75 % of the agriculture is rainfed and most parts of the country receive rainfall no more than 50 days in short but heavy showers. Water harvesting is an ancient technique dating 4,000 - 5,000 years back, and currently under revival. Rainwater harvesting is now rapidly expanding in response to an escalating water scarcity. Ranges of water harvesting techniques have been developed for both drinking water supply and irrigation, to be found in the arid plains, the semi-arid plains, the floodplains and in the hill/mountain regions. The Centre for Science and Environment in New Delhi has recently published a state of the art report on the "dying wisdom" of indigenous rainwater harvesting techniques in India. A number of *success stories of greening of villages* have been developed in response to the severe droughts of the last three decades. In Rajasthan, Gujarat and Madhya Pradesh, communities that have undertaken water harvesting have a completely different livelihood situation compared to those without water harvesting. The projects have often been initiated by individual persons (especially famous are Anna Hazare and V Salunke) or by NGO's. A problem is that local institutions needed often are inconsistent with the predominant governmental structures and institutional set-up prevailing in the country.

### ***China - way of curbing rural exodus***

In China, water harvesting has been conducted for at least a millennium in the western part. Today, rainwater harvesting is seen as a major component in curbing the rural exodus and controlling severe erosion. The projects now developing are *mega projects*, aiming at serving multimillion populations. In the Gansu province the "121 project" was initiated a decade ago, referring to 1 green house, 2 tanks and 1 mu (1/15 ha) cultivated/irrigated land per family. The objective is to ensure farmers' economic stability and living standard. Water harvesting systems are adopted to make drinking water available and stabilize farm yields through supplementary irrigation. Rainwater is harvested from a variety of compacted surfaces and the irrigation practices follows the principle "*irrigating the crops and not the land*". Water is often applied manually with a bucket and a cup, pouring water directly on the plant's stem. By

the end of 1999, 1.23 million tanks had been built and 190 000 ha land received 2-3 applications of irrigation water. Harvests have proven to increase by 40 %. Cash crops and fruits that could not previously be grown in the region have given the farmers an improved economic situation.

In the hilly and severely eroded landscape in the Hebei province a vast greening project with the aim of *reclaiming eroded hillslopes and degraded farmland to forests* is ongoing. Water harvesting is used to secure the survival of the seedlings. A number of pilot projects with government support are run in the area.

What is special for the Gansu province of China is the loess soils with a water holding capacity much greater than in many other semi-arid regions of the world. Although there is much to learn from these Chinese implementations both from their performance and for the consequences of applying systems on such a large scale, the transferability of these water harvesting structures and models is somewhat limited.

## Part 3 Research gaps

### ***Biophysical and socio-economic research needs***

The final chapter addresses the research gaps in terms of both biophysical and socio-economic research. Issues in need of analysis and clarification include:

- System adaptation of water harvesting techniques as such (system design, how to reduce seepage, evaporation and other losses, catchment treatments)
- Hydrology at farm level of production systems using water harvesting techniques
- System fit and transferability (biophysical and socio-economic criteria)
- Synergies in farming system development (linking crop water securing with soil fertility management, tillage practices, irrigation management, etc.)
- Consequences of upscaling water harvesting and protective irrigation to watershed scale (including upstream/downstream effects)
- Integration with infrastructure development (legal issues, land tenure, poverty links and cost benefit analyses)
- Impact of diverting water flows on ecosystem services at watershed scale
- Transferability of methodologies and technologies between regions and the influence on adoption among farmers of management approaches, institutional setups, land and water ownership, socio-economic constraints, and capabilities.

### ***Carbon sequestration - a fringe benefit***

There is finally a highly interesting link to climate change research in the fact that tropical soils may play an important role as carbon sinks in the efforts of reducing the emissions of greenhouse gases. All water harvesting systems have for objective, explicitly or implicitly, to significantly increase carbon sequestration through a boost in biomass productivity. The semi-arid tropical soils may be particularly interesting in view of the opportunities of significant increases in organic matter contents in the soil. Current yields are only 10-20 % of the on-farm potential. Increased farm crop yields would result in a significant rise in root production and above ground organic matter.

### ***Research area of strategic interest for Sweden***

Systems oriented research on water harvesting for upgrading of rainfed agriculture in the semi-arid regions could be a research area of strategic interest for Sweden. Not only would research and development efforts on increased biomass production concur with the Swedish

development agenda to reduce hunger and poverty among the poorest and to improve environmental conditions by reducing "desertification", but it would also concur with the objective of contributing to the reduction of human induced climate change.

# The hidden food gap

*"Hungry mouths depend on water for agriculture which provides not only the food to eat but the income with which to buy it..."*

*FAO. Water for Food pamphlet, March 2000*

Some eighty percent of the world's agricultural land is rainfed, contributing to at least sixty percent of global food production. Even though irrigation plays a very important role in supplying foods, the potential for increasing water withdrawals for irrigation is considered quite limited. Thus, production increases from irrigated agriculture largely depend on the possibility to produce more biomass per unit of water already withdrawn for irrigation purposes (more crop per drop of irrigated water). Despite the higher risks of crop yield fluctuations in rainfed agriculture, especially in drought prone areas, it is a safe assumption that the bulk of World food will also in a foreseeable future originate from rainfed agriculture.

Market-based import needs of developing countries have been estimated by IFPRI (International Food Policy Research Institute), based on grain production models (Conway, 1997). Comparing production with projected market demand for the year 2020, IFPRI concludes that "the developing countries as a whole will not be able to meet their market demand.....(T)he total shortfall is some 190 million tons. At the same time, the model predicts this can be met by imports from the developed countries.....For the developed countries the increase in net exports represents an 11 percent growth in cereal production."

In addition to the market-based import needs of developing countries, the same study however reports *a hidden food gap* in terms of cereal requirements to meet the energy needs of the population above the sum of domestic production and imports. This food gap is estimated at almost 400 million ton annually for sub-Saharan Africa and South Asia plus another 150 million tons for the other regions. This is nearly three times the predicted import of food.

Hunger and poverty are thus predicted to remain a major problem especially in sub-Saharan Africa and South Asia. In South Asia there is little room for expansion of agricultural land, and in sub-Saharan Africa there are problems with soil and terrain constraints and existing land reserves are largely under forest and conceived as non-accessible. As a result, increased crop production has to take the form of yield increases.

Furthermore it has been shown that the largest challenges of poverty-related undernutrition are found in the arid, semi-arid and dry-humid regions of the developing countries (Falkenmark and Rockström, 1993). For example, sub-Saharan Africa and South Asia, having the largest hidden food gap, also host the world's largest proportion of drought prone areas, 44% and 43% of the land areas, respectively. Yield levels of staple food crops are extremely low, for sub-Saharan Africa oscillating in the range of 1 t ha<sup>-1</sup>.

These regions are exposed to what may be spoken of as a special "undernutrition climatology" manifested as low per capita calorie level and persistent high rates of population increase (Ambio Round Table, 1998). The climate is characterized by complex *climatic deficiencies*, manifested as water scarcity for rainfed crop production. On the one hand there are challenges related to the rainfall, amount as well as distribution. The climate is largely semi-arid and dry sub-humid with a long dry season and a short wet season. Rainfall is highly unreliable, with strong risks of dryspells during crop growth even during good rainfall years. Inter-annual fluctuations are high due to the characteristics of the atmospheric circulation and the links to the ENSO phenomenon in the Pacific Ocean. Spatial rainfall fluctuations are high as well, related to the convective character of the erratic and high intensity tropical rainstorms, which further increases the risks farmers face in their entrepreneurial land management efforts.

On the other hand, there are *soil deficiencies* in terms of both soil infiltrability and soil water holding capacity: all the rainfall does not infiltrate, and what infiltrates does not stay in the

root zone but passes onwards towards the underlying aquifer. And thirdly, there are *plant deficiencies* in the sense that the dryspells tend to limit the root development of the plants, reducing their soil water uptake capacity. Field studies in sub-Saharan Africa indicates a plant uptake capacity of only in the order of 10 - 20 percent of the soil water in fact available in the root zone (Ambio Round Table, 1998).

Water stress during crop growth, even during short periods of a couple of weeks, is a major cause of yield reduction. It is well known that a properly regulated plant access to soil water is important for crop yield increases. This was clearly demonstrated by "the green revolution", for which optimal supply of water was a basic condition. As a consequence it was most successful in the regions where irrigation was already well established. The conclusion is that the most significant gain in crop production will have to come from *small-scale harvesting of water*, particularly in sub-Saharan Africa where 95 percent of the farmers depend on rainfed agriculture, and where the small rivers are empty during the dry season and the large rivers are international, calling for multinational agreements.

The potential success of water harvesting in poverty stricken areas has been amply exemplified in India already in the 1970's. One wellknown case is the Ralegan Siddhi village in the heart of a drought-prone area of Ahmednagar District in the Deccan Plateau of Maharashtra. The key driver behind the "revolution" was Anna Hazare, a retired army officer, who "transformed a derelict village from poverty to plenty.....brought about within a few years, entirely through inspired community effort and local leadership" (Pangare, 1992). The project was based on rainwater harvesting in dry rivulets by bunds, recharging the wells.

Another case is the Naigaon village in Pune district, also in Maharashtra where V Salunke and his wife were the driving force for an integrated micro-watershed development. The runoff from 16 hectares of barren land was arrested, led to a percolation tank and distributed to farmers on an equity basis, related to the needs of a family. Salunke formulated the concept of Pani Panchayat or water council, for which he was awarded the International Inventory Award in Sweden in the late 1970's. This "is a philosophy of equity that encompasses all aspects of water harvesting and equitable water resources distribution" (Pangare and Lokur, 1996).

The dominance of vulnerable crust-prone soils in large parts of the dry climate regions also implies that there is plenty of water flowing on the land surface that can be harvested before it evaporates again or runs off to the river. Ongoing research studies at Stockholm University indicate that a three-folding of the yield on the farmer's field is achievable with quite simple means: harvesting runoff, storing it in small farm ponds or micro-dam reservoirs, and applying supplementary irrigation during dry spells when the plants suffer from water stress.

The size of the food gap and the emerging famine problems if the gap is not filled constitutes a massive regional and potential global problem of the near future. The consequences of population related environmental degradation due to desperate efforts of feeding growing rural families, have been well documented, not least through the Swedish involvement in the work leading up to the UN Convention to Combat Desertification (where desertification now is clearly classified as severe land degradation). The ultimate effect of the deterioration of the physical livelihood basis for rural farming families (soil, water and vegetation) related to poor land management practices, is urban migration. The current trend of explosive expansion of urban shantytowns has its own enormous health and poverty problems, which tend, if not to spill over to, at least to trigger conflicts and refugee fluxes. Attacking the root cause to this chain of events (the uprooted rural livelihood basis) is probably one of the most sustainable development options available in many tropical developing countries.

Improving land management through wise water resource use in tropical drylands thus has clear strategic connotations, from a European perspective, in order to contribute to socio-economic development, social stability, and poverty reduction and to reduce environmental degradation.

Recent research suggests that there exists a *large window of opportunity* to reverse the worrying agricultural trend among resource poor small-scale farmers in water-scarce tropical regions (Rockström and Falkenmark, 2000). This window needs to be analysed further, in order to increase rural crop production in famine struck dry climate areas.

This report provides an analysis of the problematique and an identification of fundamental research needs.

# Part I. The problem

## Why farmers yields are so low

*"What realistic hydrological options are there to improve on-farm yields, and perhaps most importantly, how much can yields realistically be increased?"*

Global freshwater assessments, focusing only on so-called "blue" water flows (river and groundwater flow), generally suggest a link between water scarcity and socio-economic development constraints. In such assessments (e.g. the UN Comprehensive Freshwater Assessment, UN, 1997; and the World Water Vision, Cosgrove and Rijsberman, 2000), it is concluded that a large number of countries, hosting some 30 - 50 % of the world population, will be facing water scarcity problems over the next generation. This analysis is seen as particularly worrying, as a large proportion of developing countries with the highest populations growth rates, fall within the most water scarcity hit countries (e.g. in S Asia and sub-Saharan Africa). For example, countries facing water stress in 2025 in S. Asia and sub-Saharan Africa will have to feed an additional 400 million people by 2025 (Dyson, 1996).

In both these regions a large proportion of the arable land is located in water scarce areas characterized by erratic, high intensity rainfall with recurrent droughts and dry spells. For sub-Saharan Africa it has been estimated that 44 % of the land surface is submitted to high risk of meteorological droughts – the highest continental figure on Earth (Barrow, 1987). Various definitions of meteorological droughts exist, here defined as a prolonged period of rainfall below normal resulting in a significant reduction in cumulative seasonal rainfall. Definitions of "below normal" range from less than 80% of the long term average of seasonal rainfall to the long term average subtracted by two standard deviations (Agnew and Anderson, 1992).

**Table 1.** *Estimated proportion of land affected by meteorological droughts*

Region	Land affected by meteorological droughts (%)
South East Asia	2
Europe (mainly Spain)	8
South America	17
East and Northern Asia	17
North America	20
Australia	28
Central America	32
South Asia	43
Africa	44

Source: Barrow, 1987

Generally, "blue" water analyses (as mentioned above) combined with "drought" assessments (Table 1), are used as arguments to rule out semi-arid tropical savannah agroecosystems as potential breadbaskets. These so-called drylands, are generally defined as water scarce, and often denoted as marginal areas in the context of agricultural potential.

There are several problems with such conventional analyses. First, the majority of land users in semi-arid tropical farming systems of the world depend on rainfall for their livelihoods, and not on irrigation using "blue" water. Secondly, it is impossible to carry out assessments of



water resources for food production on a country scale, when hydroclimates vary enormously within a country. Finally, it is common to associate drought prone drylands with steppes and desert-like environments. These are arid lands with  $< 200$  mm of annual rainfall, and here nobody is growing any rainfed foods, and instead sophisticated nomadic societies have developed (e.g. the Masai of Eastern and Southern Africa, and the Touaregs of Western Africa). These areas are not and will not become interesting from a food production point of view (even if some very successful water harvesting methods have been developed in arid areas of, e.g. the Negev desert primarily to enable livestock to survive).

Our focus is on semi-arid and dry sub-humid agroecosystems where sedentary farmers make their living from the land. These areas receive between 400 - 1000 mm of annual rainfall that are very substantial volumes of water.

However, irrespective of the above, there is no doubt that water is a major environmental constraint in developing countries where a majority of the population still make their living from the land. And, this constraint is most acute in semi-arid and arid areas, which constitute over one-third of the entire land surface of the Earth (UNEP, 1992).

Yield levels of staple food crops such as maize, millets and sorghum, are very low in these areas, generally oscillating around  $1 \text{ t ha}^{-1}$  and even lower for sub-Saharan Africa. The question is why farmers' yields are so low? And more importantly for this study, are low yields a result of water scarcity (suggesting that the semi-arid lands really are to be considered as marginal), or are they a result of other factors?

This chapter analyses water flow partitioning in semi-arid savannahs where sedentary farming is practiced, in order to shed some light on the hydrological challenges and opportunities facing farmers. The question raised is whether there is water available to significantly increase food crop yields in semi-arid and dry sub-humid tropical areas using water harvesting.

## Hydroclimatic characteristic of semi-arid tropics

Rainfall varies from 400 - 600 mm in the semi-arid zone, and has an approximate range of 200 - 1000 mm from the dry semi-arid to the dry sub-humid zone. The length of growing period (LGP) ranges from 75-120 days in the semi-arid zone, and 121 - 179 days in the dry sub-humid zone, which is determined by the relation between rainfall and the potential evapotranspiration (PET). PET varies between 1500 - 2300 mm per year. Rainfall in the semi-arid areas exceeds PET only during 2 - 4.5 months (Kanemasu et al., 1990). On an annual basis semi-arid savannahs are characterised by  $PET > \text{annual rainfall (P)}$ , with the ration  $P/PET < 0.65$  in the "wettest" dry sub-humid zone (UNESCO, 1977). Daily PET levels are high, ranging from 5 - 8 mm day<sup>-1</sup> (FAO, 1986). This gives a cumulative PET for the growing season of 600 - 900 mm, which explains the limited water surplus recharging aquifers and rivers.

Rainfall is highly erratic, and most rain falls as intensive, often convective storms, with very high rainfall intensity and extreme spatial and temporal rainfall variability. The result is a very high risk for annual droughts and intra-seasonal dry spells. The annual (seasonal) variation of rainfall can typically range from a low of 1/3 of the long term average to a high of approximately double the average; meaning that a high rainfall year can have some 6 times higher rainfall than a dry year (Stewart, 1988).

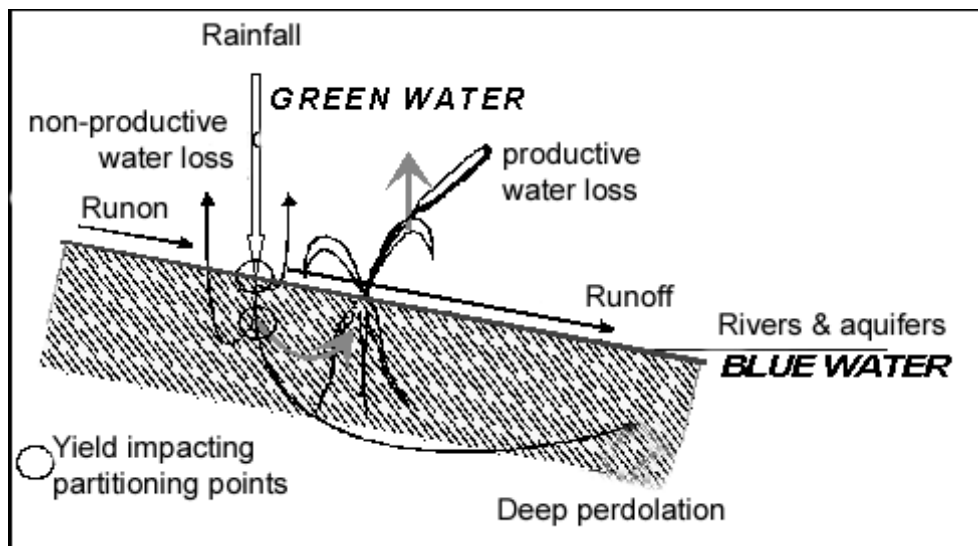
Statistically in a semi-arid region, severe crop reductions caused by a dry spell occur 1-2 out of 5 years, and total crop failure caused by annual droughts once every 10 years. Our own ongoing research in West and East Africa suggests that short dry spells resulting in crop water stress over periods of 2-4 weeks, occur almost every rainy season, negatively affecting crop growth. This means that the poor distribution of rainfall over time often constitutes a more common cause for crop failure than absolute water scarcity due to low cumulative annual rainfall.

This is why it is important to distinguish between droughts and dry spells. An agricultural drought occurs when the cumulative plant available soil water is significantly lower than cumulative crop water requirements, i.e. there is absolute water scarcity. While a meteorological drought is caused only due to climatic fluctuations, poor rainfall partitioning resulting in soil water scarcity in the root zone causes an agricultural drought. Agricultural droughts can be man-made, due for example to poor land management resulting in low infiltration, low water holding capacity and poor plant water uptake capacity. A dry spell occurs as short periods of water stress, often only a couple of weeks long, during crop growth. Such short periods of water stress can have a serious effect on crop yields if occurring during water sensitive development stages like, e.g. during flowering (Rockstrom and de Rouw, 1997).

In summary, semi-arid savannahs receive relatively large volumes of rainfall (on average more than Stockholm, with an annual rainfall of  $\sim 550 \text{ mm yr}^{-1}$ , and much more than the Swedish Archipelago with merely some  $\sim 350 \text{ mm yr}^{-1}$ ). The largest differences compared to the temperate zone, are (1) the high rainfall intensity and large variability over time, resulting in highly unreliable rains manifested as dry spells, and (2) the high potential evapotranspiration rates (of some  $4\text{--}8 \text{ mm d}^{-1}$ ). It is worth reminding though, that dry spells and even droughts are not entirely uncommon also in temperate regions. Farmers in, e.g. Eastern and Southern Sweden, often complain of early season dry spells during germination, which seriously jeopardize the economic returns of their heavy input investments.

## Where does the rainwater go?

The distinction between "blue" and "green" water flow in the hydrological cycle is a practical analytical tool for analyses of water flow partitioning on the local, regional or global scale (Falkenmark, 1995). "Blue" water flow is the total runoff including the sum of surface runoff – produced at the partitioning of rainfall at the land surface – and groundwater recharge – produced at the partitioning of soil water in the soil profile (Figure 1).

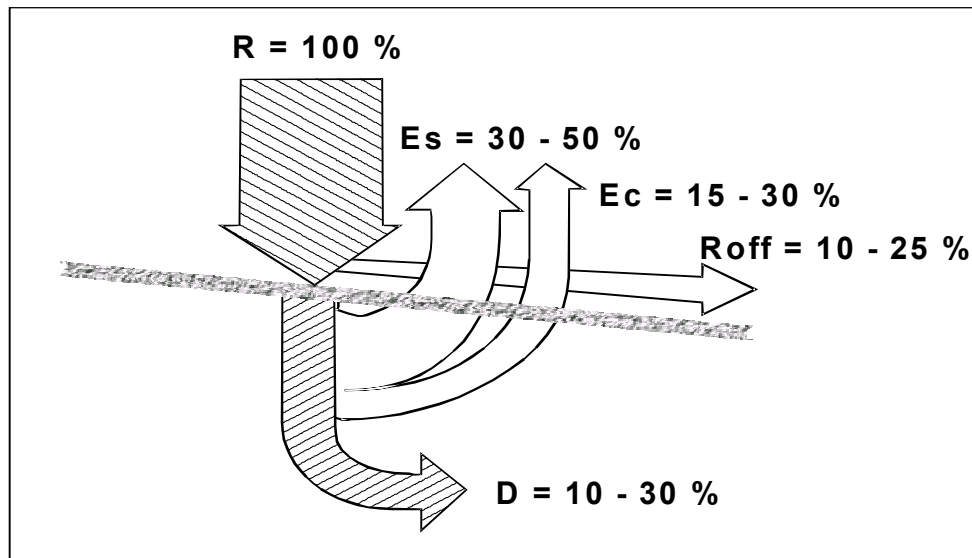


**Figure 1.** Agrohydrological flows indicating "green" and "blue" water flows and the two partitioning points determining the amount of plant available soil water in the root zone. The first point divides the rainfall and run-on between surface runoff, infiltration and direct evaporation losses from the soil surface; the second point divides the soil water between plant water uptake, soil evaporation and drainage.

”Green” water is the return flow of water to the atmosphere as evapotranspiration ( $ET$ ), which includes a productive part as transpiration ( $T$ ) and a non-productive part as direct evaporation ( $E_s$ ) from the soil, lakes, and from water intercepted by canopy surfaces (Rockström, 1997).

Figure 2 gives an indication of the partitioning of rainfall into different water flow components in rainfed agriculture in semi-arid savannahs in sub-Saharan Africa. Soil evaporation accounts for 30 – 50 % of rainfall (Cooper et al., 1987; Wallace, 1991; Rockstrom, 1997), a value that can exceed 50 % in sparsely cropped farming systems in semi-arid regions (Allen, 1990). This is a very high range, compared to many farming systems in the world, and is a result of the agrometeorological conditions under which crop production generally is conducted; high net solar radiation and high air temperatures, significant wind in sparsely cropped systems (Leaf Area Index, LAI, generally  $< 2 \text{ m}^2 \text{ m}^{-2}$ ), resulting in high turbulence.

Surface runoff is often reported to account for 10 – 25 % of rainfall (Casenave and Valentin, 1992; Penning de Vries and Ditéye, 1991). The characteristics in drylands of frequent, large and intensive rainfall events, result in significant drainage, amounting to some 10 – 30 % of rainfall (Klaij and Vachaud, 1992).



**Figure 2.** General overview of rainfall partitioning in farming systems in the semi-arid tropics of sub-Saharan Africa.  $R$  = Rainfall,  $E_c$  = Plant transpiration,  $E_s$  = Evaporation from soil and through interception,  $R_{off}$  = Surface runoff,  $D$  = Deep percolation.

The result is that productive green water flow as transpiration in general is reported to account for merely 15-30% of rainfall (Wallace, J., pers.comm.). The rest, between 70 – 85 % of rainfall, is “lost” from the cropping system as non-productive green water flow (as soil evaporation) and as blue water flow (deep percolation and surface runoff).

Figure 2 thus indicates that there is a high risk of soil water scarcity in crop production, irrespective of spatial and temporal rainfall variability. Moreover, this scarcity is often human induced as a result of long-term land degradation.

In the commonly practiced subsistence farming systems, where traditional shifting cultivation practices have been abandoned in favour of continuous cultivation without any external inputs of fertilisation, the productive green water flow component can be even lower than indicated in Figure 2. For example in a sparsely cropped millet system, on-farm experiments in Sahel (Niger) has shown from field measurements and water balance modelling that merely 4 – 9 % of the seasonal rainfall (ranging between 490 – 600 mm) returned to the atmosphere as transpiration. The cumulative “loss” of soil evaporation and deep percolation amounted to

some 400 – 500 mm (Rockstrom et al., 1998). This "lost" water would be sufficient to produce 4-5 reasonable crop yields (assuming roughly 100 mm of transpiration flow for a grain yield of 700-1000 kg ha<sup>-1</sup>) if the totality was allocated as plant transpiration.

The above indicates that major biophysical problems encountered in semi-arid farming systems are (1) a poor distribution of the rainfall resulting in short periods of crop water stress, and (2) soil structural constraints (crusting and compaction) and poor soil fertility.

Soil fertility and water constraints are closely related. Plant nutrient deficits result in a very sparse canopy cover and a weak root system, which in turn means that the crop is unable to take advantage of the available soil water during the periods of sufficient rainfall.

## Harvesting of water

Water Harvesting (WH) is usually employed as an umbrella term describing a range of methods of collecting and conserving various forms of run off water originating from ephemeral water flows produced during tropical rainstorms. In its broadest sense, WH can be defined as the collection of water for its productive use (Siegert, 1994). WH includes a sample of methods used to improve the use of rainwater at a specific site before it leaves a geographical region/space. Methods used include -1) those that improve the infiltrability of water into the soil, 2) technical implementations that prolong the duration of occurrence of the water on the spot of infiltration, or 3) means of storage of water which can be tapped over time.

Several definitions of water harvesting have been suggested (Sivanappan, 1997):

- Geddes, University of Sydney: "The collection and storage of any form of water either runoff or creek flow for irrigation use".
- Meyers of USDA (USA): "The practice of collecting water from an area treated to increase runoff from rainfall and snow melt".
- Currier, USA: "The process of collecting natural precipitation from prepared watershed for beneficial use".
- Sivanappan, R.K.: In Indian and African arid and semi-arid contexts: "WH means using the erratic rainwater for reusing and recharging purposes".

## On-farm yield gaps

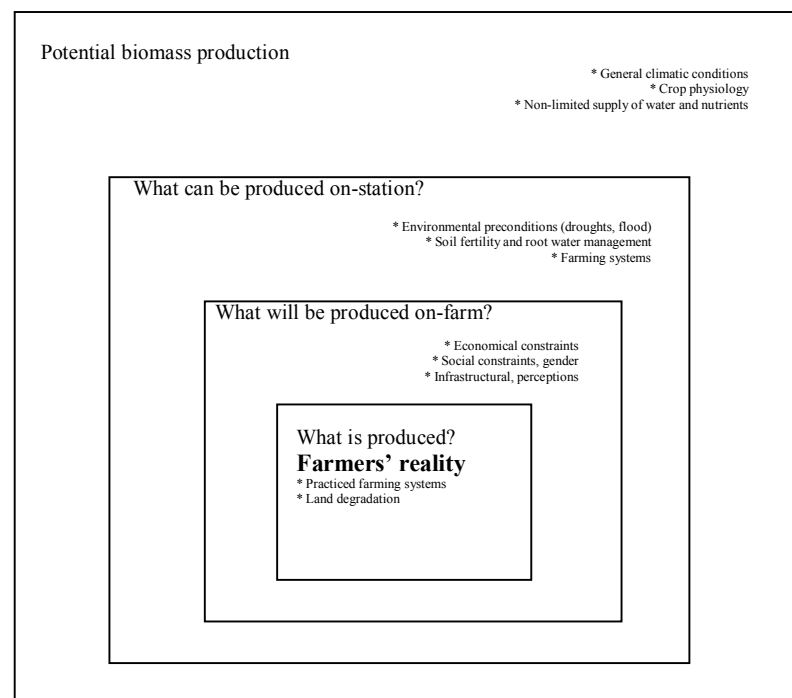
On-farm cereal food yields in semi-arid tropical farming systems are generally a factor 4 - 8 times lower than on-station yields experienced under similar hydroclimatic conditions (the term on-farm means production on farmers fields while on-station is production on a research station). On average, on-farm yields of maize in, e.g. E. and S. Africa amount to some 1 t ha<sup>-1</sup>, with on-station yields in the order of 5 t ha<sup>-1</sup>. However, more often than not, small-scale farmers experience a stable yield climax of 0.5 t ha<sup>-1</sup>, and commonly commercial farmers in adjacent areas experience yield levels of 8 t ha<sup>-1</sup>. The high yield levels among commercial farmers are explained by intensive use of inputs, e.g. improved hybrid seed, fertilisers, pest management, supplemental irrigation and the systematic use of advanced management operations.

The biophysical determinants of crop yields can be divided according to three agrohydrological deficiencies contributing to yield reductions (Rockstrom and Falkenmark, 2000):

1. Hydroclimatic deficiencies: including seasonal rainfall totals, variability of rainfall in space and over time, and the potential evapotranspiration (PET)
2. Soil deficiencies: including soil texture, soil structure, depth of root zone, slope, and chemical properties of the soil (e.g. salinity and sodicity).
3. Plant deficiencies: Include soil nutrient availability, crop species, pests and diseases, and land management techniques.

Hydroclimatic deficiencies set the boundary conditions of potential yields, and are manifested as low cumulative rain, meteorological droughts and dry spells. Soil deficiencies are manifested by low soil infiltrability and poor water holding capacity of the soil. Plant deficiencies are manifested by poor plant water uptake capacity, due to weakly developed roots and canopies, in turn related to, e.g. soil nutrient deficiencies.

The potential yield for a given crop and hydroclimate (assuming no deficiencies) is largely determined by climatic factors like radiation and temperature (de Wit, 1958). The maximum yield is achieved when the deficiencies above are reduced to a minimum for a given crop and agroecological setting. But, farmers generally do not harvest maximum yields, but are submitted to the reality of biophysical deficiencies (determining what can be produced) and they are constrained by socio-economic opportunities (determining what will be produced). Finally, as outlined in Figure 3, what actually is produced on-farm will also be affected by the practiced farming system (e.g. crop rotations, implements used, timing of farm operations) and the state of land degradation on-farm (compared to on-station).



**Figure 3.** Conceptual distinction between potential yields, attainable yields (on-station yields), yield levels possible to achieve on-farm and the farmers' experienced yields.

The question raised here, in order to assess the potential role of water harvesting for improved on-farm crop yields, is to what extent farmers' actual yields are constrained by water availability (determining the potential of satisfying crop water requirements) and by environmental preconditions (affecting what can be produced). If crop yields are strongly constrained by environmental preconditions, such as occurrence of droughts, and/or by water resource limitations, i.e. there is not enough rain to support crop water requirements, then obviously water harvesting has little to contribute. But, on the other hand, if there is a potential of producing high yielding crops, and if constraints are manageable (soil infiltrability, soil fertility etc.) then water harvesting may play a role in moving from the farmers' reality towards what actually can be produced.

## Crop production per unit of evaporated water

Plant transpiration occurs when canopy stomata open to capture atmospheric carbon dioxide. It has been shown that this unavoidable "loss" of water through the plant is linearly proportional to biomass growth for a given hydroclimate under non-stress conditions and over the yield range from on-farm to maximum yields we are discussing here (Ritchie, 1983).

The slope of the transpiration to biomass growth line, gives the transpirational water use efficiency, i.e. the ratio of the amount of carbon fixed by a plant per unit of water transpired ( $WUE_t$ ) (gr dry matter per mm of water). Improving  $WUE_t$  is often discussed as an interesting avenue of producing more food per unit of water, and is a good indicator of biophysical preconditions for agricultural production in different hydroclimates. It has been shown that  $WUE_t$  for a given crop decreases as the dryness of the air or the saturation deficit of the air ( $D$ ) increases, and that the product  $WUE_t D$  is conservative among species groups (Ong et al., 1996). As semi-arid tropics generally have a high saturation deficit (i.e. dry air) compared to wet temperate (and relatively humid) areas, more water will be needed to produce the same amount of carbon (given by the fact that carbon concentrations in the air will not differ between zones). Now this would imply that more water (transpiration) is needed per unit grain yield in, e.g. East Africa than in, e.g. Sweden. This would be true for the same crop species, but as  $C_3$  crops have a much lower  $WUE_t D$  ( $\sim 4$  kg carbon  $mm^{-1}$  kPa) compared to  $C_4$  crops ( $\sim 8$  kg carbon  $mm^{-1}$  kPa) the transpirational WUE will be relatively equal for, e.g. wheat in Sweden and, e.g. maize in Kenya ( $\sim 2$  kg  $mm^{-1}$ ).

The implications of the above is thus that one cannot rule out semi-arid tropical regions as potential bread baskets on the basis that more water is needed to produce a unit crop compared to temperate regions like Sweden. To put it in a very simplified manner; in general the water requirement, of productive green water as plant transpiration, to produce a unit of food, does not differ significantly for most cereals on Earth.

Due to the conservative nature of  $WUE_t$  and to the importance of other flow components in the tropical water balance (runoff, evaporation, drainage) Gregory (1989) suggested that water use efficiency (WUE) should, for management purposes, primarily be analysed from the perspective of all water flows (i.e. how much crop yield is produced per unit rainfall, evapotranspiration, runoff and drainage).

Empirical research has shown that there is likewise a linear relationship between evapotranspiration (ET) and crop growth (the slope being the plant growth per unit ET (kg  $mm^{-1}ha^{-1}$ )) ( $WUE_{ET}$ ). Conventionally most focus has been on  $WUE_{ET}$ , largely due to the tradition of not distinguishing between evaporation and transpiration.  $WUE_{ET}$  for tropical cereals will range between 150-300  $mm\ t^{-1}\ ha^{-1}$  grain (or 1,500 - 3,000  $m^3\ t^{-1}$ ). As will be shown below  $WUE_{ET}$  can amount to  $> 5000\ m^3\ t^{-1}$ , in highly eroded and nutrient mined soils, where evaporation losses are high compared to biomass growth.

Even though science and water resource managers tend to use  $WUE_{ET}$  estimates in research and in efforts of water management planning, it is not obvious that farmers see water use efficiency as a primary goal in water management in water scarce environments. The farmer's goal is not necessarily to produce as much "crop per drop" (advocated in the World Water Vision as a central panacea to improved water resource management in drylands), but rather to assure a stable supply of water to the crop throughout the crop season. This is important in discussing the viability of water harvesting methods, which primarily focus on reducing *risks for dry spells*, rather than minimizing the amount of water used per unit crop.

## Yield implications of the large water losses

Data on observed rainfall partitioning (see ch.2.3), indicates that only a small proportion of the rainfall is actually used in direct biomass production (transpiration range of 15 - 30 % on average from data gathered mainly from on-station research, and  $< 10$  % for a farmer's case with highly nutrient mined and soil crusted soil).

What are the yield implications of the experienced rainfall partitioning, and what realistic hydrological options are there to improve on-farm yields, and perhaps most importantly, how much can yields realistically be increased? Rockstrom and Falkenmark (2000)) have developed an analytical tool to assess the options available to improve crop yields in semi-arid tropics from a hydrological perspective.

The approach is based on a simultaneous analysis of the effect on crop growth of (1) actual crop water availability in the root zone and (2) the soil water uptake capacity of the plant. Actual crop water availability in the root zone is given as the percentage of the crop water requirements available in the root zone. The soil water uptake capacity of the plant is given as the percentage of water in the soil taken up as productive transpiration by the crop (i.e. the ratio of  $T$  to  $ET$ , or ratio of productive green water flow to the total green water flow).

Figure 4A and B show the situation of maize cultivated in the semi-arid tropical range discussed in this report. Figure 4A shows the situation for a semi-arid setting with 90 days length of growing period, a seasonal rainfall of 550 mm, a daily  $PET = 8$  mm, and a cumulative crop water requirement (CWR) of 604 mm for maximum grain yields. Figure 4B shows the wet end of the hydroclimatic range, for maize cultivated in a dry sub-humid setting with 179 days length of growing period, a seasonal rainfall of 1,000 mm, a daily  $PET = 6$  mm and  $CWR = 810$  mm.

The Y-axis in Figure 4 indicates (1) to what extent rainfall is enough to cover CWR (indicated by the upper boundary condition shown as a horizontal line) and (2) the actual fraction of rainfall entering the root zone (e.g. the  $Y = 92\%$  indicated by the upper horizontal line in Figure 4A implies that seasonal rainfall only amounts to 92% of estimated crop water requirements; and, e.g. a value of  $Y = 45\%$  implies that only 45% of CWR is available in the root zone, with the difference  $92\% - 45\% = 47\%$  being water lost as a result of poor soil infiltration). The X-axis shows the ratio of productive to total green water flow in percent ( $T/ET \times 100$ ). The concave lines in the figures are isolines of equal yield, with the lowest yield line in the lower left corner, and the maximum yield isolines in the upper right hand corner. The vertical straight line at  $T/ET = 85\%$  is the assumed maximum ratio of  $T/ET$ , and the lower horizontal line at  $Y \sim 8\%$  is the lower level of soil water before any crop yield is produced.

For the purpose of management implications, it is useful to consider the Y-axis as an indicator of the effect on crop yields of land management. These can include all water harvesting methods that aim at increasing infiltration and water holding capacity (thus reducing runoff and drainage). The X-axis is an indicator of the effect on crop yields of crop management (timing of operations, pest management, soil fertility management, crop varieties etc.).

Droughts and severe dry spells are manifested in a reduction in rainfall, which will affect the percentage of CWR available in the root zone (along the Y-axis). Only some 90 % of CWR are covered on average by rainfall in the semi-arid situation (shown by the upper horizontal boundary condition). A severe dry spell will pull down the green water availability ratio to 70 - 75 % in the semi-arid situation, and down to some 55 - 60 % during a meteorological drought year. Management options to increase the fraction of the crop water requirement available in the root zone includes runoff farming systems, flood water harvesting and storage systems for supplemental irrigation. In all these cases the additional water must be taken from an external source in relation to the crop field.

The maximum achievable yield levels are shown by the yield isoline matching the point where the upper boundary lines of percentage of crop water requirement accessible by the crop and the percentage of productive to total green water flow cross each other (in the upper right corner of Figs. 4A and B). This maximum yield level amounts to  $6 \text{ t ha}^{-1}$  in the semi-arid case and  $9 \text{ t ha}^{-1}$  in the dry sub-humid case.

The shaded areas in Figs 4A and 4B, show the estimated average range of actual experienced maize yields in rainfed farming (primarily on-station) as a result of hydroclimatic

preconditions and rainfall partitioning. The maize yield ranges from 1 - 3 t ha<sup>-1</sup> in the semi-arid zone and 1.5 - 4 t ha<sup>-1</sup> in the dry sub-humid zone. As shown by Figure 4A rainfall partitioning alone, through runoff and drainage, pulls down the achievable yield with 1 - 3 t ha<sup>-1</sup> (from a potential of 6 t ha<sup>-1</sup> to a maximum range of 3 - 5 t ha<sup>-1</sup> along the Y-axis). The low T/ET ratio further reduces yields with 2 t ha<sup>-1</sup> (from a potential of 5 t ha<sup>-1</sup> to 3 t ha<sup>-1</sup> and from 3 to 1 t ha<sup>-1</sup>). Similarly, the yield drop due to runoff and drainage is significant in the dry sub-humid setting, amounting to some 2 - 5 t ha<sup>-1</sup> (from a potential yield of 9 t ha<sup>-1</sup> to a maximum range of 4 - 7 t ha<sup>-1</sup>). Low T/ET ratio further reduces yields with 3 t ha<sup>-1</sup>.

This analysis of maize using synthesised averages of rainfall partitioning, suggest that there is a large scope for improving yield levels within the available water balance in rainfed farming systems. Average yield levels according to Figures 4A and B (the dots in the middle of the shaded areas) amount to 1.5 - 2 t ha<sup>-1</sup> in the drier zone and 2 - 2.5 t ha<sup>-1</sup> in the wetter zone, which correspond fairly well with long-term experienced maize yields in similar hydroclimatic conditions.

The large yield loss attributed to poor rainfall partitioning (the Y-axis) suggest that water management using water harvesting techniques that improve rainfall infiltration can play a significant role in boosting crop yields (*a possible yield upgrade of 1 - 3 t ha<sup>-1</sup>*). It should also be noted that an improvement of rainfall partitioning in favour of increased plant available soil water would give synergistic effects also on the T/ET ratio. More soil water over time will result in larger canopies and more shading, which will reduce E-flow in favour of T-flow.

Figures 4A and 4B also indicate the close link between plant water and soil nutrient availability. Improving plant water uptake capacity (assuming the water harvesting has improved the ratio of rainfall reaching the root zone) will depend largely on the availability of plant nutrients and organic matter in the root zone.

## The challenge

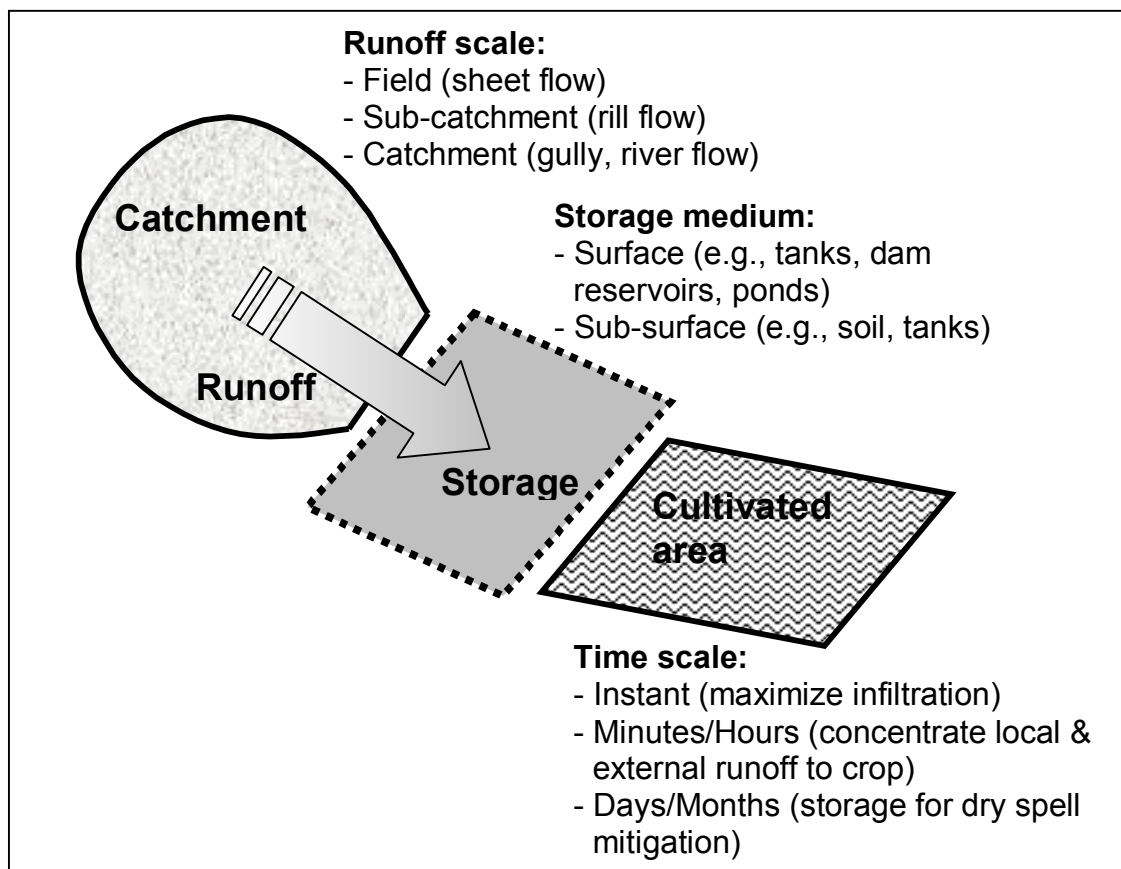
The analysis above indicates that the agrohydrological challenge in semi-arid and dry sub-humid tropics is not necessarily related to inadequate cumulative rainfall - at present basically only 1/8 - 1/3 of the rain is used in crop production on average. Instead the challenge is to manage the unreliable distribution of rainfall over time, and minimise non-productive water flow in the water balance.



# Water harvesting - the concept in short

*"Water harvesting systems will primarily supply the farmer with a tool to stabilize water availability to the crop over time."*

It is believed that the first water harvesting techniques originated from Iraq over 5000 years ago (Hardan, 1975) in the Fertile Crescent, where agriculture once started some 8000 BC. Since then, many civilisations have further developed more or less simple or sophisticated means to harvest water for specific needs. These needs normally set the conditions for how a technique is chosen and developed.



**Figure 5.** Principle of water harvesting for plant production, which includes all methods of collecting runoff for productive purposes. The various methods are distinguished based on **the scale** - and thereby the type - of runoff collection (from within-field, sub-catchment, catchment, as either sheet, rill, gully or river flow), **the medium of storage** (ranging from no-storage in water conservation and flow diversion methods to full storage in micro-dam reservoirs, in either surface or sub-surface structures), and finally the **time scale of use** (immediate for infiltration maximising methods, within the time of a rainfall event in the case of runoff farming and flood WH methods, and days/months in the case of storage systems). The same principles apply for WH methods used for domestic purposes.

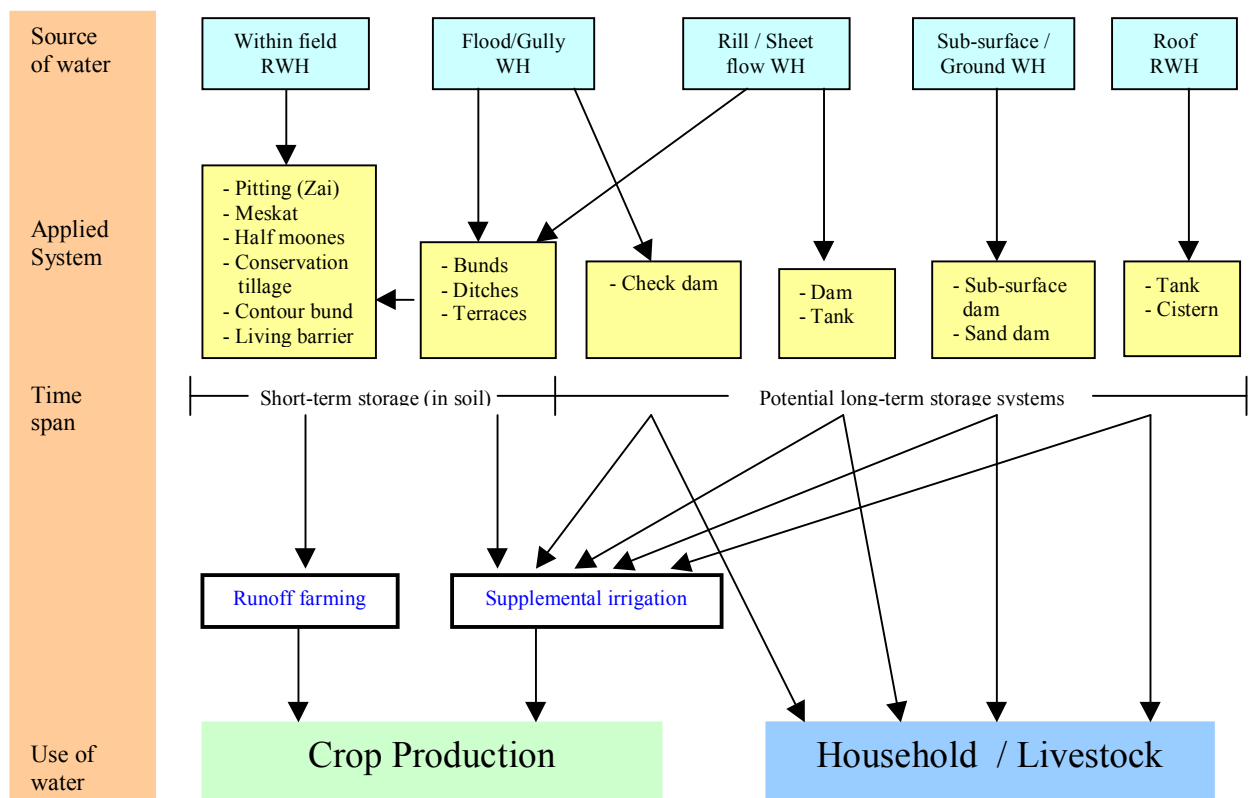
The aim of water harvesting is to mitigate the effects of temporal shortages (but not insufficient cumulative amount) of rain, so-called dry spells; to cover both household needs (for drinking, cooking, sanitation, etc.) as well as for productive use (supplemental or protective irrigation). All these techniques, in various forms, include a storage component

with longer or shorter time span. Important to note is that the intended use of the harvested water and the physical environment set specific conditions to how the technology is applied – making each implementation tailored and site-specific. Much research has, for instance, been done on various forms of improving runoff production from a given surface. In order to capture a greater part of the total rainfall liners as well as asphalt and other water repelling materials have been applied (Sivanappan, 1997). This requires that the land use in the catchment area permit such applications (often implying the sacrifice of a certain piece of land solely for runoff collection). In some regions, however, there is no abundance of land, and rainwater must be optimally used with excess water collected from the same surface as where it is applied.

There are two major forms of water harvesting (WH):

- **In situ or within-field WH:** Rainwater collected where it falls to be used more efficiently on the same surface (often referred to as water conservation).
- **External WH:** Water collected on one surface to be applied on another area or use (often referred to as runoff farming/collection and storage, see principle in Figure 5).

From a farmer's perspective water harvesting systems are not necessarily adopted in order to improve WUE, but will primarily supply him/her with a tool to stabilize water availability to the crop over time. However, water harvesting systems that enable bridging of yield reducing dry spells will in general improve both yields and the amount of crop produced per drop, i.e. improve the water use efficiency. Existing techniques can be grouped as in Figure 6.



**Figure 6.** Classification of Water Harvesting Systems on criteria of source of water and duration of storage. (Fox, 2001)

## Water collection systems

- **Within field RWH** refers to rain collected on the place it falls. Through various formations such as pits, the water will stagnate, infiltrate and thus made available to the plant root zone.
- **Flood/Gully WH** involves the collecting of storm surface floods from gullies. The harvested surface water can be stored in a reservoir (for longer term storage) or be diverted directly to a field for direct infiltration by arresting the flow of water with the help of bunds, ditches and terraces (for shorter term storage).
- **Rill/Sheet flow WH** is the collection of runoff of a gentler form than gully flooding. One definition, to distinguish this form of WH from flood/gully systems, is that the slope does not exceed 1%, along a length shorter than 50-150 meters and that the surface runoff is mainly harvested in form of sheet and rill flow. Beyond 150 meters water will generally start to flow in minor gullies and eventually gullies.
- **Sub-surface/Ground WH.** Extraction of sub-surface water flow, from either soil water trapped in shallow sand layers or from the water table, constitute a very interesting form of water harvesting. Storing water under ground is attractive as it reduces evaporation losses and often contributes to high quality water thanks to filtration through especially sand (even though soil and geological characteristics will determine the level of filtration capacity). Sand dams and sub-surface dams, where water is trapped behind small dam-walls in sandy riverbeds, is a very efficient and cheap form of WH.
- **Roof RWH (Rain Water Harvesting)** The water is usually collected through a gutter or drain pipe. The system requires a tank to be built, which if correctly constructed can give water through piping straight into the house and thereby limit various forms of contamination. The closeness to the dwellings and the quality of the water potentially obtained makes it a valuable resource for the household and can greatly limit the work load of having to carry the water to the house if piping does not exist. Roof RWH is primarily used for household use since the quantity obtained is seldom enough to cover agricultural needs greater than small-scale gardening. A combined area surface from several houses or school buildings, garage buildings, hospitals etc. can though produce considerable amounts of rainwater runoff, enough to be used for irrigation (Zhu and Li, 2000).

## Storage and storage losses

Whether for household or agriculture, water that is harvested for a longer time of duration, and tapped only when required, involves a storage component. Various forms that exist include:

- **Micro-dams, earth dams, farm ponds.** Runoff water is stored in open structures, which can consist of small concrete dams, earth dams or simply ponds.
- **Sub-surface dams, sand dams or check dams.** Water is stored under ground - in an artificially raised water table or local sub-surface reservoir (e.g. water stored in sand on top of a sealing layer of clay).
- **Tanks** of various forms (plastic, cement, clay, soil etc.). These can be either under or above ground depending on space, technology, investment capacity and forms of extracting the water.

Seepage and evaporation losses are the main forms of losses from storage reservoirs. Evaporation losses can be reduced through the minimisation of open water surfaces and the covering of the surfaces (shading). Sub-surface dams are one solution to prevent water surfaces to be fully exposed to atmospheric demands for water. Covering open surfaces with soft wax or foamed plastic reduces evaporation greatly but is costly.

Seepage losses can be considerable, especially in soils that are too permeable. Prevention is done by reducing the wetted surface area, self sealing through siltation and/or applying

various types of lining. Materials used are cement, asphalt, epoxy liners etc.. Because of the high costs it is often cheaper to include the losses in the water needs calculations and construct storage capacities that include the losses as well (Critchley, 1991). However, efforts are underway to investigate low-cost alternatives to reduce seepage by using locally available materials such as clay, lime and stones.

## Supplemental irrigation and Runoff farming

The differentiation between Supplemental irrigation and Runoff farming lies in the differences of storage time and form. Both are practices applied during the crop season /rainy season with the aim of making excess runoff water available to the plant root-zone. For semi-arid regions, the effects the systems carry are limited to the rainy season period.

Runoff farming diverts overland flow into the crop fields through a variety of bunds, ridges and furrows (depending on material available and the physical environment where it is applied). The water is then arrested in the field through the use of terraces, interception ditches, micro-catchments etc., to increase the time for infiltration and thereby replenish the stock of soil moisture.

Meanwhile, storage structures permit water to be stored for longer periods of time making it possible to mitigate water stress periods occurring during the cropping season. The aim is to reduce risks of crop failures caused by poor rainfall distribution. Storage structures range from small farm ponds to micro dams, and include both surface and sub-surface storage of water (e.g. in sub-surface dams or by recharging water extracted from wells). The stored water is conveyed to the crop using conventional irrigation methods (ranging from overland furrow irrigation to drip irrigation methods). A further purpose of this system can be to extract water from the reservoir to give water to livestock and to cover various other household needs.

## Irrigation forms

Supplemental or protective irrigation is applied a few times through the crop season. The number of applications depends on the frequency and severity of dry spells as well as the amount of water available. The method of application of irrigation depends upon the landscape, the crop grown and investment capacity.

**Table 2.** *Irrigation forms (Sivanappan, 1997).*

	Gravity fed	Gravity and/or Pressure fed
Furrow irrigation	x	
Pair row/skip row irrigation	x	
Overhead sprinkler		x
Pitcher or porous cup method		x
Drip irrigation/ micro irrigation		x

The first two methods (Table 2) generally require a limited amount of monetary investment, but may be very labour intensive. Water losses during application through evaporation and deep percolation may be high as the water in the channels and furrows is normally exposed to the soil and atmosphere. This needs to be taken into account in the storage capacity design.

The latter three irrigation methods require a more substantial monetary investment into equipment and has until recently been beyond the investment capacity of the resource poor farmers. For example, drip irrigation systems are today available at low cost and adapted for small-scale farming in several parts of the developing world. These systems are interesting if linked to water harvesting in semi-arid areas, as water losses can be reduced with at least 50 %, and the methods are generally less labour intensive.

## Runoff enhancing methods

In order to enhance runoff, various methods have been investigated. These include: land alterations, soil compaction, soil deflocculents and additives, spraying asphalt membranes, liners, cement lining, natural clay layers and pottery clay liners (burned). The percentage of runoff, combined with total rainfall and the aim of the water use will decide the size of the needed catchment area. In agriculture, the crop will be the water user, and normally the catchment requirement is described as the ratio of the runoff producing catchment to the cultivated area (C:CA ratio). A rule of thumb is a C:CA ratio of at least 3:1 (Anschutz et al., 1997). However, depending on the hydroclimate, runoff coefficients, and crop water requirements, catchment to cultivated area ratios will vary from 1:1 to 10:1.

In some areas, land use is so intense that there is no land available to set aside purely for runoff purposes. The catchment area may have a number of functions already, such as grazing land, roads and other vehicle grounds, school yards and likewise, as well as already cultivated land. Depending on utilisation, the runoff coefficient will vary greatly and the catchment area in relation to its intended use needs to be designed accordingly so as to correspond to the objective. Often, it can be fruitful to combine uses of land surfaces. Paved roads and schoolyards with a high runoff coefficient can be successfully used for runoff harvesting. The risk of contamination has to be observed depending on the intended use of the harvested water.

## Choice of WH technology

The choice of technique is a complex question and will depend not only on the biophysical fit but also on the socio-economic environment as well as the capacity to maintain the system. All systems require various degrees of maintenance, mostly of erosive damage caused by rainfall and runoff. Also the time the structures lay idle through the dry seasons can give rise to needs of maintenance (e.g. cracking of concrete lining). This must be included in the operation procedures of the technique. The choice of technique will also be affected by the type of crop production (Table 3).

**Table 3.** Presentation of runoff farming techniques suited for various production needs depending on the local availability of material (Critchley, 1991).

For rangeland and fodder	For trees	For crop
<ul style="list-style-type: none"> <li>- Planting pits</li> <li>- Contour bunds</li> <li>- Semi-circular bunds</li> <li>- Contour stone bunds</li> </ul>	<ul style="list-style-type: none"> <li>- Contour bunds</li> <li>- Closed micro catchments</li> <li>- Semi-circular bunds</li> <li>- Infiltration pits</li> </ul>	<ul style="list-style-type: none"> <li>- Contour stone bunds</li> <li>- Earth bunds with stone spillways ("Meskat")</li> <li>- Contour earth and/or vegetation bunds</li> <li>- Living barriers</li> <li>- Planting pits (Zai)</li> <li>- Semi-circular bunds</li> </ul>

The true potential of a technology can only be realized if it is well understood and the site conditions (physical and social) to which it is suited are identified. The proper evaluation of the environmental and social factors surrounding a system in combination with technologies best suited for a particular context is a major step towards the wider use of runoff techniques (Diemer and Huibers, 1996). It is important not to forget that any system developed in its best-applied form is indeed site specific and must be tailored accordingly. The system has to function well from a technical point of view and it should "fit" within the production system of the users – including socio-economic constraints etc. (see further chapter).

The factors determining which system to use depend on several factors:

- **Potential source of water: rainfall and retention** (plus the impact of atmospheric conditions) – WH is particularly suited for semi-arid regions (300-700 mm average annual rainfall (Anschutz et al., 1997)) but is also used in more arid regions such as the Negev desert and parts of Northern Africa. In more arid regions the implementation costs are higher due to the need of larger catchment structures.
- **Storage capacity** (in time): For human consumption the needs must be estimated and compared to potential storage volume. In agriculture if the purpose is supplemental irrigation, then irrigation requirements and scheduling need to be assessed in relation to (i) the depth of water required, (ii) most likely timing of yield affecting crop water stress and (iii) the possible depth of water that can be harvested
- **Purpose of use**: single or multi purpose use (i.e. a combination of objectives such as irrigation, household water, livestock etc.)
- **Volume of water required**: Can be obtained by analysing rainfall data to assess probabilities of dry spell/stress occurrence and the actual requirements of water for the various intended uses (e.g. daily crop water requirements).
- **Investment capacity** of the owner of the system (individual farmers, farmer groups, communities etc.).
- **Physical site conditions**: Land availability including catchment availability and the runoff coefficient (i.e. the estimated percentage of rainfall that generates runoff) of the catchment surface are decisive factors in calculating runoff potentials. It is not recommended to conduct WH from slopes exceeding 5% due to uneven distribution of runoff, soil erosion and the high costs of the structures required.
- **The characteristics of the catchment area**: should preferably permit as much runoff as possible (i.e. have a low infiltration capacity as possible). The more compact (rocky), sealed and barren as possible, the better.
- **The application area**: In agriculture - Preferably fertile soils with good infiltration and moisture storage capacity.

It is also important to realize that an investment in water harvesting may well result in a shift in crop production system. Therefore, in many cases the estimated costs and benefits from a certain water harvesting system should be based on a different crop production system than the original system practiced prior to any WH introduction. For example, water harvesting structures with storage components are rarely seen as economically viable by farmers in East Africa, if used only for staple food crops. Instead, the construction of, e.g., a farm pond, will most probably result in a shift in production system, toward high value crops such as tomatoes, garlic, onions, fruits, etc..

Detailed descriptions of various WH techniques can be found in part II of this report.

# Farmers approach to drought risks

*"Any effort of improving land productivity in small holder farms in the semi-arid tropics must take into account the entrepreneurial risks perceived by farmers trying to make their living."*

As pointed out in earlier parts of this report yield levels experienced by small-holder farmers in semi-arid tropical regions are low and far from the on-farm potential. It is clear that the causes behind such low yield levels are complex and related to interacting biophysical and socio-economic constraints. Still, the hydroclimate plays a crucial role in determining the entrepreneurial risks a farmer is prepared to take, and thereby the investment levels made on a farm, which in turn will affect the long-term yield levels. Erratic rainfall resulting in high risk for crop failure due to frequent dry spells and droughts (or loss of invested capital and of cash income from produce), forms the basic backbone of farmers' risk management strategies and incentives for investment in the land.

Added to this temporal variability resulting in high risk for annual droughts and intermittent dry spells, is the extremely high spatial variability related to the convective character of tropical rainfall. The result is large differences in rainfall amounts between adjacent villages, and often even adjacent crop fields. Predicting rainfall is therefore a very difficult, if not an impossible task. The spatial and temporal variability forms a normal part of the semi-arid landscape setting, which means that annual rainfall data, as well as rainfall data recorded at one site and assumed to represent, e.g., a District (municipality), has very little meaning for the land use decisions to be made by farmers.

Any effort of improving land productivity in smallholder farms in the semi-arid tropics must take into account the entrepreneurial risks perceived by farmers. The majority of the farmers in the Sahel, for instance, are more or less subsistence farmers, depending for their survival on rain and land. The Natural Capital (ecological services, renewable and non-renewable natural resources) over which they have any control is very limited. The Sahelian farmer is an entrepreneur as any other farmer, and will not invest in his land or crop should the risks involved in doing so be too high. Farmers tend to act rationally to the high risk for yield reductions caused by water stress by avoiding investment. It is not very surprising that a farmer, making his/her living on a semi-arid savannah where meteorologically caused crop failures occur statistically two years out of ten, will not invest in fertilisers, improved varieties and pest management. Also, although all communities have more or less strong social networks, every household is ultimately left to fend for itself, making tailored farm-level solutions for risk-minimisation an important entry in efforts of improving rural livelihoods (Agarwal and Narain, 1997). He/she has no insurance company compensating for yield reductions caused by climatic calamities, which means that non-investment strategies may be the most rational given the risks at stake.

There is evidence showing that soil fertility constraints often constitute the primary limiting factor to crop growth also in drylands (Klaij and Vachaud, 1992, Penning de Vries and Djitéye, 1991). This is explained by the inherent low fertility of some of the major soils and the progressive mining of soil nutrients. Nutrient balances in farming systems in several countries in Eastern and Southern Africa are highly negative (Stoorvogel and Smaling, 1990). For example, for the Kenyan highlands, the average annual losses were estimated at 73 kg ha<sup>-1</sup> of N, 7 kg ha<sup>-1</sup> of P and 51 kg ha<sup>-1</sup> of K. Fertiliser use in sub-Saharan African agriculture is the lowest in the world, with an average of some 11 kg of fertiliser applied on average per harvested hectare. Developing countries apply an average of 62 kg ha<sup>-1</sup> (FAO, 1995).

The above points out the necessity to address water constraints together with soil nutrient constraints. It also suggests that different water harvesting technologies, which lower the risk

for crop failure, can function as an entry point for successful efforts of increasing investments in soil nutrients.

## **Adaptive technology to hydroclimatic hazards**

Even though water harvesting practices can be efficient in increasing the plant available soil moisture in water scarce areas, each set of techniques obviously has a limited spectrum of utility. Figure 7 describes which climatic hazards that can be tackled by different water harvesting techniques. It also gives an indication of the technical and socio-economic implications of implementing different methods.

Three major hydroclimatic hazards in dryland farming are distinguished (Figure 7). First, the problem of poor rainfall partitioning, where only a fraction of the rainfall reaches the root zone, combined with within-field crop competition for soil water (as a result of high planting density, inter-cropping or agroforestry). Secondly, the high risk of periods of below optimal cumulative soil water availability during the growth season (i.e., not necessarily droughts, but rather landscape settings where soil water availability most often is below crop water requirements for optimal yields due to low cumulative rainfall levels). Finally, the high risk of dry spells, hitting during critical growth stages of the crop (i.e. not necessarily a lack of cumulative soil water availability, but rather periodic water stress due to poor rainfall distribution).

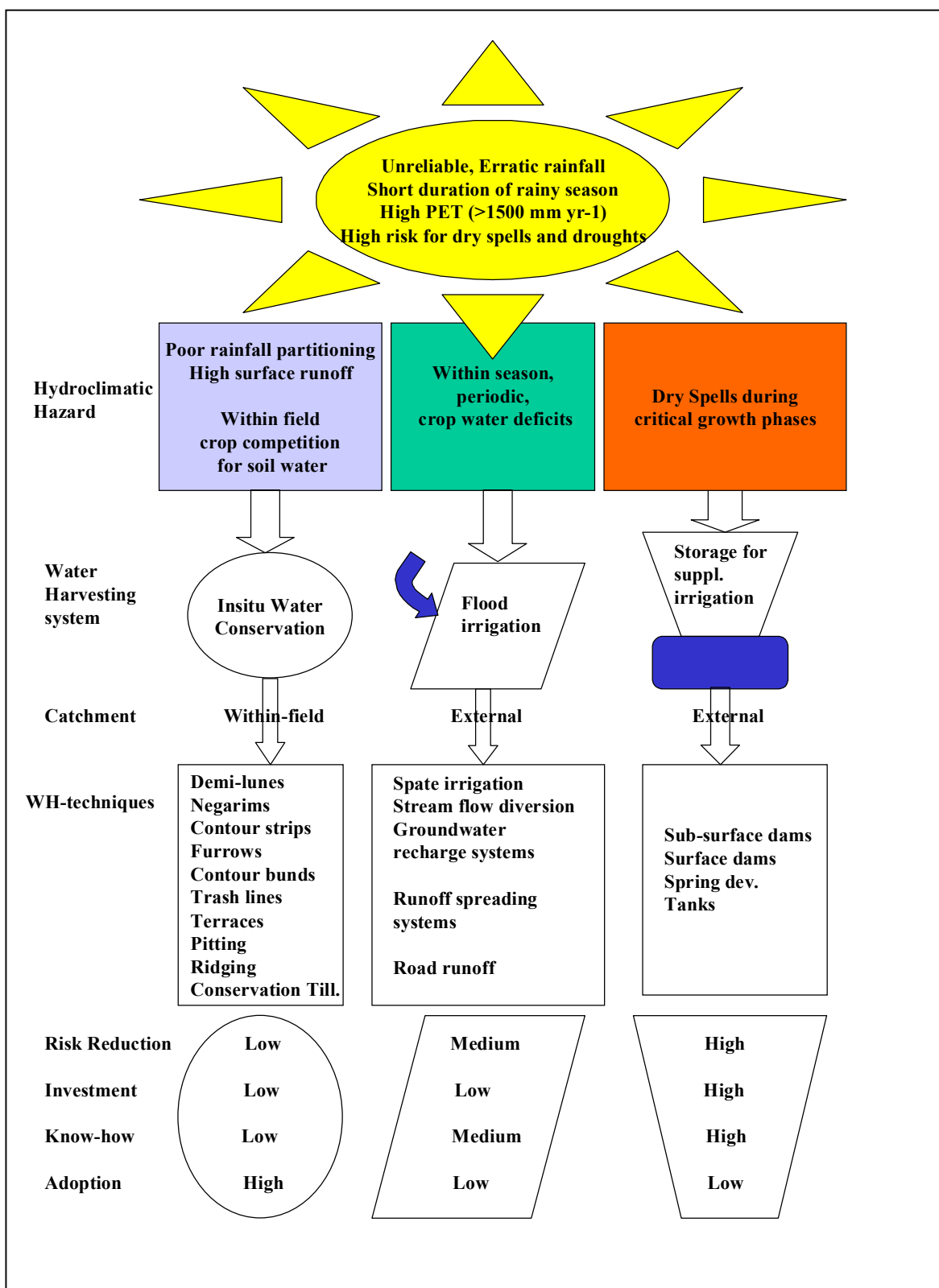
The positive soil water effect of in-situ water conservation techniques is to concentrate within-field sheet runoff to the crop. In a semi-arid context, especially on coarse-textured soils with high hydraulic conductivity, this means that in-situ conservation offers little or no protection against the poor rainfall distribution (the farmer is still living completely at the mercy of the rain). The effect is that the risk for crop failure due to dry spells is only slightly lower than without any measures (this may not apply on clayey soils with high water holding capacity in situations of adequate rainfall prior to a dry spell).

The use of external catchments for runoff collection immediately adds water to the field scale water balance. With flood irrigation systems in drylands where absolute crop water scarcity is common, yields can be improved substantially during years with reasonably good rainfall distribution. The farmer still lives at the mercy of the rain, but when it rains, the supply of water to the roots exceeds rainfall depths. These systems can assist in mitigating dry spells if the root zone is deep and the water holding capacity is high.

Storage systems give the farmer a tool for water stress control. Risks for crop failures are reduced, but investment costs and the need for know-how are high. However, these systems still depend to some extent on rainfall distribution. For example, during drought years, even earth dams are dry, and very little can be done to bridge a dry spell during the vegetative stage of a crop if no runoff producing rainfall events have fallen during germination.

It is also important to note that the three main systems interact in a farming system, with, e.g., in-situ water conservation often being applied within flood irrigation systems and micro-irrigation schemes. An interesting issue is also to what extent one system is a prerequisite for the successful implementation of another system, within the context of a farming system. It has been noted, e.g., in Kenya, that it is easier for the extension services to promote storage water harvesting systems on farms, or in catchment areas, where in-situ water conservation already is practised (Hai, pers. comm.).

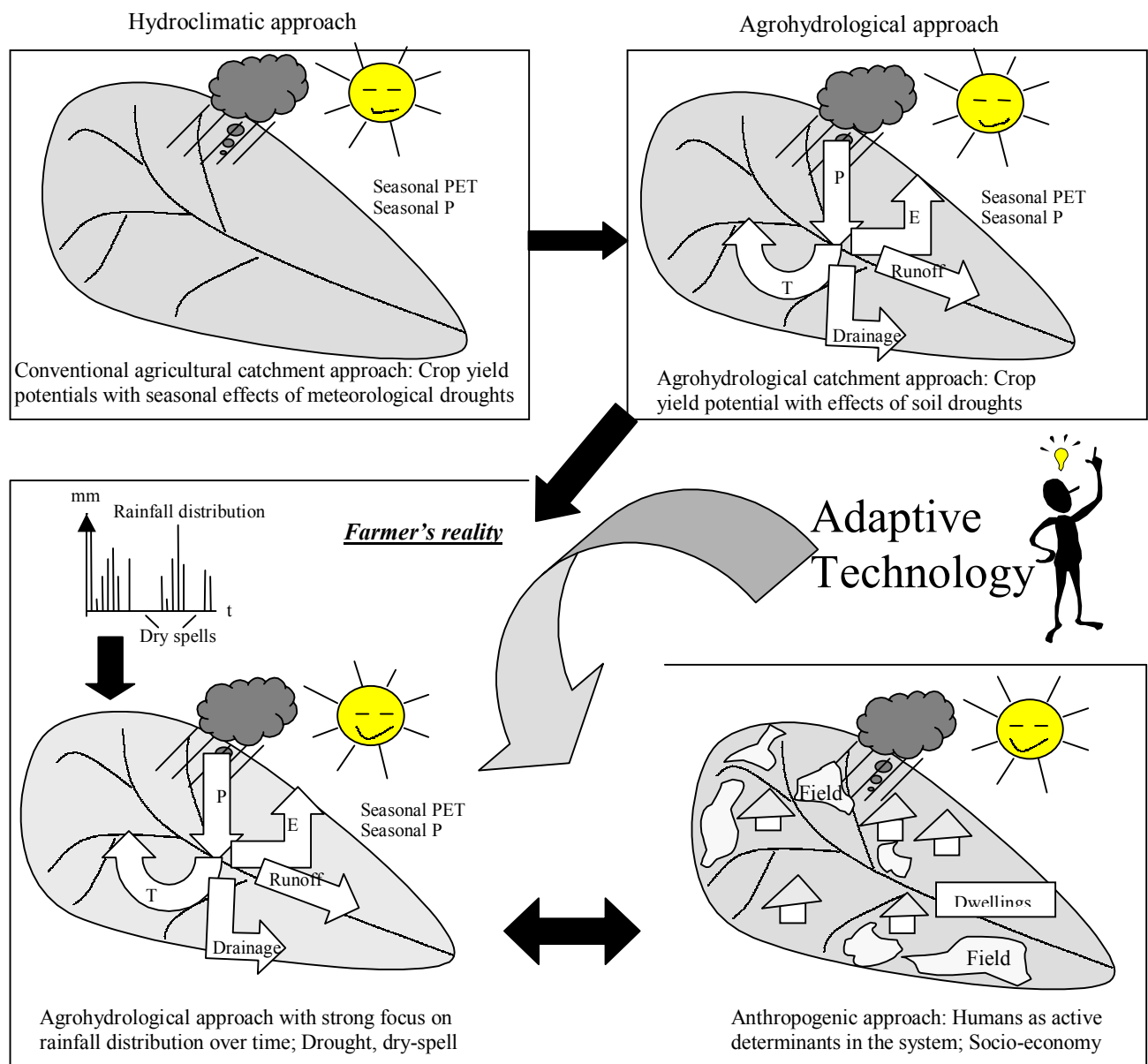




**Figure 7.** Flow chart indicating the hydro-climatic hazards tackled by different water harvesting methods, and the relative socio-economic implications of implementing them in rural communities.

## System analysis of farmer's reality

The conventional scientific and planning approach to the assessment of the agricultural potential in semi-arid tropical regions has largely focused on the ratio of P (Precipitation) to PET (Potential Evapotranspiration) on a seasonal basis linked to the assessment of access to arable land (Figure 8). The agrohydrological approach takes into account the partitioning of rainfall, but still on a seasonal basis and based on arable land availability. The system approach combines the agrohydrological approach with a strong focus on erratic rainfall distribution and the dynamic process of technical development, capabilities and incentives on a farm level. These latter issues are necessary in understanding the role water harvesting can play in a farming system, and in assessing the actual viability of different water harvesting techniques.



**Figure 8.** Agrohydrological system analysis of farmer's reality. P = Precipitation, PET = Potential evapotranspiration, E = Evaporation and T = Transpiration.

A systems approach to water harvesting is required for several reasons:

- It is unlikely that yield increases can be sustained on the long-term with water management alone
- Every water harvesting decision, be it on a farm, community or watershed level, is also a land decision, as water harvesting manipulates the way water flows through the landscape
- Water diversion at one point in a watershed will affect potentially both surface and sub-surface water flow downstream water users

Regarding the first point, large yield increases in rainfed semi-arid farming systems can not be achieved with water management alone but has to be linked simultaneously with soil fertility management, timing of operations, marketing information, tilling practices, pest management, crop rotation and capacity building among farmers and extension services.

## **Investment for Multi purpose**

The limited investment capacity faced by the resource poor farmers also indicates the necessity for the household not only to look at an immediate need singularly. A number of innovative introductions have failed because they address only the needs required by one family member whereas the actual innovative construction has to be produced by another family member. It is therefore necessary to observe a potential investment in WH as a multi-purpose input into the strategy for sustainable livelihood. A study conducted in Eritrea (Fox, 1994), describes an example of a system (small earth dams) which serves the community with:

1. Irrigation water for fields below the dam structure
2. Water to the animals as a trough is placed just below the dam structure
3. The seepage water below the dam is collected in a small pond and used for washing clothes and hygienic purposes and
4. For drinking water as the ground water level is increased through underground seepage from the reservoir, permitting shallow wells to be dug producing clean, filtered water

A number of experiences where WH is conducted to supply one solution to a number of issues, including both the agricultural aspect and the immediate household needs, are presented in literature (Pacey and Cullis, 1986; Ferroukhi, 1995; Davis and Lambert, 1995; Agarwal and Narain, 1997; Morgan, 1990). The conclusion, even though it is difficult to generalize between farming communities, is that basically all water harvesting methods serve multiple uses, ranging from agricultural to domestic needs. But, it is also clear that the by far dominating form of water harvesting is for domestic purposes, which is partly explained by the fact that farmers generally prioritise water for household and livestock before water for crops. The other reason is the low volumes (compared to crop production) needed to cover water demand from households and animals (often a factor 100 lower for a household). The consequence is that water harvesting techniques designed for crop production are generally always used for multiple purposes (if the water quality so permits), while domestic system less often are used for agricultural uses (due to the smaller storage volumes).

## **Yield increases and the landscape**

The analysis of rainfall partitioning in semi-arid tropics suggest that, in general, the farming systems are operating, from a hydrological perspective, significantly below optimal biomass productivity level. The prospect of doubling or even quadrupling yields (from say 0.5 t ha<sup>-1</sup> in a semi-arid environment, which at present is the common case for small holder farmers, to 2 t ha<sup>-1</sup>) actually seems realistic, even within the context of high risk for meteorological droughts (Rockstrom and Falkenmark, 2000; Hatibu and Mahoo, 2000).

Such large increases in biomass productivity per unit soil and water can only be achieved if adopting a systems approach discussed above. The challenge is to achieve a win-win development, where progressively, as yields are increased through wise soil and water management, environmental landscape factors are conserved. All forms of water harvesting have the common objective of reducing runoff in favour of vertical vapour flow back to the atmosphere (preferably through crops). A direct implication of such yield increase is thus a significant reduction in water induced soil erosion. Furthermore, yield increases in most developing countries, can play an important role in reducing the exploitation of virgin land, which more often than not constitutes natural habitats for wild flora and fauna. Using water harvesting as an entry point for farming systems improvements thus has a direct link to conservation of land and protection of biodiversity.

From a strategic research perspective there are several biophysical opportunities on regional and global scale linked directly to improved water management in semi-arid farming systems. Sweden has ratified several UN-declarations and conventions on climate change, biodiversity and desertification. They all have in common the urgent need of reducing the negative effect of human induced land degradation and mismanagement of natural resources. A central element is the need to reduce the emission of greenhouse gases. Carbon sequestration in soil is an important component in such efforts (Bruce et al., 1999). Improving biomass productivity in semi-arid tropics as a means of reducing land degradation, improving livelihoods and reducing the effects of climate change, seem interesting. Especially as semi-arid agricultural lands in general experience such a large gap between actual yield and possible yields, which is not the case in temperate industrialised countries where the biomass production on farm land is at or very close to present achievable yield levels (with more and more incentives to accept yield reductions by reducing inputs of especially fertilizers, in order to reduce pollution).

The question is what implications increased water diversions in agriculture will have on water dependent ecosystem services downstream. The surface runoff generated at present on upstream farmland will eventually join rivers, or be ponded in wetland areas or contribute to recharging water tables. This water is "lost" from the upstream farmer's perspective, but is a resource for generation of ecosystem or other services (like drinking water from a downstream located well) at a downstream location. There are several large-scale cases showing the serious downstream effects of overexploitation of water resources upstream, e.g. from the Colorado River (Postel, et al., 1998) and the Aral Sea. But these cases are based on diversion of water due to large developments such as irrigation schemes or industry. For small-scale water harvesting, where the largest storage structures may be in the order of some few 1,000 m<sup>3</sup>, it is still unclear what the impact on downstream water users would be. For example, observations on runoff farming from small gullies in the Sahel seem to indicate that the alternative use of harvested water for crop transpiration is to a large extent open water evaporation from inundated lowland areas (so-called basfonds). There has not been any thorough research carried out on hydrological effects on human uses and ecosystem service production of upscaling water harvesting techniques on a catchment scale.

## Part II. Regional approaches

### Sub-Saharan Africa- rapidly growing interest

*"In many farming communities water harvesting has been independently invented and used for centuries with large success, often even forming the very basis for the socio-economy and culture of the society."*

There is a growing interest for water harvesting (WH) in sub-Saharan Africa (SSA), as a method to increase productivity in small-scale rainfed agriculture. Crop yields among smallholder farmers, which in many countries constitute some 80 % of the population, oscillate around 1 t ha<sup>-1</sup> or less. This is, as mentioned earlier in the report, < 20 % of the potential yields even in water scarce savannahs. Inadequate soil water in the root zone at the right time of crop growth is a major factor behind such low yield levels, which indicates the scope of water harvesting in sub-Saharan Africa. Awareness of the potential of WH grew out of the meteorological droughts in the 70s and 80s and the opportunities documented in the successful WH work carried out in the Negev desert of Israel (Evanari et al., 1971).

During the period from the arrival of the colonial powers and until recently, the emphasis outlined in government policies and donor priorities, was set primarily on erosion control, in order to minimise the often huge (and many time highly exaggerated) soil losses reported from tropical farmlands (Stocking, 1987). Swedish support to the agricultural sector is no exception; on the contrary, Swedish collaboration with e.g. Ethiopia, Kenya, and Tanzania in the field of soil conservation is renown worldwide (e.g. the catchment approach adopted in Kenya during the last 25 years) (Lundgren, 1993).

The focus on erosion control is gradually changing, with a more integrated approach, where the simple question (but with complex answers) of "what to do between the terraces?" is being addressed, in order to shift focus toward land productivity enhancement (as a means of a more clear focus on poverty alleviation).

This means, that in the field of water harvesting in sub-Saharan Africa, within-field systems conventionally classified as soil and water conservation (SWC) techniques dominate. These methods are primarily implemented to control erosion and are generally perceived as soil conservation measured (Thomas, 1997). These include all systems of runoff water management for regulation or disposal of excess runoff flow (e.g. cut-off drains). In reality, however, they also contribute to recharge soil water to the root zone and finally to the water table, and are therefore to be considered as WH techniques. However, infiltration-enhancing techniques (e.g. Fanya Yuu terracing in Kenya, stone bunds in Burkina Faso, terracing in the Ethiopian highlands), give little assistance in mitigating dry spells.

So, in many parts of sub-Saharan Africa the challenge that grew out of the frustration from the devastating meteorological droughts in the 70s and 80s still remain; when crops are hit by 3-4 week dry spells even on well-conserved lands, the crop still fails.

The following sections outline experiences covering the major types of water harvesting, but with less emphasis on SWC methods that have been well documented elsewhere (e.g. Reij et al., 1996), and with more emphasis on flood water harvesting and storage systems.

The chapter is divided into four main sections, according to the type of water harvesting considered:

- 1) Within-field water harvesting
- 2) Runoff farming
- 3) Flood water harvesting
- 4) Storage systems for supplemental irrigation

For each section the (i) role the water harvesting methods play in the farming system is summarized, (ii) practiced systems are presented, and (iii) the performance for crop productivity increase is assessed.

## 1) Within-field water harvesting

Within-field WH systems are micro-catchments using sheet flow from short slopes within the cultivated fields. The systems (1) maximize infiltration of rainfall and (2) concentrate within-field sheet runoff flow from micro-catchments to a cultivated crop/tree and are very important among small-scale farmers in SSA. Many of these techniques originate from indigenous knowledge among farmers and are "beyond research" and are disseminated on a large scale (e.g. pitting techniques, demi-lunes, contour stone bunds, trash lines, terracing). Other techniques are based on old indigenous principles but use innovative methods, and are therefore still on the research/development borderline (e.g. conservation tillage systems).

The transition from top-down, imposed rural development approaches during the colonial period, to a progressive adoption of community based participatory approaches in most sub-Saharan African countries (Lundgren, 1993; Hagmann and Murwirwa, 1996), has probably favoured the development of the diversified set of runoff farming techniques present today in various farming systems in the region.

An important advantage with in-situ WH systems is that they normally operate at the scale of a household, or a crop field. This means that design is reasonably simple and that ownership issues do not have to be considered. Also, service giving institutions, like extension services, in general have the capacity to disseminate in-situ WH systems, while the know-how in the field of flood and storage WH systems is generally limited, in many cases very limited.

As earlier pointed out in the report, within field systems can assist in managing two distinctly different hydroclimatic hazards; (1) minimize runoff by maximising infiltration *where the rain falls* and (2) to supply additional water to crops/trees during a rainstorm, by concentrating sheet runoff from one part of the field (defined as micro-catchment) to the cultivated area. The distinction is important as methods to minimize runoff (1) fit in a very broad rainfall range, from dry semi-arid to dry sub-humid, while systems concentrating runoff (2) fit primarily in dry semi-arid and some arid areas as a means of bridging absolute water scarcities caused by situations where crop water requirements exceed soil moisture availability. Below we start with experiences on the latter systems.

### **Strip cultivation and contour ridges**

In dry semi-arid areas, with < 300 mm of seasonal rainfall, crops often suffer from absolute water scarcity, i.e., crop water requirements exceed the available soil moisture even during a "good" rainfall year. Strip cultivation systems have been developed in, e.g. Botswana (annual rainfall = 250 - 300 mm), where deep tillage is carried out in permanent planting lines along the contour. The planting density is reduced by half (i.e. every second row is abolished) and the soil surface in the inter-rows is shaped in a convex form, in order to maximize sheet runoff flow into the planting lines (Gedion Shone, pers.comm., Nilsson, Guss, pers.comm.).

Contour ridges (or contour furrows) follow the same principle as strip cultivation, with the difference that ridges are constructed along the contour at a spacing usually of some 1-2 m. Sheet flow is collected from the uncultivated strip between ridges, and concentrated along a roughly 0.5 m wide cultivated zone. According to Critchley and Siegert (1991) these systems

are mostly suited for higher rainfall areas (annual rainfall = 350 - 750 mm) then strip cultivation systems, due to the limited runoff production from the narrow inter-ridge zones. Contour ridges are tested in various areas in SSA (Chritchley and Siegert, 1991) on small-scale using manual labour, as in Baringo and Katumani in semi-arid parts of Kenya (Farmesa, 1997a), in Botswana (Farmesa, 1997b) and in Zimbabwe (Murwira, 1998). There are also examples of large-scale implementation as in Niger (the Fondo Aiuti Italiani, FAI, Damergou project in Department of Zinder), where several tractor established contour furrow systems were tested in the late 1980s (Antinori and Vallerani, 1994). Furrows with micro-basins for tree planting (as windbreaks) were combined with downstream-located furrows for dryland crops like sorghum. According to Antinori and Vallerani (1994) these furrow systems increased crop water availability in an area with 260 mm of annual rainfall, with a factor 5, and sorghum yield levels were estimated at some 2 t ha<sup>-1</sup>. In the early 60s similar efforts were made on the Mossi central plateau of the Yatenga region in Burkina Faso, where the GERES project used heavy machinery to install earth bunds on entire catchments (some 120,000 ha were treated). The project failed, not because the technique was wrong for the task (to conserve water and reduce soil erosion on severely crusted lands of gently sloping dry semi-arid bush/tree savannah) but due to the complete lack of farmer involvement. Farmers felt no ownership of the conservation structures and consequently never maintained them (van Dijk and Reij, 1994).

There seems to be limited documentation on the agronomic performance and socio-economic viability of contour ridges and strip cultivation systems compared to systems maintaining full planting density. As the core concept is to sacrifice a portion of the agricultural land only for runoff harvesting, the system does encounter problems of adoption in densely populated areas where land is a limiting factor to sustain livelihoods (Mwangi Hai, pers.comm.).

### **Micro-catchments**

Micro-catchment systems follow the same principle as above, with a portion of upslope land being allocated for sheet runoff collection, which is "harvested" in a cultivated down slope portion. These systems generally have a ratio of catchment to cultivated area of 1:1 to 5:1. The Soil and Water Management Research Group at Sokoine University, Morogoro, Tanzania has carried out extensive research on so-called Meskat systems in collaboration with the University of Newcastle, United Kingdom. Their research, which was carried out in a semi-arid area, suggests that the systems give significant yield increases on the runoff receiving proportions of the land, but that farmers are not willing to adopt the system due to the sacrifice of land needed (Hatibu, N., pers. comm.). Similar concerns have been raised from experience in the Sahel by Tauer and Humborg (1992).

An observation is that in most extension literature on water harvesting much attention is given to design of micro-catchment systems (how to calculate catchment-to-cultivated ratios based on runoff estimates, crop water requirements and design rainfall). Both the above-cited experiences, from dry semi-arid areas in Tanzania and the Sahel, originate from regions with low (Tanzania) to medium (the Sahel) human pressure on arable land. If farmers are reluctant to invest in micro-catchments in these areas (due to the need to sacrifice cropland for runoff harvesting), then the question is how socially viable this system really is in sedentary semi-arid agroecosystems with annual rainfall > 300 mm.

### **Pitting systems**

Pitting techniques, where shallow planting holes (< 35 cm deep) are dug for concentration of surface runoff and crop residue/manure, are found in many farming systems throughout sub-Saharan Africa. The *zai* pitting technique from Burkina Faso has proven to improve millet yields, especially during low rainfall years in semi-arid Ouagouya area in the Yatenga region (annual rainfall ~ 600 mm) (Ouedraogo and Kaboré, 1996). A similar system is the *ngoro* pitting technique from the Matengo highlands of Tanzania, which is used to conserve soil

moisture in steep lands (35 – 60 %) (Temu and Bisanda, 1996). In Arusha and Arumeru districts in North-western Tanzania, farmer managed trials have shown that small planting pits dug with hand-hoes are very efficient in breaking notorious plough-pans (caused by disc-ploughing and animal drawn mouldboard ploughing), and in concentrating surface water and plant nutrients. The technique is labour intensive, but simple and an efficient way of assuring that the crop benefits from the limited investments in fertilisation afforded by the farmers (Rockstrom et al., 1999).

In Katumani, Kenya, at the Kenyan Agricultural Research Institute (KARI) another locally adapted manual pitting system has been developed (the so-called Katumani-pit), which is similar to the small *zai*-pit found in Sahelian countries.

Farmers in Uganda and in Kenya have developed a very successful pitting system for bananas in semi-arid areas. In Machakos district, Kenya, farmers dig large almost 1x1x1 m basins, often connected with a furrow to a road or path drainage ditch. In these pits manure and crop residue is mixed with topsoil and then bananas are planted inside. These sheet and rill runoff harvesting pits are able to sustain a banana crop in areas with less than 300 mm of seasonal rainfall (though in this case in areas with bi-modal rainfall). Some progressive farmers in, e.g. Babati, Tanzania (Gösta Eriksson, pers.comm.) and in the semi-arid Southern Province of Zambia (Kebede Tato, pers.comm.) have adopted this system.

The relatively common use of manual pitting systems among African small-scale farmers is interesting as the system in general conforms very badly with national agricultural policies focusing on modernisation of agriculture, which normally means transition to tractor traction or at least to animal traction. The reality in SSA is that some 80 % of the cultivated land is manually tilled, and in many areas, like, e.g. Southern Zambia and large parts of Ethiopia, there is a lack of draught animals, either due to disease (corridor disease in Zambia) or due to poverty (in Ethiopia). Pitting enables the farmer to carry out tilling during the dry season, and to concentrate investments in only a limited portion of the cropped land (compared with broadcasting of fertilizers and seed often used in conventionally ploughed systems). For example, our own experience on conservation farming dissemination in Arusha, Tanzania (an area where tractors have been used for decades also by small-scale farmers) is that pitting systems often rate highest in performance according the farmers.

### ***Demi-lunes and Negarims***

In the Sahel, small micro-catchments using semi-circular earth bunds (demi-lunes) are common and used both for annual crops and to establish, e.g. fruit trees. Similar semi-circular earth bunds are found in arid and semi-arid areas (annual rainfall = 200 – 275) of Kenya, for both rangeland rehabilitation and for annual crops on gently sloping lands (normally < 2 %) (Thomas, 1997). For the establishment of fruit trees in arid and semi-arid regions (seasonal rainfall as low as 150 mm), Negarim micro-catchments are often used. These are regular square earth bunds turned 45 degrees from the contour to concentrate surface runoff at the lowest corner of the square (Hai, 1998).

In Niger efforts have been done to mechanize the establishment of demi-lune micro-basins using specially designed ploughs (Fondo Aiuti Italiani, FAI, Damergou project) (Antinori and Vallerani, 1994).

### ***Tied infiltration trenches***

In the Southwestern parts of Uganda, where banana production constitutes the backbone of rural food security, efforts have been made, especially in Mbarara district, to develop water harvesting methods for banana fields. This work has largely been promoted by USCAPP (Uganda Soil Conservation and Agroforestry Pilot Project), and was initiated in 1992 by the Regional Soil Conservation Unit of Sida (RSCU, presently RELMA, the Regional Land Management Unit of Sida). Bananas are cultivated on the relatively steep foothills, which are



often submitted to severe water erosion. The result is soil fertility depletion and reduced soil infiltration. To tackle this problem water infiltration trenches have been developed, which are dug along the contour, at specified intervals according to the slope (Plate 1). Even though not properly documented, farmers in the area report stabilised and substantially increased banana yields. The technique is widely adopted in the Mbarara district and is spreading to other regions of Uganda (Nyakuni, pers.comm.).



*Plate 1. Tied infiltration trench in banana field in Mbarara district, Uganda (photo: RELMA).*

In low rainfall areas in southern parts of Ethiopia, farmers have developed a highly specialised water harvesting system. The cropland is prepared in multitudes of circular depressions (3 - 4 m in diameter and < 1 m deep) where a variety of crops are inter-cropped. There is literally no runoff from the fields. In good years, all crops are harvested. The kind and amount of crop yield decreases with the reduction of the seasonal rainfall depths. The decline/loss of yield follows a pattern or sequences like maize, and then sorghum followed by cotton and pigeon pea, flax (Shone, pers.comm.).

### **Conservation Tillage**

A major cause to human induced land degradation in small-holder farms, is the intensive soil preparation by hoe or plough, which together with the removal or burning of crop residues, leaves the soil exposed to climatic hazards such as rain, wind and sun (Benites et al., 1998). Conventional tillage using ox- or tractor drawn ploughs has over the years been perceived as the indicator of agricultural modernisation in developing countries. It is, however, becoming more and more apparent, that ploughing techniques developed in temperate regions with gentle rains and low wind and water erosion problems, can have seriously adverse effects on the long-term productivity of erosion prone tropical soils. Conventional ploughing has proven to contribute to increased runoff and reduced plant available soil moisture, due to the creation of impermeable plough-pans at roughly 12 - 15 cm soil depth. Also, ploughing in biomass poor hot tropical areas lead to accelerated combustion of organic matter, thereby reducing water-holding capacities of soils. Ploughed land also has higher evaporative water losses due to increased soil surface exposed to the atmosphere.

Conservation tillage includes any tillage system that minimizes the loss of soil and water. As these systems have shown to be efficient in maximising infiltration and soil water-holding

capacities, we have opted to include them as an interesting water harvesting strategy. In the conventional terminology conservation tillage also involves the operational threshold of leaving > 30 percent mulch or crop residue cover on the surface throughout the year (SSSA, 1987). Translated to farming operations it basically means abandoning the plough (i.e., no inversion of the soil), in favour of alternative tillage practices with a minimum of soil disturbance. Conservation tillage is thus a broad umbrella term, used to define a wide spectrum from zero tillage systems at one extreme (no soil disturbance), via minimum or reduced tillage, to systems where the inversion of the soil is substituted to production systems involving subsoiling, ripping and perhaps even mechanical weeding between permanent planting lines.

From a rural development perspective this means that for the small-scale farmers in sub-Saharan Africa many facets of conservation tillage are not new, but rather developments of the very original farming practices based on shifting cultivation and long fallows. However, from a water harvesting perspective, our focus here is primarily on conservation tillage systems that are used to rehabilitate seriously degraded soils by maximising the harvesting of water where it falls.

Tillage implements used in conservation tillage efforts in Eastern and Southern Africa are e.g. ox-drawn subsoilers, rippers (chisel plough), and ripper-planters (Kaoma-Sprenkels et al., 1998), ridgers and donkey drawn tie-makers (Nyagumbo, 1998), manual hand-hoeing of planting pits, to direct-drilling of seeds in zero-tillage systems. There are many examples of successful conservation tillage systems that reduce land degradation, labour needs and often increase yield levels among small-holder farmers in, e.g. Botswana, Ghana, Nigeria, South Africa, Tanzania, Zambia and Zimbabwe (Benites, et al., 1998; Kaumbutho and Simalenga, 1999). Following are but a few examples of experiences from the field.

#### **Box 2. Zambia - Conservation farming**

In Zambia conservation tillage (termed conservation farming) has been lifted up as the mainstream government policy on agricultural development of small-scale farming in the country. Several government institutions, donors and NGOs are involved in promoting systems ranging from zero/minimum tillage using herbicides for commercial cotton rotations (CFU, 1997), manual pitting systems (a USAID financed organisation called CLUSA), to animal drawn rippers and subsoilers (IMAG-DLO, 1998). Sida, through the SCAFE-Land Management and Conservation Farming programme, is in the process of taking onboard animal drawn conservation tillage using ripper and subsoiling methods.

The Dutch institution IMAG-DLO, has some 15 years experience from Niger, Zambia and South Africa, in developing implements for conservation tillage (e.g. the Magoye Ripper, Palabana Subsoiler, ripper-planters). These implements are used by Sida programmes in Tanzania (SCAPA - Soil Conservation and Agroforestry Pilot Project in Arusha, LAMP - Land Management Programme in Tanzania, RELMA - Regional Land Management Unit of Sida) and in Kenya (RELMA). IMAG-DLO in partnership with Africare (an American NGO) is also carrying out production systems research on conservation tillage in collaboration with GART (the Golden Valley Research Trust), as well as manufacturing of implements in collaboration with a private company (SAMS).

**Box 3. Kenya - Conservation Tillage Initiative**

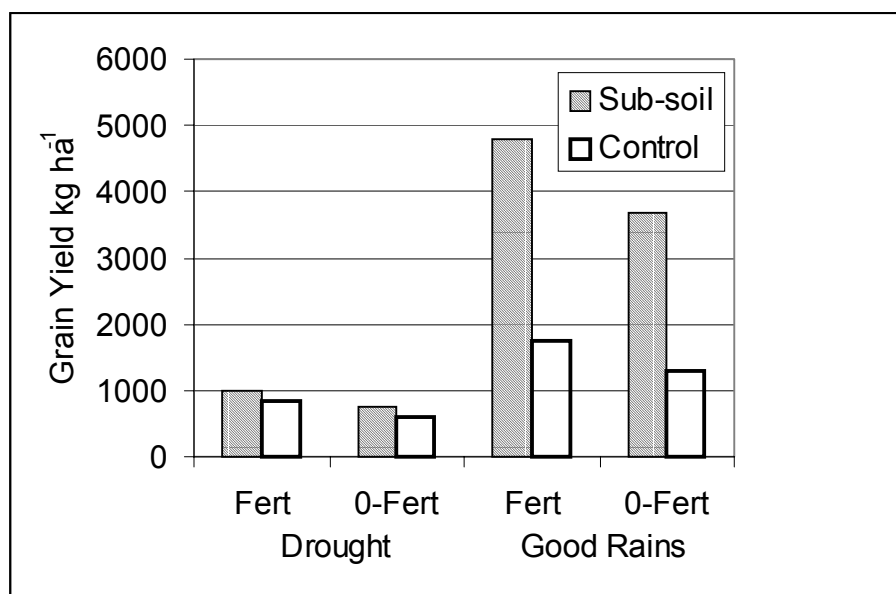
In Kenya an initiative on promotion of conservation tillage systems for smallholder farmers has recently started (in 1999). On-farm trials on various animal drawn and manually tilled conservation tillage practices are carried out by RELMA in partnership with the Ministry of Agriculture, KARI, KENDAT (The Kenya Network for Draught Animal Technologies, and Nairobi University (Dept of Agricultural Engineering). The long-term objective is to initiate piloting activities including capacity building of extension staff, on-farm research, extension, manufacturing and marketing.

**Box 4. Northern Tanzania - Conservation tillage**

Human induced land degradation to large extent due to decades of disc ploughing, has resulted in serious yield losses on cropland in Northern Tanzania, with average on-farm yield levels of 0.5 - 1 t ha<sup>-1</sup>. To alter this vicious spiral of land degradation some commercial farmers have converted to conservation tillage practices, where the disc plough is abandoned in favour of subsoiling, which breaks the hardpan without turning the soil. As a contrast, smallholder farmers in the area have continued with conventional practices (mouldboard plough or disc-plough), and progressively abandon land that becomes too unproductive.

Recently, farmer driven research and demonstration trials have been initiated in the area to improve water harvesting through conservation tillage systems for small-scale farmers, involving an initial subsoiling followed by ripping. The results on both soil and water conservation, reduced labour requirements and increased yields are in general so good that farmers are making efforts to adopt the new tillage practices (Brunner et al., 1998; Jonsson, 1998; LAMP, 1999; Rockstrom et al., 1999).

Figure 9 shows the results from demonstration trials carried out by the LAMP/Sida program through ORGUT-Consulting and the Ministry of Agriculture (LAMP, 1999) in Babati area on maize, where tractor subsoiling was carried out before the onset of the rains. Cattle manure was applied at a rate of 5 t ha<sup>-1</sup> (defined as FERT treatments in Figure 9). Subsoiling more than doubled maize grain yield during a year with good rainfall (1995/96). Even during a drought year (1996/97) the yield from the subsoiled plots was higher, but the difference was less distinct, which is a result of the overall water deficit during that year.



**Figure 9.** Maize yields from demonstration trials in Babati during a good rainfall year (1995/96) and a drought year (1996/97), showing the effects on yield of subsoiling and fertilisation (manure) (Source: Jonsson, 1998; LAMP, 1999).

The reason to present the Babati results here is that they point at two crucial issues regarding water harvesting in SSA. First, it shows the huge opportunity of drastically improving the amount of crop produced per drop of rainfall, just by increasing soil infiltrability (by breaking up plough pans), moreover, through easily adopted, cheap and available techniques.

These results suggest that before even considering more investment requiring WH techniques such as flood or storage systems, easily available and cheap infiltration maximising techniques should be exhausted. Secondly, the results indirectly address the need of integrating WH with soil fertility management. Fertilisation gives additional value (as grain yield) to the rain through relatively higher grain yields within the same amount of rainfall. Also, it is probably doubtful if the, though at first sight successful, unfertilised subsoiled system is sustainable on a longer term. The breaking of plough-pans enable roots to penetrate and extract soil water from deeper, since year's untapped layers of the soil. Once depleted on soil nutrients, yield levels may start falling.

In Arusha and Arumeru districts, RELMA in collaboration with SCAPA (the Sida-financed Soil Conservation and Agroforestry Pilot program in Arusha) and LAMP/ORGUT, is presently carrying out demonstration trials on different conservation tillage systems for smallholder farmers in the area. The basic tillage implements involved are; ox and tractor drawn subsoilers, ox-drawn Magoye ripper from Zambia, and hand-hoe. Production systems, addressing timing of operations, fertilisation, weeding, and post harvest management of crop residues (mulch materials), were designed together with the farmers. After two years of on-farm trials, results indicate that manual pitting and ripper/subsoiler treatments linked with soil fertility management (in this case manure, rock-phosphate and urea), substantially increases maize yields in the area.

### **Moisture retention/conservation (terracing and bunds)**

Techniques to slow down sheet and rill runoff produced within crop fields and thereby reduce soil loss due to water erosion are probably the most common water harvesting systems in sub-Saharan Africa. These include techniques like terracing, retention ditches, stone bunds, and trash lines. They are normally defined as soil and water conservation (SWC) structures, and are primarily promoted to reduce soil erosion. Technically moisture retaining structures are

very similar to the contour ridges and strip cultivation systems described above, but the field scale design is entirely different. While the contour ridges are used to harvesting sheet flow from the upper 3/4 or so of the inter-contours for concentration in the lower 1/4 or so of cultivated land, the widely promoted moisture retaining systems are applied while keeping the entire cropland under cultivation. The primary objective is thus to avoid that sheet flow develops into rill flow over longer distances. These systems thereby apply over a wide range of rainfall depths, but always in areas where average annual rainfall is sufficient to cover crop water requirement, i.e. generally with seasonal rainfall > 300-350 mm.

These moisture retaining or water conservation techniques have been very well documented, are implemented directly by farmers throughout SSA and form the very foundation of many development projects with agricultural development and land management on the agenda (Reij et al., 1996; Lundgren, 1993; Hurni and Tato, 1992; WOCAT, 1997).

In Kenya the famous *Fanya Juu* terraces, which are made by digging a trench, normally along the contour, and throwing the soil upslope to form an embankment, has had a very significant effect on reducing soil erosion in semi-arid areas with relatively steep slopes (Thomas et al., 1997). Tiffen et al. (1994) present evidence from Machakos district in Kenya suggesting that the adoption of *Fanya Juu* terraces played an important role in reducing land degradation over a period from the 1930s – 1990s when population increased more than fivefold. Similar widely spread techniques are the *Fanya chini* developed in the Arusha region, Tanzania (soil thrown down slope instead of upslope), stone bunds, and trash lines (successfully promoted through extension in dry areas of South-eastern Kenya). In Ethiopia annual mobilisation campaigns are used to rehabilitate degraded lands by constructing retention ditches and stone terraces (Lundgren, 1993). In the northern province of Tigray, micro-basins (roughly 1 m long and < 50 cm deep) are often constructed along these retention ditches for tree planting. In the Axum area in northern Tigray these retention ditches, which prevent large volumes of surface runoff from flowing down the steep escarpments, have contributed to the revival of natural springs that according to the local communities had dried out (probably due to severe upstream deforestation, authors comment).

In Burkina Faso contour stone bunds, which were an improvement of traditional stone lines, have proven highly successful in reducing water erosion in the semi-arid Yatenga region. The hydrological impact and agronomic performance of this system has been extensively studied, indicating substantial yield increases if efforts are done to maintain soil fertility (Reij, 1988). Serpentié and Lamachère (1992) showed that treating small watersheds with contour stone bunds could be a very efficient way of increasing plant water availability throughout the rainy seasons.

Trash lines, where crop residue or any other dead or living mulch material, is concentrated to form organic bunds along the contour, are commonly used by farmers in, e.g. Kenya. Research by KARI (Kenyan Agricultural Research Institute) has shown that trash lines can be an efficient and labour extensive technique to improve infiltration and increase yields of maize.

### **Assessment of performance**

It is most probably safe to say that in-situ water conservation and within field micro-catchment systems are the most studied of all water harvesting systems in sub-Saharan Africa. As shown above, there is thorough documentation of indigenous methods, which have been developed by farmers over a long time and form an integral part of many farming systems (e.g. the pitting techniques). There is probably no land management oriented development program anywhere in sub-Saharan Africa during the last 20 years that have not had at least some component of soil and water conservation promotion on the agenda.

Even though these systems are widely promoted among farmers, there is relatively (to their importance and prevalence) little biophysical research on the performance of different methods. An important global effort of documenting the biophysical and socio-economic

knowledge about soil and water conservation is presently carried out through the WOCAT project (World Overview of Conservation Approaches and Technologies, WOCAT, 1997). One of the major challenges within this initiative is the difficulty in finding quantitative data on water balance parameters, soil loss, agronomic performance etc., of the various soil and water conservation techniques that are documented. Several research programs have been carried out, e.g. the Soil and water conservation research program in Ethiopia, which generated much knowledge on plot scale, especially on runoff and sediment generation. Similar research has been carried out on several soil and water conservation techniques (FAO, 1987; Hurni and Tato, 1992; Kessler et al., 1995).

#### **Box 5. The knowledge gap**

There is a lot of documented knowledge on design, function and adoption of in-situ systems and micro-catchment systems, less on biophysical preconditions and hydrological functions of the systems (but still much more than runoff farming, flood and storage systems). As most of these systems have been promoted primarily for erosion control, there is little documentation on yield impacts. However, the principle gap seems to be in the hydrological impact of these systems on the scales above the plot scale (hillslope, watershed, river basin).

Finally, we have put much focus in the above on conservation tillage. There are three reasons for this. First because conservation tillage systems, where they have been tried out, offer cheap, labour extensive, and effective methods for maximising infiltrability of degraded soils in a wide spectrum of hydro-climates (from humid to semi-arid locations). Secondly, conservation tillage systems have equal emphasis on productivity and conservation of land. While traditional soil and water conservation methods of course have a favourable impact on soil productivity, the primary objective has always been to reduce soil movement and get rid of excess runoff water. Conservation tillage focuses on zero runoff and maximised soil productivity. Thirdly, after over 20 years of scattered efforts on conservation tillage in sub-Saharan Africa, there seems to be a broader movement building up, which can have a real long-term impact on farming system performance throughout the continent if given a chance to develop (see Africa Conservation Tillage Network below).

## 2) Runoff farming

Runoff farming systems, where sheet and rill runoff flow is harvested from external catchments and diverted onto cropped land, are common in many areas of sub-Saharan Africa. Many of the systems fall in the transition between runoff farming and floodwater harvesting, depending on the size of external catchment and the type of runoff that is harvested.

Circumstantial innovations by progressive farmers seem common in the field of runoff farming. Farmers observe the flow of surface water through their own watershed, and based on experimentation on trial and error basis, sophisticated runoff farming systems are developed. This can for example be the tapping of sheet flow from asphalt roads, diversion of sheet flow from rocky areas adjacent to farmland, or diversion of surface runoff from footpaths.

Runoff farming systems play an important role in small-scale farming systems in SSA, which probably is explained by the fact that:

- (1) The techniques are easy to design,
- (2) The runoff volumes are reasonably limited (sheet and rill runoff), which means that the farmer can with little effort control the inflow of water (especially to avoid water logging),
- (3) With relatively simple means significant volumes of water can be added to crops during rainfall events.

### ***Runoff collection from roads, foot-paths, compounds***

In many parts of Eastern and Southern Africa, farmers have developed simple runoff farming techniques, where sheet and rill runoff generated from compacted surfaces such as roads, footpaths and household compounds, is diverted either directly onto cropped land, or into storage structures such as ponds. Road runoff harvesting diverted for crop production in Kenya is promoted by the Ministry of Agriculture (Mutunga, K., pers.comm.). There are several examples of progressive farmers in semi-arid areas of Kenya tapping road runoff, for supplemental irrigation and subsurface irrigation of fruit orchards. These systems vary from very simple diversion structures directing surface water into crop fields, to deep trenches with check-dams in order to enable both flood and subsurface irrigation. In the latter case, where gully flow is diverted to crop fields, the system strictly speaking is a flood WH system, but as the transition from runoff to flood water harvesting is diffuse we have chosen to describe them here.

In the Nyando river basin, one of the two Kenyan tributaries to Lake Victoria, ICRAF (the International Centre for Research in Agroforestry) together with the Ministry of Agriculture/Sida (the National Soil and Water Conservation Programme) and RELMA, is studying the role of footpaths as a source of eutrophication of Lake Victoria. Footpaths, dirt roads and compounds, consist of compacted soils often with heavy erosion crusts that produce high volumes of runoff. These can be used to harvest runoff upstream for productive purposes.

In the Southern Province of Zambia, efforts are presently being made (by the Ministry of Agriculture, Food and Fisheries, SCAPE-Land Management and Conservation Farming, and RELMA) to train extension staff on techniques to harvest sheet runoff flow from household compounds in subsurface farm ponds. These can then be used for irrigation of small home-gardens or for livestock.

### ***Road and railway infrastructure for runoff farming***

In Tanzania there is an increasing attention being paid to the possibility of utilising excess runoff generated from road construction and railway systems. In Tanga, Tanzania along the

Arusha-Mwanga highway, farmers adjacent to the highway are using storm-runoff flow coming through culverts to inundate farmland. Railway culverts are connected to an irrigation scheme of 150 ha for smallholder farmers in semi-arid Singida, Tanzania (Hatibu et al., forthcoming). In many locations in sub-Saharan Africa farmers use borrow-pits (which are pits along roads resulting from construction excavation) as an important source of domestic and productive water. This is, e.g. common for Masai communities in Tanzania, who use borrow-pits along the Morogoro-Dodoma highway for their livestock.

These water harvesting structures are, from the perspective of the authorities responsible for implementation of the infrastructures, there only to get rid of a problem - runoff. There is a large scope to link infrastructural development with local water demanding communities when designing infrastructure.

### ***Trapezoidal bunds in dry semi-arid areas***

In dry semi-arid areas farmers have developed various systems using large soil bunds (often > 100 long structures along contours) to concentrated sheet runoff from land adjacent to the field. These are generally designed with a flat base and wing-walls. The systems have been defined as trapezoidal bunds according to the layout where the angle between base and wings often is set at 135 degrees, creating large trapezoidal structures. Bunds are generally spaced some 20 m apart, to allow overflow of runoff to discharge over the tip of the wing walls, down slope to the next row of bunds (Chritchley and Siegert, 1991). The crop is cultivated within the enclosed area of the bunds. These systems have an indigenous foundation, and are used by farmers in several arid and dry semi-arid environments in, e.g. the Horn of Africa (Kenya, Somalia, Sudan). They are generally constructed by hand and used for subsistence cultivation. An example is the so-called "Teras" system, a widespread system of large earth bunds with straight walls, used to cultivate drought tolerant crops like sorghum, in areas with as low as 150 - 300 mm of annual rainfall (van Dijk and Reij, 1994). Efforts of project implementation of large designed trapezoidal bunds (120 m between upstream wings and 40 m at the base) have been done as well like, e.g. in Turkana in northern Kenya for sorghum, tree and grass growth (Thomas, 1997). According to documentation, these systems seem to have a good agronomic performance (even though there is little or no published yield data), and the main concern is whether they are socio-economically viable depending on labour costs, and what equipment is used to construct them.

### ***Earth bund and spillway systems***

Runoff farming by inundation, harvesting sheet and rill flow from external catchments, is very common in India, but less practiced in sub-Saharan Africa. Systems tested in, e.g. Kenya; include soil bunds aligned along the contour, with spillways at 20 m intervals to control the application of surface water in each bund-section where the crop is cultivated. Bunds are set at 15-20 m intervals and the catchment to cultivated ratio ranges from 5:1 to 20:1 (Pacey and Cullis, 1986).

Again, these runoff farming systems harvesting external runoff, often fall under floodwater harvesting techniques, basically as soon as the runoff flows in permanent gullies. Some of the diversion systems using soil bunds and spillways for inundation irrigation are described below under floodwater harvesting.

### ***Assessment of performance***

Runoff farming systems more often than not form an indigenous part of farming systems in sub-Saharan Africa. As these systems are more purely water harvesting systems compared to in-situ systems (promoted primarily to collect water for improved land productivity and not to reduce erosion), there is generally more emphasis on hydrological parameters in documented experiences.



However, there is still only very scattered knowledge on hydrological and agronomic performance of runoff farming systems compared to conventional farming without runoff farming. Also, as with in-situ and micro-catchment systems, little or no research has been carried out on upscaling of the systems, and the impact on the hydrological cycle of upscaling.

The experiences on road runoff collection, the use of infrastructure such as roads and railway, borrow pits etc. for runoff farming, has not been systematically studied. There is probably a large scope to investigate options of improving the performance of such systems.

Runoff farming systems include the first level of techniques that require knowledge on catchment hydrology for their design and to assess their performance. There is a large need for further systems research, looking at runoff farming from a watershed perspective. This includes research on runoff dynamics of catchment areas, techniques for runoff speed reduction and maximising infiltrability in command area, and land management methods to maximise water-holding capacities of the systems.

### **3) Floodwater harvesting**

Floodwater harvesting systems, where storm floods in gullies and ephemeral rivers are diverted onto cropped land, play an important role in several arid to dry semi-arid regions of sub-Saharan Africa. They are in general much less common than within-field and runoff farming systems. An important reason for this is certainly the larger planning scale involved (watershed scale) and the potentially large volumes of water to manage (which, if wrongly designed can result in serious water erosion).

In rural communities where flood water harvesting plays an important role, the techniques generally form part of an old tradition, some times (like in the case of the arid valley farming in Eritrea) even forming the core basis making the existence of a sedentary community possible.

Under this category we have also included the often very successful efforts of harvesting gully flow along the gullies, on it's way downstream, using various biological treatments (e.g. elephant grasses and bananas) and engineering structures (like check dams). These systems obviously have a double objective, of controlling gully erosion and to harvest floodwater and thereby making gullies productive.

#### ***Spate irrigation for paddy rice in Tanzania***

In semi-arid central parts of Tanzania (e.g. Dodoma, Singida, Shinyaga), farmers have since the 1920's developed extensive flood irrigation techniques for paddy rice. Farmers cultivate rice on sediment rich lowlands (so called "Mbuga" soils). Surface water from gullies originating from steep hilly areas, is diverted into small cultivation basins (so called "Majaluba"), which are ~ 10 by 10 m and some 0.2 - 0.5 m deep with 25 – 100 cm high earth bunds (Mwakalila and Hatibu, 1992). It is estimated that some 32 % of Tanzania's rice production originate from cropland where this water harvesting technique is practised. It has enabled a significant increase in both cultivated area and in rice yields. Over the last 15 years the largest increase in rice production in Tanzania has occurred in semi-arid regions (Hatibu, pers.comm.). In fact, this is quite remarkable. The expansion and productivity increase of such water demanding crop like rice occurs in semi-arid areas and not in more humid areas, and it can be attributed to the locally developed floodwater harvesting system.

A related technique in the same region of Tanzania is the conveyance and concentration of sheet and rill flow from small catchments into crop fields of, e.g. maize and sorghum, using shallow channels and soil bunds.

### ***Spate irrigation in Eritrea and Ethiopia***

The centre excellence of flood irrigation in Eastern and Southern Africa is probably found in Eritrea and Ethiopia. Spate irrigation has a long history in the horn of Africa, and still forms the livelihood base for rural communities in arid parts of Eritrea and the upper rift valley in Ethiopia. Storm-floods are harvested from rainfall-rich highlands, which are diverted into levelled basins in the arid lowlands. In Eritrea the embankments conveying the storm-water can be extremely large (5 – 10 m high), and are built by shovelling the sandy soils using animal traction. The maintenance of the embankments is very labour intensive, and carried out on community scale.

### ***Flood water harvesting for agroforestry in Turkana***

Lehmann (1997) presented interesting results from an arid area in Turkana, northern Kenya, showing the potential of using flood irrigation in alley cropping systems with sorghum and *Acacia saligna*. In this dry bimodal area farmers normally do not plant any crop during the short rains (September-October). In the experiment storm floods from an ephemeral stream carrying water from a nearby mountain range, was directed to level irrigation basins (ratio cropped to catchment area = 1:100). The system enabled a second sorghum harvest, with high biomass production of both sorghum (~2000 kg above ground DM ha<sup>-1</sup>) and of acacia growth (some 1000-1500 kg ha<sup>-1</sup>). A similar system has been tested for sorghum in the same area, using a water spreading scheme diverting storm floods from an ephemeral river using a gabion weir for flood irrigation of some 6 ha crop land (Fallon, 1963).

### ***Productive gullies in Tigray, Ethiopia***

In the densely populated and water scarce areas of Tigray in northern Ethiopia, gully reclamation for productive purposes (Plate 2) has been practised with favourable agronomic results (encouraging potential of successfully cultivating banana, elephant grass, and sugar cane), but with complex socio-economic implications (Rockstrom et al., forthcoming). Unclear land tenure resulted in difficulties in privatising the reclaimed gully, which in the progressive abandoning of crop husbandry in the gullies.



**Plate 2.** Rehabilitated gully in Adaga Lemne watershed, Axum, Tigray Province. (Photo: Johan Rockstrom)

### **Assessment of performance**

As stated initially, flood water harvesting systems often form part of flood water harvesting cultures, i.e., the very existence of a rural society depends on production systems where floodwater is harvested, generally from external catchment areas with higher rainfall levels than in the command areas where the flood water harvesting is carried out (e.g. Ethiopia, Sudan, Eritrea). In these systems the issue of performance is not necessarily relevant as the system is a *sine qua non* for human settlement in the area. However, there is a scope for improved biophysical understanding of the function of the systems, in order to identify options for improvements of e.g. water use efficiencies, and increases in productivity (Amanuel Negassi, pers. comm.).

However, as shown above for the example of paddy rice production in Tanzania, flood water harvesting plays a significant economic role even in semi-arid farming systems, where flood water harvesting (1) is a relatively late introduction (20th century) and (2) normally is not directly is perceived as a viable hydrological option.

## **4) Storage systems**

In general, water harvesting systems with a storage component for supplemental irrigation are the least common of all water harvesting systems in sub-Saharan Africa. Even though it is common to find micro-dams and farm ponds for storing water in semi-arid areas (e.g. Central Province in Kenya), they are generally located downstream in watersheds, and the water is predominantly used for livestock and to cover household needs. It has been shown though that farmers in, e.g. semi-arid areas of Machakos district in Kenya, use earth dams for spot irrigation (with buckets) of small vegetable gardens (< 0.25 ha) (Farmesa, 1997b).

This indicates a very essential character of storage water harvesting structures; namely that they generally serve multipurpose uses. A survey carried out in Machakos district indicated that farmers first of all prioritise domestic water uses and not until these are covered, consider supplemental irrigation (Jurdell and Svensson, 1998).

The large water requirements (in general some 1,500 – 3,000 m<sup>3</sup> ton<sup>-1</sup> dry matter yield) in crop production also means that earth dams (generally 200 – 1,000 m<sup>3</sup> storage capacity) normally are used only to supplement a crop with water during stress periods. The choice of small vegetable gardens when considering irrigation is also logic, as the water generally has to be lifted from the earth dam/farm pond to the crop field, which is very labour intensive. Irrigating, e.g. cereal crops on larger fields would simply not be feasible.

Storage systems cover a broad spectrum of techniques, from open surface water storage in micro-dams, retention dams recharging soil water and shallow water tables, sand dams and subsurface dams in sand rivers.

Four major challenges are directly related to development of storage systems in smallholder farming communities in sub-Saharan Africa:

- They operate at a larger scale than within-field systems, often on a watershed scale, and thereby necessitate addressing issues like ownership, local institutions, and land tenure.
- They necessitate relatively high capital and labour investments (often too high for individual households).
- They are relatively complicated systems to design.
- Service giving institutions generally have very little capacity to disseminate and assist in design of storage water harvesting systems.

Added to the above is the complication that storage water harvesting often does not have a clear "institutional" home in government administrations. Earth dams used for irrigation evidently form part of an agricultural development, thereby falling under the mandate of Ministries of Agriculture. But, as soon as rainfall (which generally is not considered being a

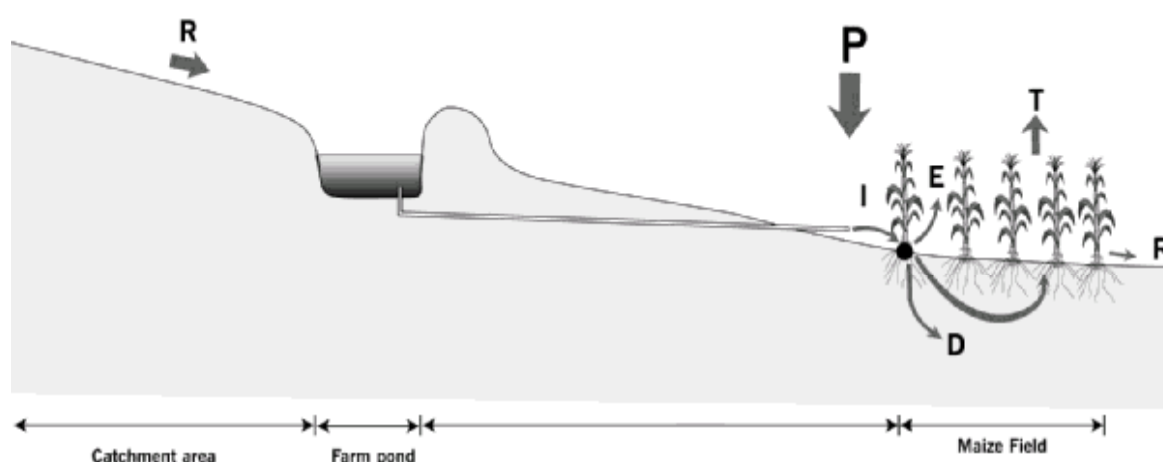
water resource) is stored in a dam reservoir, it turns legally into a water resource, which normally falls under a Water Act, managed by a Ministry of Water Resources (or similar).

### **Surface storage: Earth dams, farm ponds and rock catchments**

The possibility of using farm ponds for dry spell mitigation using supplemental irrigation of staple food crops is currently studied in a semi-arid area of Machakos district, Kenya (Barron et al., forthcoming) and in a dry semi-arid area in Northern Burkina Faso (Fox and Rockstrom, 2000; Rockstrom et al., 1999b). Farmers in large parts of semi-arid Kenya traditionally build hand-dug earth dams and farm ponds, but these structures are generally placed at the downstream end of a gully or rill, and do not permit the use of gravity for irrigation. In the case of the ongoing research hand-dug ponds are located upstream, harvesting sheet and rill flow from small (< 3 ha) catchments, in 15 - 300 m<sup>3</sup> ponds.

Figure 12 shows the schematic catena of the system developed in Machakos district, Kenya. Tentative results using these systems, capturing sheet and rill flow from small catchments to bridge dry spells during sensitive growth stages of the crop (sorghum in the Burkina case and maize in the Kenyan case), show that are viable both from an agronomic and hydrological perspective. Yield levels are significantly increased and especially stabilized over time.

However, the most relevant farming systems factor to consider, is the indication that dry spell mitigation using supplemental irrigation reduces risks for crop reductions/failures to the extent that farmers may start considering it worthwhile to invest in inputs (such as fertilizers, improved varieties, pest management). This is generally not the case in the conventional system where complete crop failure occurs statistically 1 year out of 5 and dry spells hit the crops a majority of the rainy seasons.



**Figure 12.** Schematic view of catena showing the storage water harvesting system used in Machakos district, Kenya, for dry spell mitigation of maize, through gravity-fed supplemental irrigation of maize in an area with an average seasonal rainfall of 300-350 mm (from Barron et al., forthcoming).

In the semi-arid parts of Laikipia district, in central Kenya, underground water tanks have been promoted for multipurpose uses (Mbugua, 1999). The tanks are semi-circular (Plate 3) with a storage capacity of 100 m<sup>3</sup>. The bottom is smeared with cement to avoid seepage, and the tanks are covered (with local materials) to reduce evaporation losses. The water is harvested from rill- or sheet flow from small sub-catchments near to the tanks. These small tanks only permit irrigation of small kitchen vegetable gardens (100 – 200 m<sup>2</sup>).





**Plate 3.** Construction of a semi-circular underground tank for domestic uses and micro-irrigation of vegetables in Laikipia district, Kenya. (Photo: John Mbugua)

In the Tigray region of Ethiopia small earth-dams harvesting stream-flow diverted from small gullies are used for supplemental irrigation of mainly Tef (*Eragrostis tef*), wheat and barley (Rockstrom et al., forthcoming). An alternative use of micro-dams is shown in Plate 4. This dam reservoir in Tigray primarily recharges a natural spring located downstream. This protected spring supplies enough water to enable micro-irrigation of vegetables.



**Plate 4.** Micro-dam harvesting surface runoff from gully on plateau escarpment. The water is used for livestock and to recharge ground water flow. (Photo: Johan Rockstrom)

Harvesting of surface runoff from rock catchments for storage in masonry dams is a common practice in several countries in SSA. The largest concentration of rock catchment dams in East Africa is found in the semi-arid parts of Kitui district, in Eastern Kenya (Nissen-Petersen, pers.comm.) (Plate 5).



*Plate 5. Example of rock catchment masonry dam from Kitui district, Kenya. (Photo: Erik Nissen-Petersen)*

Rock catchment dams in the region are found in a wide range of storage capacities (20 – 4000 m<sup>3</sup>), and are generally used primarily for domestic purposes (Nissen-Petersen and Lee, 1990a). However, they can also be used for small-scale irrigation of vegetable gardens.

### ***Sand dams and subsurface dams***

Sand-dams and subsurface dams are common in semi-arid regions with ephemeral sand-rivers. They are used in combination with shallow wells located upstream of the dams (Nissen-Petersen and Lee, 1990b). The wells are again, primarily, used for domestic purposes, but in several cases also for small-scale irrigation. Sand-dams and subsurface dams are cheap to implement and if correctly designed produce good quality water. However, the siting and design of the structures, necessitates technical know-how, especially to avoid siltation and leakage. According to Nissen-Petersen (pers.comm.) who carried out an investigation on sand/subsurface dam performance in semi-arid parts of Kenya, some 80 % of the dams are not performing as they should, due to poor design.

### ***Constructed wetlands***

In South Africa, Auerbach (forthcoming) has experimented with constructed wetlands as a means of harvesting storm runoff for productive purposes. Similarly, natural lowland wetlands, as the "dambo" areas in Zambia, and the "bas-fonds" in the Sahel, harvest surface runoff, which is stored as shallow groundwater and used for dry season vegetable gardening.

### ***Assessment of performance***

Storage systems for crop production are the least common in sub-Saharan African smallholder farming systems. There are several scattered experiences, but overall there is very little data

available to make conclusions on biophysical and socio-economic performance. Especially, there is a large knowledge gap on the hydrological pre-conditions for and impact of storage systems. This makes it very difficult to assess the role storage systems can play to improve livelihoods of resource poor farmers in semi-arid environments.

Added to the above, there are still a number of technical challenges associated with storage systems. Storage systems for crop production require reservoirs which can hold even in the smallest scale  $> 3 \text{ m}^3$ , but generally  $> 1,000 \text{ m}^3$  to make them viable for, e.g. supplemental irrigation. Moreover, they have to be as deep as possible, in the case of surface storage, in order to minimise evaporation losses. Evaporation and seepage are major losses of water in open water reservoirs ( $> 2 \text{ m}$  of water can be lost over a year), and it is generally expensive to seal dams and reduce evaporation. There are efforts ongoing on trying to develop low-cost sealing techniques (G. Shone, pers.comm.) and trials are ongoing to test living roofs of passion fruit and a crawling plant called "lupher" (Erik Nissen-Petersen, pers comm.). The performance of open storage systems depend to a large extent on these three factors: soil depth, soil texture (determining seepage), and evaporation.

Storing water in the soil, and using WH to recharge shallow water tables, are very interesting techniques, as they can produce water with little cost, low losses, and with a good quality. Sand dams and subsurface dams have been promoted in dry areas with sand rivers for several decades (in e.g. Kenya), and are still used to supply domestic water to several rural communities (i.e., they perform very well in covering domestic needs). There are only few examples of subsurface storage for production, at least for larger scale than small home-gardens (of say  $< 250 \text{ m}^2$ ).

## **Regional water harvesting initiatives**

### ***Africa Conservation Tillage Network***

As a response to the urgent needs for efforts of increasing land productivity and reducing environmental degradation in African smallholder farming system, the Africa Conservation Tillage (ACT) network was launched early in year 2000. Apart from sharing information the network has the objective of facilitating piloting activities on conservation tillage systems in different hydroclimatic settings in Eastern and Southern Africa. This initiative may be the most interesting effort of within-field WH at present in sub-Saharan Africa.

### ***GWP Associated programme on Water harvesting network***

The Regional Land Management Unit (RELMA) of Sida in collaboration with the Centre for Science and Environment (CSE) in New Delhi, are the core institution in a newly established associated programme within the Global Water Partnership (GWP) on setting up a network on green water harvesting in S. and E. Africa and S. Asia. This network will have the objective of concentrating and sharing knowledge on rain water harvesting, sharing experiences between Africa and Southern Asia, and to facilitate studies on the viability of WH systems. In Africa the network will build on existing national water associations, and on existing networks on water harvesting. These existing networks focus mainly on domestic water harvesting, and the objective is to broaden their scope.

### ***Mvula Trust Water harvesting network***

In Southern Africa, DFID (the Dept for International Development, UK) is supporting a regional water harvesting network that is coordinated by the Mvula Trust in South Africa. The network has as a primary objective to focus on policy issues related to water harvesting, and to function as an advocacy for WH in the member countries.

## **WATERNET**

With support from Sida and the GWP, the International Institute for Hydraulic and Environmental Engineering (IHE) in Delft, the Netherlands, is coordinating a regional network on water resources management in southern Africa (named WATERNET). A research fund based in Zimbabwe, financed by Sida, is linked to WATERNET. Even though water harvesting is not the core activity of WATERNET there is a window for small-scale water harvesting initiatives within this network.

## **Conclusions regarding water harvesting in sub-Saharan Africa**

Water harvesting for crop production is absolutely nothing new in farming systems in sub-Saharan Africa, and there are numerous indigenous and more recently introduced techniques practiced by small-scale farmers on the continent. In many farming communities water harvesting has been independently invented and used for centuries with large success, often even forming the very basis for the social institutions, the economy and culture of the society (like e.g. the spate irrigation systems in Eritrea and the Matenga pit systems among the Irakwe farmers in Tanzania).

However, when doing a general continental overview (which of course is difficult as there are so many local initiatives that are difficult to capture in one limited report), it seems clear that in-situ water conservation and runoff farming systems are the most commonly practiced systems, while flood water harvesting and especially storage systems are less common, and in many farming systems unknown, or not practiced at all. Following the same scale from in-situ systems to storage systems, the documented knowledge on biophysical and socio-economic preconditions for adoption and performance, seem to decline (from an already quite low level) from in-situ systems to storage systems.

This suggests that there remains much research work on the viability of flood and storage water harvesting systems, within a farming systems setting.

Runoff farming are simple and generally produce a good source of water. Perhaps because of their simplicity and small construction scale (the crop field), the focus of development efforts have mainly been on technical aspects of the runoff farming structure in the field. Very little systems research has been carried out, where the total system; catchment, diversion, and cropped land has been studied. Runoff farming systems require soils with good infiltrability, well designed structures to slow down speed of runoff flow during large storms, and good soil water holding capacities in order to function.

In general there is very little agro-hydrological documentation on different water harvesting systems, both regarding preconditions for use, and impact on downstream water users of adoption. This relates especially on larger scale adoption, e.g. what happens on a catchment scale if a significant proportion of farmers upstream adopt storage water harvesting for supplemental irrigation of grains, and full irrigation of vegetable gardens?

Two questions on storage and flood water harvesting remain unanswered, (i) why they are not adopted on a larger scale (in areas where the systems are known), and (ii) why they are not adopted in areas with no such systems but where the biophysical conditions would seem to be very well suited for these systems. This gap on the understanding of adoption criteria for WH is very wide, and must include issues like biophysical preconditions for system function, socio-economic preconditions, market issues, land tenure issues, and the critical issue of human capacity. While adoption of within field systems requires relatively little knowledge capacity among extension agents and farmers, storage and flood systems require a relatively high level of knowledge in design and construction to be successful. This addresses the very critical issue for SSA of what external services must farmers expect when developing their production systems. There has been a tendency over the last 10-20 years in development efforts to be reluctant in relying on external knowledge and investments in rural development (and instead rely on farmers indigenous knowledge and the farming communities own



capacity to solve their own problems). Water harvesting is an excellent test case in trying to find the dependency balance between external trained expertise and indigenous expertise. To establish even the smallest earth dam, there is a need of expertise on assessing catchment size, runoff production, water balance accounting, and interpreting rainfall and climatic data (just in order to assess possible volumes of surface water that can be harvested). Added to this is the engineering expertise required to design and construct, e.g. an earth dam that can cope with tropical storm floods (spill ways, intakes with sediment traps etc. are needed), and which results in a minimum of water losses through seepage and evaporation. This requires expert knowledge on soil properties. Can we expect front line extension staff or farmers on village level to master all this knowledge? Of course not. No farmer in Sweden would ever be expected to be able to perform the large task of assessing river flow, design diversions and water reservoirs. Instead they buy the service from private companies. How to blend indigenous knowledge and this need of expertise is a huge challenge in general for rural development in SSA, which especially affects WH development.

# India - revival of ancient technique

*"If rain is not caught and stored, it will be impossible to live in India."*

*-Anil Agarwal, CSE director*

The increase in population coupled with accelerating industrialisation and urbanisation has led to increased demand for water. At the same time a decreased supply of fresh water is at hand. Seventy percent of available water is polluted. An overexploitation of water resources decreased water quality and increased competition over the resource call for actions.

India has an ancient history of water harvesting. Proofs are found in archaeological material and ancient texts. The classification of rainfall regimes, soil types, crop mixes and irrigation techniques were well known. The colonial state dramatically changed the economy and as a consequence these systems collapsed.

The ancient art and science of 'collecting water where it falls' needs to be revived to meet today's needs of fresh water sustainability. Both for drinking and small-scale irrigation purposes India's traditional water harvesting systems as well as the successful examples of today have a lot to teach.

## Water - an unevenly distributed resource

India has 2.4 percent of the world's land area and 16 percent of the world's human population. 75 percent of the Indian population lives in villages and farms. About 70 percent of India's farmers are marginalized or landless.

India is one of the wettest countries in the world but also one of the countries facing frequent droughts. The resource is distributed unevenly both in time and space. Seventy-five percent of India's agriculture is rainfed.

Of the 1050 km<sup>3</sup> of blue water (rivers, lake and groundwater flow) projected for use in year 2025 (Table 4), about 70 percent is expected to come from surface water and the rest from groundwater. This may be hard to achieve. Numerous rivers are today heavily exploited and the groundwater table is falling rapidly in many parts of the country. There is also a decreasing quality caused by urbanisation, industrialisation and agricultural modernisation.

**Table 4.** India's use of water on 1974 and the projected use in 2025, in km<sup>3</sup>/yr (Agarwal, 1997)

	Year 1974	Year 2025
<b>Irrigation</b>	<b>350</b>	<b>770</b>
<b>Domestic and industrial uses</b>	<b>30</b>	<b>280</b>
<b>Total:</b>	<b>380</b>	<b>1050</b>

Dr Anil Agarwal has shown that rain captured from 1-2 percent of India's land can provide the population of 950 million 100 litres per person and day.

## Rich water harvesting traditions

*"Indian kings knew the value of water. They maintained ancient traditions of harvesting rainwater."*

The kings rarely ever built tanks themselves but encouraged people to build water harvesting systems by providing them fiscal incentives. If agricultural production fell in a drought year,

the king got less money through taxes. Therefore, he had an interest in a stable and high agricultural production.

The water harvesting tradition dates back 4,000 to 5,000 years. Indians were forced by the laws of nature to develop the techniques. The high amount of yearly rainfall, about 1100 mm, is unevenly spread in time and thus needed to be stored. Most parts of the country receive rainfall during not more than 50 days and when rainfall occurs the duration is short, less than 4 hours. It is often characterized as heavy showers. In response to this ephemeral resource, Indians developed a range of water harvesting techniques (Table 5).

**Table 5. Water harvesting techniques in different Indian regions (Agarwal, 1998)**

Region	Type of WH system	Use
Arid plains	Artificial catchments to capture rainfall ( <i>tankas, kundis</i> )	Drinking water
	Tanks ( <i>sarovars</i> or <i>talabs</i> ) captures surface runoff. Often in conjunction with wells or step wells ( <i>bawdis, jhalaras</i> ) that capture seepage from the tanks	Drinking water /Irrigation water
	Embankments thrown across drainage channels to capture surface runoff and moisten soil for cultivation ( <i>khadins, jodas</i> )	Irrigation water
Semi-arid plains	Tanks to capture surface runoff ( <i>eris, keris</i> )	Irrigation water and Drinking water through recharge of groundwater accessed through wells, sometimes made adjacent to tanks or even in tank beds
	Chain of connected tanks depending on diverted stream flows and surface runoff from individual catchments	Irrigation water and Drinking water through recharge of groundwater accessed through wells, sometimes made adjacent to tanks or even in tank beds
Floodplains	Mud embankments which were breached during the flood season to carry away the crest of the floodwaters containing rich, fine silt and fishlings into channels which would irrigate farmlands and fill up village ponds	Irrigation water /Drinking water
Hill/ mountain regions	Diverted stream flows ( <i>kuhals, kuls, guls, pats</i> )	Irrigation water
	Diverted stream flows stored in tanks ( <i>zings, zabo</i> )	Irrigation water
	Diverted stream flows taken to farms through animal yards	Manured irrigation water
	Springs	Drinking water

### **Traditional WH techniques adopted to the environment**

There are a number of different WH techniques in India, well adapted to the local environment. The Centre for Science and Environment (CSE) has made an excellent work in collecting information about old WH techniques in India presented in the book "Dying wisdom" (Agarwal and Narain, 1997). Below are some of the WH systems presented.

1. Artificial glaciers made close to the village, to ensure water before the natural glaciers melt in late summer.

2. Bamboo pipelines - a 200-year-old system of tapping stream and spring water, by using bamboo pipes. Water is carried over inhospitable terrain in southern Meghalaya, and used as irrigation system for betel leaf plantations.
3. Beris - collects water within the desert sand.
4. Eris -water catchers (tanks) built into the terrain collecting surface runoff. Overflow from eris at higher levels travels into the lower ones.
5. Johads - reservoirs behind small dams constructed across the slops to collect runoff and force it to infiltrate.
6. Khadins - artificial wells, typical to Rajasthan but can be made and used to store rainwater wherever land is available.
7. Kui - collects rainwater trapped in the sand above a hard gypsum layer. They are usually covered with planks of wood (Plate 6).
8. Kuls- diversion channels for irrigation. They carry water from glaciers to villages.
9. Kundis - covered dome-shaped storage tanks holding rainwater for the local people and animals, Rajasthan (Plate 6).
10. Mughal groundwater-based water supply system in Madhya Pradesh.
11. Pynes - channels constructed to utilise water flowing through hilly rivers.
12. Qanats - underground canals tapping an alluvial fan on mountain slopes and carry the water over large distances to a well.
13. Surangam - tunnels carved out in the rock to gather rainwater.
14. Temples in south India played a role in irrigation. The endowments were used to maintain tanks and irrigation channels.
15. Virdas - shallow wells dug in low depressions to collect rainwater, used by the nomadic Maldharis.
16. The zabo system - Below a catchment area, kept under natural vegetation, are ponds dug to harvest water for irrigation and animal consumption. It is common to maintain a fenced cattle yard below the ponds and above the paddy fields. Thus runoff water enters the fields rich in manure.



**Plate 6.** Three examples of old technology. A kundi (top left), kui (right) and an ancient dam. (Agarwal & Narain, 1997).

## Overexploited groundwater

The policy of promoting large dams and mechanised ways of exploiting groundwater has led to a lack of public interest in government projects. The state subsidised water, which lead to overexploitation of groundwater. Then more wells were installed. In the past 40 years the extraction of groundwater has increased tremendously. In 1951 there were 3.86 million dug wells and in 1990 the number had increased to 9.49 million (Table 6). The water is lavished and the demands grow, triggered by an expanding population. Increased human pressure on a finite groundwater resource combined with widespread mismanagement has resulted in serious deterioration of groundwater quality and quantity.

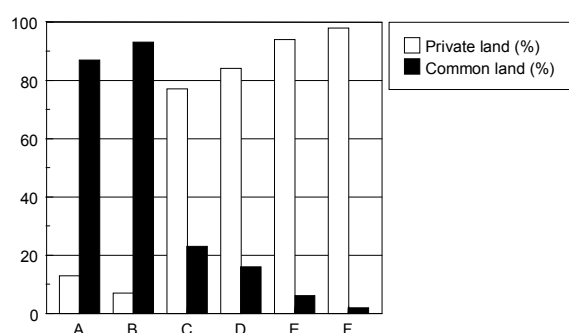
**Table 6.** Number of wells and pumps in 1951 and 1990 respectively (UNICEF, April 1998)

Source of groundwater	Year 1951	Year 1990
Dug wells	3 860 000	9 490 000
Shallow tube wells	3 000	4 750 000
Public tube wells	2 400	63 000
Electric pumps	21 000	8 220 000
Diesel pumps	65 700	4 360 000

This recent development of groundwater resources resulting in unsustainable extractions is a debated issue. On the one hand the large scale adoption of farm level electric and diesel pumps formed the very backbone of the green revolution. Without water the external input based packages of improved crop varieties, fertilizers and pesticides would never have yielded either crop nor farmer response. On the other hand the negative environmental impacts are strongly felt today. The hidden loss during this process of unprecedented agricultural development (that many claim saved India from extensive and otherwise unavoidable famines) was the traditional legacy of water harvesting.

## Land ownership causes social tensions

Traditionally wealth of a family or a person was counted on basis of four aspects: land, knowledge, money and livestock. The patterns and levels of inequality and domination vary across India. Village communities are relatively homogeneous in many tribal regions and hill, mountain and desert areas. Social tensions are usually between the village community and government agencies controlling the common land. In the plains the society is sharply stratified with a high concentration of land ownership (Figure 11).



**Figure 11.** Private versus common land ownership in India (Agarwal and Narain, 1989). A=Mountain, B=Arid plains I, C=Arid plains II, D=Irrigated arid area, E= Irrigated semi-arid area, F=Humid plains.

Promotion and adoption of water harvesting systems relies strongly on reasonably secured local ownership of land resources. It is difficult for farmers to invest in storage systems for supplemental irrigation on land they do not control.

## Overpopulation of poor maintained animals

India has 20 percent of the world's livestock population. This in itself forms a huge water harvesting challenge in terms of drinking water for livestock. India's share in the total milk production of the world is around 13 percent. The annual average milk yield of Indian cattle is 51 percent less than the world average (DAHD= the Department of Animal Husbandry and Dairying of the Union Ministry of Agriculture). Cattle comprise 43.5 percent of India's livestock population. About six percent of India's population are pastoral nomads.

Animals form an essential part of the food security, especially with declining soil fertility. However, humans compete with livestock for food and water. The choice is between growing food grain to feed the poor or growing crops for animal feed. Some argue that culling is needed but generates a lot of religious motion. Others mean that great precautions have to be taken if slaughter is carried out. Not because of the religious problems but even the low productive animals produce *gobar* (cowdung) and *gaumutra* (cow urine). The fertility of soil in India has been maintained for millennia from cattle manure, which also constitutes a source of fuel. The greatest quality of the indigenous cattle is that they are hardy and resistant to diseases.

The large livestock has put tremendous pressure on the available land. About 90 percent of the cattle population in the country subsists on natural grasslands or common pasturelands, which are in an extremely poor state. There is a great scarcity of fodder. In the absence of proper feed, productivity is low, which means that more animals are required to produce the same amount of milk, putting further pressure on resources. The livestock economy of India is characterised by low productivity, overpopulation of animals, poor management and lack of adequate maintenance of stocks.

India's livestock population of 450 million large and small animals depend on a meagre area of 12 million hectares for green fodder. This means 40 animals to one hectare of land. It should be no more than 5 animals. As a consequence, livestock goes into forest to graze. This causes disputes between livestock-owning communities and those involved in management and research of forest and wildlife. Barely 4.6 percent of the land area of India is protected forest. However, some mean that the loss of forests is due to corruption in forest departments, which make illegal logging possible, rather than overgrazing.

Another aspect of the livestock is their importance as draught power.

### Box 6. The importance of livestock in India

- \* There are 84 million draught animals in India, 72 million of which are rural based.
- \* They plough 65 percent of the total cultivated area in India
- \* 70 million farms, smaller than 3 hectares cannot go for tractors
- \* Five times the freight and four times the passenger traffic as compared to the Indian railways, are carried by non-mechanised transport, primarily draught animals.

Source: Down to Earth, Vol 9, No 2, 2000.

## India today - water crisis

The highest rainfall in the world is recorded in Cherrapunji, which today (Year 2000) faces water shortage. The monsoons failed at the end of the 1999 and the areas Gujarat and Rajasthan were drought-hit. The strategy in such cases has been to provide employment in massive drought relief works. Drinking water is provided through emergency digging of new tube wells, which further mines the groundwater assets.

Gradually realising that water mismanagement has led to the crisis and not absolute scarcity of water, the government rediscovers WH. The present scenario is that mayors are taking lessons in WH and organisations and governments are promoting WH, both in urban and rural areas. The government is planning to finance 10,000 WH structures in the drought-affected regions. Some are doubtful. People have to be aware of the need to play an active role in water management and frameworks are needed for their participation. Otherwise, there is an obvious risk of failure.

There are other projects realizing the importance of decentralization plans to tap rainwater, including rooftop harvesting and channel storage are made in Delhi. This project aim at gradually replacing the government-oriented centralised water supply system with a people-oriented, decentralised and demand driven programme.

## Glimmers of hope

The severe drought hitting Rajasthan, Gujarat and western Madhya Pradesh in 2000 manifested, besides the extensive human suffering, also the opportunities at hand to use water harvesting for drought mitigation. There have been a lot of incidents regarding water disputes and the police have even shot people. Groundwater resources have been overexploited and everyone is fighting for the limited resources available. The dispute is not seldom between urban and rural areas (the city contra the villages). The communities in the region that have undertaken WH have a completely different situation to those who have not (Plate 7). The villages practicing water harvesting have water to drink and also some water to irrigate their crops. In the neighbouring villages many villagers are fleeing the drought. Many communities are, after the drought, expected to demand support for WH-programmes.



**Plate 7.** Left: Mahudi village in Gujarat's Dahood district is unaffected by the severe water crisis in the state due to stored water in check dams. Right: Drought affected Madar village of Udaipur, Rajasthan. Source. *Down to Earth*, Vol 9, No 1, 2000.

Hardevsinh Baldevsinh Jadega, *sarpanch* (head) of Raj-Samadhiyala villages in Rajkot district is a "warrior". He has encouraged the villagers to build 12 check dams and undertake watershed development. This year (2000) the rainfall is less than two-thirds of the normal. Despite this fact and thanks to WH actions, the farmers can sow cotton, wheat, groundnuts and vegetables. To raise funding for the project several rules, including fines, have been developed in the village. For instance, if anyone's livestock eats the leaf of a tree, the person has to pay Rs 5 per leaf. If the owner is a member of the panchayat (council), he has to pay the doubled amount.

Harnath Jagawat, head of Sadguru Water and development Foundation, is working on water conservation with poor tribal communities in Panchmahals district. In 1994, when he first discussed the idea of working on water problems in the area, government officials and politicians did not understand. "There is no water here". Jagawat turned to the villagers of Thunthi Kankasiya and got them to build a check dam and take up intensive watershed

development work. Today the river flows round the year. The rainfall year 2000 was only 40 percent of the normal. Even so, the farmers have irrigated 135 hectares and the 23 wells have enough water to meet the drinking water needs. Jagawat works with many such villages today.

**Box 7. Positive examples from WH in drought areas**

**Borkhedi village, Rajasthan:** There is water and people have been able to irrigate land to a large extent.

**Mahudi village, Gujarat:** Check dams dot the rivulet. A virtual 'flood' is seen in the village.

**Polapan, Gujarat:** Covered with greenery and groundwater at 4.5-6metres.

**Raj-samadhiyala, Boria, Rampar and Belda villages in Rajkot district:** Drinking water and enough food

**Villages in Surendranagar district:** Despite a rocky topography, a high rate of evaporation and annual average rainfall 330-380 mm, water harvested in 1999 helps the people cope well.

Source: Eklavya Prasad, Down to Earth, Vol 9, No 1, 2000

**The Arvari story - a river is revived**

*"Scarce natural resources need to be developed and utilized in a sustainable manner, which is possible only if the villagers believe in the program and participate in its implementation."* -Mr Anna Hazare

In the 18<sup>th</sup> century the 45 km river Arvari in Alwar district, Rajasthan was considered as the main groundwater recharge stream for the villages on its banks. In the beginning of the 1980's the river was considered dead and the fields surrounding it were barren. In the village of Bhaonta-Kolyala 30 wells were empty and only 30 percent of the 221 hectares of land were cultivable. The villagers used to take one, rain-fed, crop. In 1986 the villagers through voluntary labour built a huge johad. It caught the water from surrounding hill-slopes. Since 1986, 238 water harvesting structures, mostly *johads*, have been built in the 70 villages in the 503 km<sup>2</sup> watershed. The effort was to catch and allow water to percolate. Each monsoon stream was dammed and hill slopes were treated to stop run-off and soil erosion. The structures were collectively recharging groundwater that was seen as rising watertables in the wells. Gradually the Arvari River began to flow even after the monsoon period and since 1995 the flow did not cease. It has become perennial because of the regulated distribution of run-off. The people of Bhaonta-Kolyala village were awarded as the most outstanding environmental community of India.

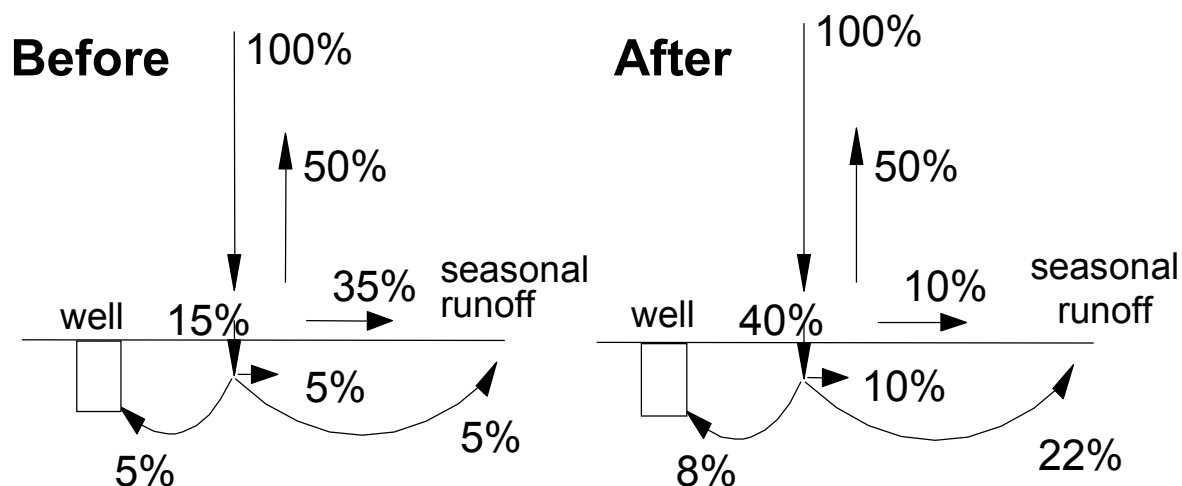


**Plate 8.** The entrance of Hamirpura village, a revived river. Source: Down to Earth, Vol.7, No 19, 1999.

Today about 5 percent of the rainwater is used for irrigation. This seemingly small percentage makes a huge difference. Not because of the amounts but the water is now available at critical stages of plant growth. Small-scale water harvesting systems operate in a similar way, giving the farmer a tool to supply water to the crop when it is most needed. Before the WH structures



were built, the water was lacking during those critical periods and thus resulting in poor yields or crop failure. The annual average rainfall in the region is about 600 mm (comparable to Sweden) but about 80 percent falls during the monsoon. R N Athavale, emeritus scientist at the National Geophysical Research Institute has made an estimate of water partitioning before and after introduction of WH (Figure 12).



**Figure 12.** Rain water partitioning before and after water harvesting structures in the Alwar district, Rajasthan. Based on estimates by R N Athavale, emeritus scientist, presented in *Down to Earth*, Vol 7, No 19, 1999.

The seasonal run-off has decreased by 25 percent and there has been an increase in soil moisture from 5 to 10 percent. About 22 percent of the rainfall is now spread out over the year and recharge the Arvari River.

### **Ralegan Siddhi - a lesson to learn from**

Ralegan Siddhi is a village with 2000 persons and rainfall of barely 400 -500 mm. In the beginning of the 1980's the people only got one meal a day and about 50 percent of them had to buy food grain from outside the village. Hardly any drinking water was available. Men walked 5-6 kms everyday in search of wage employment. Today, about fifteen years later, irrigated land has increased from about 70 acres to 1200 acres. The village is exporting vegetables. This improvement was made through watershed development.

Mr Anna Hazare stresses the importance of considering the village as the unit of development and that technically sound installations are made. He further stresses the importance of developing the whole watershed. This includes contour trenches, percolation tanks, gully plugs, check dams and also regeneration of grasslands and planting of trees.

He also points out the importance of people's participation, which can lead a village towards self-reliance and self-sufficiency:

### **Decentralized structures needed**

*"The challenge that India faces in the coming decades is that of balancing the increasing demand with the diminishing supply of water."*

The success stories are often initiated by single persons or by NGO's and made possible by the villager's voluntary work. This decision of taking control of their own development and

not depend on the government seems to be a very important part of the success. With the slow awakening of officials and the huge problems due to long drought periods and increasing demands, the future is an open question. India has the knowledge of WH, slowly arising from history. Sometimes buried in sand and wastes, in the form of mismanaged old structures. The reuse of old knowledge is not only a question of techniques. Water harvesting is a practise related to local community needs and sensitive to local ecological demands. Decentralized social structures are needed for sustainable development.

## China – attempts to curbing rural exodus

*"The water is so precious that the principle -irrigating the crop and not the land- is adopted and application often performed manually with a bucket and a cup, pouring water on the plant's stem."*

It is expected that by the year 2030, 70% of the population in China will live in urban cities, and therefore, emphasis is put on city water resource development. Nevertheless, to curb the exodus from the rural areas, attention has been put on securing water resources in threatened villages. Primary attention is put on securing drinking water resources including water for livestock, and secondly for agricultural supplementary irrigation. The semi arid regions are seen as potential areas for investment in rural societies since there is enough water, but are nevertheless periodically scarce. Only recently has this part of the country-recognised water as the backbone for development. The west (such as Gansu) was first to recognise this fact.

China is for a second consecutive year suffering from a drought (1999-2000). Water shortages and decline in water availability has been an alarming trend the past decade and has, in combination with increasing land degradation leading to desert-like conditions, triggered extensive action by the central party committee. The so-called. "greening project" in the northeast and north western arid and semi-arids is one such attempt. Within the project, an extensive reforestation programme is undertaken to reclaim low yielding cropland, slopes under extensive erosion, over-logged areas and land areas in danger of desertification. Millions of trees are to be planted within the frame of this 50-year project, and Water Harvesting (WH) is the method by which the tree seedlings are to be ensured survival under the hydrologically harsh climate.

This chapter is based on experiences on water harvesting in the water scarcity prone regions of Gansu and Hebei provinces. In general, there is a fundamentally opportunity based attitude to water harvesting in drought prone China, where water availability to Man, crop and animals, is directly linked to rain; a resource presenting an untapped potential of being harvested.

### Gansu province: Megaproject to support economic stability

The population of the Gansu province is 26.7 million. The Yellow river flows in a north-south direction forming a natural border between the arid east and the semi arid west. 33% of the land is cultivated and inhabited by 66% of the population. The total water resources are estimated to 26.9 billion m<sup>3</sup>, making an average of 1.200 m<sup>3</sup>/capita for the eastern part and a mere 800 m<sup>3</sup>/capita for the west (the national average is 2.100 m<sup>3</sup>/ capita). The annual rainfall averages from 30 mm in the northwest to 860 mm in the southeast, and the potential evaporation ranges from more than 2000 mm to 1300 for the respective zones.

The middle and east is semi arid and mountainous, composed of deep loess soils with a runoff level below 10%. Due to the loess soil conditions, with depths measuring to hundreds of meters, the rain does not reach the ground water and farming relies exclusively on the rain. However, a mere 19-24% of the rain falls in the period between May to June when crop water requirements account for 60% of the total growing period.

Water harvesting has been conducted for at least the past millennium in the western part, and presently, 2,5 million people are estimated to have insufficient drinking water in the east.

### ***The "121" project***

With the above information at hand, a project named the "121" project was initiated in 1988. The "121" refers to 1 green house, 2 tanks and 1 *mu* (Chinese land area measurement equivalent to 1/15 Ha or 667 m<sup>2</sup>) cultivated /irrigated land. A variety of surfaces have been tested for their runoff producing capacities including: natural surface, compacted soil surface, cemented surface, asphalted surface, plastic lined surfaces, roof surfaces of both tiles (cement and clay) and cement roofs. The cemented surface was found to be the most efficient – and not too costly – with 70-72% runoff (percent of rainfall generating runoff on seasonal basis) to be expected. Natural soil surface generally produce a mere 2% runoff, and already by compacting the soil, the runoff is increased to 20%. Professor Zhu Qiang and Mr Li Yuanhong have presented the project background in the report: Zhu and Li (2000). Therein is presented the outline of the project and its objective: to better secure the living standards of farmers by adopting WH systems to make available drinking water and stabilise yields on farms by ensuring water availability by means of supplementary irrigation.

In particular the high water retention capacity of the dominating loess soils in the region have proven to be a vital factor in the agricultural conditions of Gansu province. According to experience, there will be a crop to harvest - albeit a drastically reduced one - even if no rain falls following a rain after sowing. With this prospective, farmers can concentrate on the crucial development stages of plants (germination, flowering and grain setting) for additional soil moisture to enhance production, rather than having to focus on all dry spells.

In the "121"-project, to ensure the farmers' economic stability, a greenhouse model was designed making use of, to the greatest possible extent, locally available material. The walls are made of loess soil bricks and the bows holding up the plastic sheeting are of metal and bamboo wood alternatively for strength and support. Farmers generally do not have direct access to markets due to long distances, so produce is sold to merchants through contracts or ad hoc., who then bring the produce to the markets. Under normal conditions, at least two harvests can be collected per year, and sometimes even three! But if rains have been poor and the tanks have not been filled with collected runoff water, then one or two harvests are to be expected. Nevertheless, the investment of roughly 7000 Yuan (880 USD (excluding labour costs)) made by the farmer can be recovered already after its first year of operation. Maintenance costs, apart from labour, is roughly 330 Yuan/year (42 USD) for the plastic, which needs to be changed roughly every 3 years – depending on quality of plastic used (cheaper plastic quality require annual change).

### ***RWH efficiency - a new tank programme***

A follow-up programme to the "121" project is already under way. This new programme named "RWH efficiency", includes the construction of a further 50.000 tanks with the capacity to store more than 2 million m<sup>3</sup> of harvested rainwater. The programme is primarily orientated to sustain fruit trees and medical plants rather than cereal production. Every person is to have one tank and every family is to have one greenhouse. Under normal years in a family one tank is needed for drinking water. During bad years two tanks are needed for drinking water and 2 tanks for irrigation. This has resulted in the "1 tank per person" objective. Within the "121" project, 86.000 tanks have been constructed. In order to fulfil the objective of the RWH efficiency programme, the goal is to construct about 156.000 tanks in total.

### ***RWH irrigation - a megascale project***

The Rain Water Harvesting Irrigation (RWHI) project covers an area of 156.200 km<sup>2</sup> with 17 million people and 2,9 million Ha of cultivated land in 65 counties. In view of the funds made available, the project is restricted to regions with at least 300 mm of annual precipitation. The government provides funds or credit to farmers who wish to be part of the programme, for investment in construction material including greenhouses, cement/artificially treated

surfaces, cement slabs and plastic film. The tanks constructed vary from 10 to 60 m<sup>3</sup>, though 30 m<sup>3</sup> tanks have proven to be most economically suitable as the construction (underground tanks lined with 10 cm cement including sealing) generally requires no reinforcement. Water is collected from a variety of surfaces as described above, including roads, courtyards, playing grounds etc. The water is stored in the underground tanks minimising any evaporative losses and later extracted for irrigation. The water is so precious that the principle “irrigating the crop and not the land” is adopted – similar to drip irrigation – and application is often performed manually with a bucket and a cup, pouring water on the plant’s stem. The application is low, about 5 m<sup>3</sup>/*mu* (75 m<sup>3</sup>/ha) (7.5 mm/ha) for each application (to be compared with 60 m<sup>3</sup>/*mu* (90 mm/ha) per application in conventional irrigation schemes). A 30 m<sup>3</sup> tank can supply irrigation water to 1-1,5 *mu* (667-1000 m<sup>2</sup>). By the end of 1999, 1,23 million tanks were built and 190.000 Ha of land received 2-3 applications through the RWHI project. This corresponds to a total quantity of about 36,9 million m<sup>3</sup> of water. If all precipitation was to be harvested from a land surface, with an annual precipitation of 300 mm, the land surface required is equal to 12.300 Ha. The runoff efficiency is more likely to average about 10%, meaning that 123.000 Ha land is required. The ratio between irrigated and catchment area is then a mere 1:0,7. This should be compared with the rule of thumb that is generally 1:3. The efficiency of water usage with simple techniques is clear, but the application of the concept in such large numbers gives cause to wonder of the implications on downstream users.

Under normal conditions, wheat harvests range from 150-800 kg/*mu* (2.250-12.000 kg/Ha) and millet harvests range from 100-225 kg/*mu* (1500-3400 kg/Ha). Nevertheless, harvests have proven to increase by 40% through supplementary irrigation (comparable to results obtained in both Indian and African semi-arid regions). Furthermore, by using greenhouses (providing a better evapotranspirational water use efficiency (the amount of crop produced per unit evapotranspiration) and biomass production thanks to shading) and making better use of the water, cash crops and fruits which could not previously be grown in these regions have given the farmers an improved economic situation. At best, the economic return has improved with 100% (from about 125 USD to 250 USD per capita). However, as one farmer put it: “our lives have improved, but we have to work harder now”.

### ***Technical equipment***

A variety of equipment is in use to supply and deliver water to the sites:

- Manual or diesel pumps to extract the water from the wells or tanks.
- Tractor pulled tanks are used for irrigation primarily of tree seedlings.
- Kombi sowing and irrigation is performed (irrigation parallel to sowing – a water tank is constructed on the sowing machine and delivers water to the seed pocket as the seed is dropped) 2-5 m<sup>3</sup> of water/*mu* is generally applied.
- Drip irrigation is performed with priority in the greenhouses. (Investment cost: 600 meters pipe for 300 Yuan (37 USD)). Many families can use this as it can be moved. Drip irrigation nipples are used: Investment cost: 1 Yuan (0,12 USD)/nipple
- Low irrigation sprinklers. Also primarily used in green houses. (Investment cost: 8 Yuan (1 USD)/sprinkler)

### ***Achievements and findings***

- The project has developed viable storage cellars/tanks with efficient sealing wall material, which permits little infiltration losses.
- The project has provided with education to farmers setting RWU (Rain Water Using) standards for the province – primarily adopting the principle of applying irrigation only during the 3 most important cropping stages (germination, flowering and grain setting).
- Two international conferences have been held on WH issues.

- 1996, 100.000 Yuan (12.500 USD) was raised through donations by people in the region to promote the “121” project.
- People are taught how to siphon water out of the tanks should the setting permit it.
- The most cost efficient tank has been found to be the 30 m<sup>3</sup> tank with an implementation cost of about 1.300 – 1.500 Yuan since it requires no reinforcement. Increasing the volume to a 50 m<sup>3</sup> tank raises the cost to above 3000 Yuan. Also, smaller tanks need less infrastructure in water works and channels.
- In reclaiming land to the forests, 1 m<sup>2</sup> plastic sheeting is spread around a tree seedling, sloping inward towards the stem increasing the amount of rainwater made available to the seedling.
- Crops are cultivated in furrows either *on* plastic sheeting or *between* plastic sheeting rows: an estimated 40% of the land is cultivated and 60% is used for collection to support the crop in water harvesting. Such applications increase water availability to the crop, reduces weed growth and limits soil evaporation.

### **Education**

- The municipality supplies with material and know-how, and the population delivers unskilled labour and transport local material to the site. Meanwhile, the farmers receive training in masonry and other necessary skills to conduct the work.
- Local organisations/agencies give courses and arrange for field visits for farmers.
- Farmers are given information on water standards and usage.
- Maintenance training involves cleaning tanks if possible at least once per season (from sediment transport etc.), leak detection and maintenance of the cement works.
- Information is given on strip/alley cropping: In particular maize and wheat seem to perform well combined.
- Information is provided through courses on new varieties, fruits, cereals, vegetables, etc.
- During information meetings, the greenhouse design is explained, costs involved presented and loans/credit schemes outlined.
- The households are given training in how to treat water with chlorine and general sanitation measures.

### **Future tasks**

According to the senior engineer on the water resources department, Mr Li, improvements can be done on, and attention will be put on:

- More studies on surface covering material that effectively and economically promotes runoff.
- Irrigation equipment needs to be further developed and optimised.
- Micro systems improvement: Family systems management and economic viability, including for farmers to obtain credit loans.

Problems encountered are lack of financing as a major issue and lack of better (cheaper) surface treatment material to improve runoff. Another problem is the reduced availability of suitable RWH area since the best areas are already in use.

## **Ongoing projects**

### **Box 8. Ganchao town in Yuzhong county**

Ganchao town is one of the first sites developed under the RWHI programme: A pilot site. Large surfaces on top of 2 hills have been levelled slightly and capped with a cement layer of 3 cm in depth, each hill covering 650 m<sup>2</sup>. (350 tons of cement was used, 50 kg costs 18 Yuan (2,2 USD)). The cement-capped surfaces have a runoff average of 72%. Other surfaces including roads and schoolyards have also been paved. From these surfaces and other not paved areas, cemented gutters deliver the water to tanks in the fields.

Houses are completed with cemented or tiled roofs. Water is collected in tanks in the house courtyards and then extracted through the use of hand pumps or a bucket and a rope. Left to settle for a week, the water obtains a turbidity of < 5 NTU and according to international WHO water standards, do not require any treatment with flocculants.

### **Box 9. Anjia Ying village**

This village is under a poverty alleviation project. It involves assisting 100 families (500 persons). One hundred greenhouses have been constructed under the 121 project, covering ½ *mu* each. 2000 m canals have been built to divert water, two hundred 30 m<sup>3</sup> tanks and one 200 m<sup>3</sup> tank have been built and a total of 2000 m<sup>2</sup> have been paved with cement. The system is designed to support 3 harvests per year, bringing an annual income of 10.000 Yuan (1250 USD) per greenhouse. The families have opted to invest (take loans) to purchase drip irrigation systems.

The greenhouses are built on a terraced slope, making it possible to harvest the rain falling on the above lying greenhouse for collecting water to supply the greenhouse below. Water is extracted by use of hand pumps.

Some of the families are further sponsored through ecological departments and are prohibited from using any pesticides or herbicides. Optimism and spirits were high among the families!

### **Box 10. Jing Quan township**

This region is one of the poorest in the province. Annual rainfall ranges from 340-450 mm. It is inhabited by some 460.000 people, who cultivate some 1,8 million *mu* of land, out of which 40.000 *mu* is under supplemental irrigation. In reclaiming the poor hillside farming land for forest plantation, the government offer annual incentives to the farmer of 100 kg of grain and 50 Yuan (\$6 US) per *mu* the farmer sets aside. The farmer obtains this incentive for about 7 years, until the tree produces fruit that the farmer can sell for his own profit. The most common forms are of the in-field WH type and involve primarily contour ridging and pitting with each tree allowed a space of 9 m<sup>2</sup> (3 x 3 m). 360.000 *mu* is intended for the reforestation programme. The programme is called ecological conservation and is part of a new national policy set by the government and involves turning poor farming land into forestland.

The vast floods in 1999 and desertification are mentioned as the primary causes for this action. The tree seedlings each have a pocket of a 3x3 m<sup>2</sup> that collect rainwater for the seedling's benefit. These holes are distributed in a chessboard formation covering large surfaces across the terraced hillslopes. Hilltops are sometimes paved and often ornamented with national monuments and the surfaces collect rainwater into tanks that are used to irrigate the tree seedlings.

**Box 11. Go Cu Chan - Road WH pilot project**

In collaboration with the department of road works, a pilot project for road WH (asphalted roads) was initiated. 27 families are involved in this pilot project. It includes diverting rainwater through viaducts and gutters to supply the tanks of the greenhouses by the road.

Up to date, 99 x 50 m<sup>3</sup> tanks and 1 x 100 m<sup>3</sup> tank have been built. They store water for a total of 100 *mu* and a further aim is to build one greenhouse (½ *mu*) per family, following the 121 project.

Irrigation is in average performed once every 10 days, and requires 7-8 m<sup>3</sup> per application. The farmers have generally invested in drip irrigation systems. The net income per season is estimated to 8.000 Yuan (1000 USD) with harvests. This corresponds to 35 *mu* worth of wheat grain (about 7-14 tons of wheat).

Farmers are very optimistic, and have not observed any problem with using the asphalt-road harvested water.

**Hebei province: water harvesting for fruit trees**

Annual precipitation amounts to 500-600 mm, and potential evaporation is about 1300 mm. The landscape is hilly with gradients ranging from 1 to 50%. The surface is rocky from extensive erosion. It is recognised that this hilly region has to depend on rain for its survival. About 100 million *mu* (6,7 million Ha) support a population of 65 million.

Within the vast greening project, with the aim of reclaiming eroded hillslopes and degraded farmland to forests, WH is used to secure the survival of tree seedlings. To spur the farmers to look after the trees, fruit trees are planted to be harvested by the farmer who may claim the profits. Furthermore, WH for supplementary irrigation is being investigated, in particular in combination with drip irrigation systems. Hully research station is experimenting with and building a trial site for pomelon fruits trees on a hill slope of about 8 *mu*. The slope varies from 25-42% and is terraced with steps typically about 2-3 meters wide and 0,5-1 meter high. It is estimated that one tree can produce 10 kg of fruit at a value of 8 Yuan/kg. One *mu* can support 80 trees. An annual production income should amount to 6.400 Yuan (800 USD) per *mu* (in a region where average income is about 125 USD per capita and year). The owners of the land intend to invest in two tanks, each of 10 m<sup>3</sup> on the 50% slope (the steep slope would make it difficult to build the tanks any larger). The intention is to irrigate during dry spells.

Many regions have suffered extensive erosion on the slopes, having left the slopes with little topsoil. Experiments are made with dynamite to blast into the rocks and create a potential hole for the plantation of a tree seedling, with reasonable water holding capacity. On the trial site, this seems to have had a successful effect.

Other experiments on the Hully research station include surface runoff trials on steep slopes, wells dug in gullies, and development of roof WH systems to be used for supplemental irrigation in orchards. Water is also harvested on the walkways in the compound and collected in ponds. The water is then pumped out of the cisterns, centrifuged in a cylinder to remove the sediment particles. The water is then finally pushed through a filter before the water is pumped out to the drip and sprinkler irrigation systems developed at the station in collaboration with the forestry department.

A number of pilot projects with government support are run within the area.

**Arid wells programme**

In an attempt to curb the exodus from rural areas and create better living standards for the rural population, some villages are involved in the "Arid-well programme". The aim of this project is to try to primarily ensure drinking water availability to the population, but also improve potential supplementary irrigation. For this, spring catchment development and/or



deep wells (~20 m) are dug in the house compound. Water is then lifted through pumping to a sealed tank (10 m<sup>3</sup>) on a nearby height from where water is delivered by gravity through piping to the house. Should these sources produce insufficient amounts of water, roof WH is conducted to keep the arid wells full for usage under the dry periods. Otherwise, the roof WH is primarily intended for irrigation water since this water quality is not as high as the other sources generally produce.

The 20 m deep wells produce limited amounts of water and pumping is done frequently to the arid wells. Due to economic reasons, the 20 m wells are seen as most viable costing 2000 Yuan each to construct. Deeper wells require more than 10.000 Yuan due to more extensive reinforcement needs. The government support the farmers with the required material and skilled labour, and the farmers supply local material and unskilled labour. Courses are given parallel to the work to teach the farmers how to conduct the work themselves.

The water is seen as a very precious and limited commodity. The wastewater produced, therefore, is also carefully used and either given to animals or applied to the trees in the garden, depending on what the water was primarily used for.

Activity is high in these supported areas, with many new houses built. It is believed by the project authors that the population would leave the villages without this support through the programme.

### ***Irrigation programme***

A variety of techniques are implemented in the province to support the agriculture – especially cereal production. Some in situ WH is conducted, but since this form of WH is seen to have limited (or no) effect in preventing yield losses caused by drought, water is preferably collected into 15-30 m<sup>3</sup> tanks for supplementary irrigation. Irrigation is done under the theory of “irrigate the crop and not the soil” and applied with the use of a bucket and a cup. One tank is constructed in the middle of each plot, ranging from ½ - 2 *mu* (300 – 1.300 m<sup>2</sup>). Water is collected from a variety of sources including roads, spring catchments, roofs, slopes etc.. The tank is expected to supply the field with at least 1-2 applications of 5-7 m<sup>3</sup>/*mu*. This project is implemented extensively throughout the region. Almost all plots have one tank in the field, which is part of the government’s plan for the region.

### ***Community WH collection schemes***

In many villages and communities, the villagers have gone together to build large tanks of up to 2.000 m<sup>3</sup> in volume. Such constructions cost about 37.000 Yuan each and requires about 10 km<sup>2</sup> of catchment area. Water is harvested on slopes and springs far away and delivered through waterways and piping to the tanks. The top water is primarily intended for drinking water purposes, and the bottom layer is generally reserved for irrigating the fields. The government supports these construction schemes with material and know-how, while the farmer has to supply local material and unskilled labour. The share sponsored by the government amounts to about 30% and the remainder is then invested by the farmers. It takes about one year to complete one of these reservoirs. The farmers manage these structures together and decide on application time and distribution among owners. In the region, about 20.000 such tanks have been built.

Other schemes include dam construction in gullies with water arrested from upstream or water harvested from roads and open space surfaces in the villages. Much silt is, however, transported with the water, and the unusually dry year of 2000 permitted the cleaning of the reservoirs and tanks for the first time in many years due to the low water levels. Siltation chambers are built in the waterways, but even so, the silt occupies large volumes of the tanks and reservoirs over short periods of time. One 1500 m<sup>3</sup> tank that was cleaned for the first time in 4 years (and does have a siltation cube (filter) in the delivery ditch) had collected an estimated 80 m<sup>3</sup> of silt.

In a schoolyard, a 200 m<sup>3</sup> tank is being constructed with the aim of harvesting and storing rain falling on the roof and courtyard for drinking water. The construction is also seen as an opportunity to teach the children how harvesting can be done.

### ***Roof WH programme***

An extensive programme of roof water harvesting has been launched in the region. This means that in all new houses constructed, 10-50 m<sup>3</sup> tanks are built under the courtyard collecting the water harvested from the cemented rooftops. Rain availability is not seen as a problem here, rather the financing of the water structures. The total cost for such a system including the tank, cement pavement and a hand pump is about 700-800 Yuan (80-100 USD). Ingenious filters and valves are constructed that permit the exclusion of the first rain water only to collect the cleaner water once the first rain has cleaned the roofs. This programme has received wide support from the inhabitants who stand in line to receive the incentives offered by the government.

### **Much to learn from**

It seems clear that the water holding capacity of the Loess soils in the area are much greater than in many other semi-arid regions of the world. This makes it possible for the farmer to strategically choose to mitigate dry spells only during critical growth stages. The Chinese use growth stages as indicators for when supplementary irrigation should be applied. The applied irrigation practice is very labour intensive and time consuming and follows the principle of “irrigating the crop and not the land”. The method used is to extract water from the tanks in the field and applying water to each individual plant with a cup -precision farming.

The loess soils, furthermore, make the transferability of these WH structures and models more constrained. Nevertheless, there is much to learn from these implementations, not only from its performances but also on the consequences on applying systems on such a large scale.

## Part III. Research gaps and avenues

*"The war against poverty in Tanzania will be won or lost in the semi-arid areas." - President Nyerere*

Albeit the vast knowledge and experiences accumulated in the field of water harvesting, it follows from this study that there are still large gaps in research that need to be filled. Fields identified as primary constraints for the successful transfer of innovations and technologies are within the socio-economic domain and relate to the flexibility of concepts introduced so as to fit into the social context. Often lack of education is a primary constraint, but sometimes the proper understanding of underlying social factors can make a difference between a success or failure in introduction/implementation of water harvesting systems.

There is also a need of research regarding technical solutions, taking into account the catchment requirements and dynamics as well as the design of the system as such. The main issue is to reduce water losses by evaporation and seepage.

In many cases, the individual farmer will carry little effect on the downstream users of the resources he/she is tapping. However, with increased adoption of technologies as an innovation "catches on", it is important to have good pro-active knowledge on consequences of upscaling at the catchment and river basin scale. Maybe even the regional and national scale.

At present very little is known on socio-economic, environmental and hydrological impact of upscaling small-scale water harvesting technologies. This requires understanding of complex biophysical processes at different time and spatial scales, as well as inter-sectoral dynamics between, e.g. processes in the agro-ecosystem and driving forces behind human land-use decisions. Further more, this understanding has to span over a broad scale spectrum, from the farm level to the river basin scale, in order to anticipate impacts between upstream and downstream water uses and users.

### The adoption of water harvesting systems

#### ***Biophysical and socio-economic criteria***

A critical characteristic of water harvesting is that even though each system can be applied in many different landscapes and societies (e.g. the principle concept of capturing gully flow for storage in tanks being generic), the way each system is designed and constructed is site specific (construction material, size, water extraction method, etc.). This means that a successful technology at one site only with great care and most probably after thorough modification can be transferred to another location with different physical and/or social setting.

Some basic criteria determining the potential for different WH systems are:

- Hydroclimatic setting (rainfall, potential evapotranspiration)
- Rainfall partitioning (the actual production of surface runoff flows)
- Physical characteristics of catchment area (run-on areas, gullies, rills, roads, etc.)
- Soil types
- Soil depth
- Slope (most water harvesting methods suitable only if slopes < 5 %)
- Water demand (crops, animals, humans)
- Water quality (salinity, sodicity of harvested water as a result of leaching)

- Land tenure and availability of land
- Possibilities of using gravity-fed water supply (depending on the spatial location of WH components along catena)
- Socio-economic setting
- Risk minimisation achieved by water harvesting
- Cost/benefit and payoff time

A large research gap is found in the field of understanding under which biophysical and socio-economic conditions different WH systems actually perform in a satisfactory manner. Research on factors affecting the adoption of WH by farmers is needed to better understand under what agro-ecological and socio-economic settings that various WH systems become viable options for farming systems improvements.

### ***Adaptive on-farm research***

The research on pre-conditions for functioning of WH systems is closely linked to the need of further research on adaptive, participatory research on WH technologies. In many cases the pre-conditions (physical and social) for adoption of an existing system will differ from the pre-conditions in another location, even though water harvesting may be in high demand. Adaptive research, based on participatory methods where the end-users are equal partners with the scientists in the research, can be very successful when trying to introduce innovative technologies from one cultural/biophysical setting to another.

Farmers have in-depth knowledge of the biophysical characteristics of their farming environment, and can generally express their problems in a very pertinent manner. Many times, solutions to land-use problems exist as indigenous knowledge either within the rural community or elsewhere under similar agro-ecological settings. But, in the field of water harvesting, this is often not the case. Appropriate technologies to deal with severe water scarcity in crop production, are often more or less novel, and sometimes even originate from modern science/development (although ultimately originating from old indigenous practices) and are not directly available from local, e.g. national research (e.g. ox-drawn ripper ridgers, spherical subsurface tanks, zero-tillage systems using herbicides, low-pressure drip irrigation systems etc.). This is a challenge, which requires strong partnerships with all stakeholders involved, in applying adaptive research on innovative technologies, where on-farm experiences assist in forming site-specific solutions.

## **Implications of upscaling**

### ***Upscaling of water harvesting systems to a watershed scale***

Our conclusion is that the few attempts of studying the biophysical and socio-economic implications of water harvesting systems have primarily been carried out on field scale, studying the functioning of individual technologies. A large remaining challenge is to analyse the potential and the implications of upscaling of water harvesting on a watershed and/or community scale. Based on the research discussed above on criteria determining the viability of WH implementation, the first spatial question to answer (that at present is unanswered) is to what extent various water harvesting technologies actually can be upscaled. For example, given the criteria required for successful implementation of earth dam reservoirs for gravity-fed supplemental irrigation, what proportion of farmers in a certain region can actually benefit from such systems, given the biophysical limitations involved? Similar spatial questions have to be raised for the full set of WH systems (in-situ systems, runoff farming systems, flood WH systems, and storage systems). The next analytic step is to study the implications - socio-economic, legal, biophysical, institutional, etc., of upscaling.

### ***Upstream-downstream effects of water harvesting***

Very little is known on the hydrological effects of upscaling water harvesting. A critical research gap is the upstream-downstream effects of up-scaling water harvesting. A WH system may be very successful in harvesting surface runoff and converting it to transpiration in an upper sub-catchment. The question is what happens if such successful and sustainable systems - at a hillslope scale - are up-scaled to a watershed/catchment scale. If fully up-scaled, does WH adoption threaten surface and subsurface water availability downstream? Nobody knows. However, already at present the upscaling of small-scale water harvesting can be perceived as a real threat to downstream water availability. For example, in the Pangani river basin in Tanzania, upstream water harvesting was seen as a serious threat to water availability in a planned hydropower and rice irrigation scheme downstream. Water harvesting was strongly discouraged (Hatibu, pers.comm.). Such an attitude was not based on any solid data on the actual rainfall partitioning in the river basin, but only on assumptions (there is no data available on hydrological impact of water harvesting on watershed scale).

Another example is from Australia where a moratorium had been built into the Murray-Darling Agreement on further diversions from the river system to ensure sufficient river flow to support healthier aquatic and riverine ecosystems (Pigram 1999). A decision in 1998 to allow upstream landholders to harvest up to 10 % of the runoff into small farm dams was met by opposition both from the environmental community and from landholders downstream because of possible reduction in streamflow.

Even a hypothetical back-of-the-envelope calculation indicates the potential hydrological effects of upscaling of water harvesting. For example, let's assume a watershed of 2,000 ha with 50 % cultivated land (1,000 ha) and an annual rainfall of 500 mm and grain yield levels of 1 t ha<sup>-1</sup>. The evapotranspiration water use efficiency is in the order of 1,500 m<sup>3</sup> t<sup>-1</sup> or 150 mm t<sup>-1</sup> ha<sup>-1</sup>, which would correspond to an annual return of 1.5 million m<sup>3</sup> of water to the atmosphere from cropland on a watershed scale (or 75 mm/yr). This means that 15 % of the total available rainfall (amounting to 10 million m<sup>3</sup>) in the watershed originally was used for grain production. If yields were doubled through water harvesting, where runoff was harvested from non-cultivated land into storage systems with 20 % water losses through open water evaporation, then an additional 90 mm (over the whole watershed), or 1.8 million m<sup>3</sup> of water would be needed. This roughly amounts to an additional appropriation of 20 % of the rainfall (with a total return of one third, or 165 mm of the rainfall). This is a considerable increase in the return flow of water to the atmosphere on a watershed scale.

However, regarding water harvesting there is even a rationale logic for the reverse argumentation, i.e. that applying water harvesting may actually not affect water availability downstream and in some instances even increase availability. Conventionally the monitored water resource at river basin scale is perennial surface river flow and ground water flow. Surface runoff generated at the upstream partitioning of rainfall, which initially flows as sheet or rill runoff and eventually merges to form gully flow, is ephemeral in hot and dry tropical catchments. This means that the runoff generated upstream flows for only a couple of hours during and after intensive rainstorms. This upstream runoff, defined as "upstream blue" water flow by Rockstrom et. al. (1999) is rarely monitored, and it is not well understood what proportion that actually feeds perennial river flow and accessible water tables downstream. There is, e.g. evidence suggesting that upstream blue water flow (which would not be there if water harvesting was applied securing infiltration and upstream storage), often inundates flat seasonal wetland zones along its journey downstream, and is lost (to a large extent) as open water evaporation. In these instances water harvesting will convert non-productive water losses (as open water evaporation) to productive use upstream, and at the same time reduce soil degradation (caused by the erosive impact of surface runoff). Whether water harvesting has beneficial or negative environmental and/or hydrological impact on downstream water uses/users is at present speculative, and requires in-depth research efforts.

## Ecological impact

Runoff generated in a crop field, is a loss of water from the crop's perspective. But, that runoff, accumulating from rills into gullies, can constitute the hydrological precondition for the existence of downstream biota. Many wetlands depend on a certain minimum annual flooding from runoff generation, like e.g. the so-called "dambo" and "bas-fond" areas in Southern and Western Africa, respectively. These seasonally saturated and ponded zones are habitats to numerous bird species and function as essential water holes for wildlife. Successful water harvesting upstream will reduce the ephemeral floods of upstream blue water reaching downstream ecosystems. The question is whether water harvesting threatens the functioning of downstream ecosystems, and what management strategies and institutional arrangement that are needed to manage a balance between water harvesting for economic production and natural water harvesting for ecological production and service delivery in a watershed.

Runoff flow also carries large volumes of sediment. From an agronomic point of view this sediment should be kept as close as possible to its source. However, in many areas suspended sediments in storm floods are important environmental criteria for the biological functioning of, e.g. flood deltas. The effect of reduced floods on river deltas are well documented for conventional dam reservoirs (e.g. the effects of the Aswan dam reservoir on the flood delta in northern Egypt), but very little is known on the effects on delta environments of trapping sediments using water harvesting upstream.

## Systems approach

### *Groundwater harvesting*

In India there are several examples of severe over-exploitation of shallow water tables for irrigation purposes. As a contrast, in sub-Saharan Africa, the use of shallow water tables for crop production in semi-arid areas seems to be a largely under-utilized resource (Savenije, 1998). Improved abstraction of water in shallow wells, by drilling horizontal boreholes from large diameter traditional wells, has shown to sustain community vegetable gardens in semi-arid Southern Zimbabwe (Institute of Hydrology, 1998).

Watershed management research, including groundwater management as a water harvesting option, could be an interesting avenue for upgrading rainfed agriculture.

### *Conservation tillage - need for systems research*

Conservation tillage (CT) may be the most interesting water harvesting option available in order to achieve quick improvements in rainfall partitioning and crop yields on a large scale. The reason is that CT focuses on maximising infiltration and the improvement of soil productivity, by abandoning the inversion of the soil through conventional ploughing.

There are many documented examples of successful conservation tillage practices from different parts of the World. Despite these successes, and the increased adoption of conservation tillage in other parts of the world (e.g. North and South America), the adoption among small-scale farmers in, e.g. Eastern and Southern Africa has been very low. On the other hand, conservation tillage has been adopted by many commercial farmers in degradation sensitive landscapes in, e.g. Zimbabwe and Tanzania, as a means of building up long-term soil productivity and reducing especially traction needs (i.e., diesel costs) (Jonsson, Lars-Ove, pers. comm.; Oldreive, 1993).

The low adoption of conservation tillage systems among smallholder farmers in sub-Saharan Africa has been attributed to a set of different constraints. First of all the level of mechanisation is very low in most countries. For example in Kenya and Tanzania, 84 % and 80 %, respectively, of the farms are still operated by manual practices (hand-hoe). The availability of alternative tillage implements is low. In Zimbabwe, for example, a country

with a relatively high proportion of mechanised farming, 80 % of the farmers in the high potential areas own mouldboard ploughs, while ridgers are owned by 2 – 5 % and ripper tines by less than 5 % (Nyagumbo, 1992).

Weed control is a major constraint in the efforts of introducing conservation tillage. Many observers attribute the high adoption of conservation tillage practices among commercial farmers to the simple fact that they can afford to buy herbicides (Nyagumbo, 1998), and that many of the successful results on zero-tillage systems have been achieved by introducing systematic herbicide applications (Findlay 1998; Boa-Amponsem et al., 1998). Weeding is generally the most labour demanding land operation, and is often carried out directly or indirectly through the use of a mouldboard plough. Reduced tillage or no-till systems tend to result in higher weed infestation, which creates problems for resource poor farmers who often consider that they cannot afford herbicides. With the introduction of conservation tillage systems, timing of operations becomes very important for the success of the practices. Also, cultivating in lines, and especially returning to the same planting lines year after year, becomes necessary. These increased and changed management skills can also affect the adoption rate.

Mulching is normally seen as an absolute precondition for a production system to be classified as CT in the first place (a minimum of 30 % mulch cover on the soil throughout the year is the orthodox definition). In the semi-arid tropics, in rural societies where livestock graze freely after harvest, it has been argued that mulching is difficult if not impossible due to the large demand of crop residue for other uses (livestock, fuel, construction).

On-farm research is ongoing in some scattered places in, e.g. Ethiopia, Ghana, Kenya, North-west Tanzania, South Africa, Zambia, and Zimbabwe, where site-adapted CT systems are being developed. However, it could be argued that the low adoption of CT among smallholder farmers may be linked to the lack of systems research studying all the components - tillage, timing, livestock management, fertilisation, soil conditions, farm management, etc., which together form the basis of a successful conservation tillage system. There is a research gap on systems oriented adaptive on-farm research on the design, functioning, biophysical criteria and implications of CT-production systems.

Furthermore, there is a large need for research on the transition from conventional plough based farming to conservation tillage. Zero tillage systems are often promoted as a panacea for reduced labour needs, reduced land degradation and frequently improved yields. But, when the starting point are structurally collapsed soils, with thick plough pans and < 0.5 % organic matter in the A-horizon, then the most pragmatic way may be to progressively introduce CT, via a series of alternative interim tillage strategies, using, e.g. subsoiling and ripping to break hard-pans, with strong emphasis on manuring (animal and green). Such transition phases have been loosely estimated to 5 years for Tanzania (when going from ploughing to zero tillage), but there is little empirical research to confidently justify such transition periods.

### ***Farming systems improvements***

Loevenstein (1994) noted that while the hydrological aspects of runoff systems seem to be well documented little attention has been paid to agricultural aspects. While we argue that there is still large hydrological research gaps, especially related to dry spell mitigation and issues regarding up-scaling, the point is certainly still valid regarding the lack of a systems approach to rainwater harvesting as an integral component of a farming system.

Water harvesting, as argued earlier, may be the most pertinent entry point to farming systems improvements in water scarce regions. The reason for this is the reduced risks for crop failures due to dry spells, which in turn will increase the willingness among farm entrepreneurs to invest in other inputs. The most interesting aspect of such synergistic effects is the interactions between soil nutrients and soil water. There is strong empirical evidence to suggest that soil nutrient deficiencies often are the primary limiting factor for crop growth

even in semi-arid areas, due to persistent soil mining. It has also been strongly argued by, e.g. the former director of ICRAF, Dr Bjoern Lundgren (Lundgren, 1998) and Dr Norman Borlaug, the Nobel Peace Prize laureate and the father of the Green Revolution (pers.comm., 2000), that without a major replenishment of soil nutrients no substantial gains in smallholder grain yields can be achieved (the soil nutrient deficits being so large that fertilizer use is the only realistic option, even though combined with organic sources). But, fertilizer promotion alone will not do the job - as shown with painful evidence from decades of subsidized fertilizer programmes in several developing countries.

A hypothesis worth investigating is that substantial and sustainable upgrading of crop yields in rainfed farming systems in semi-arid areas can only be achieved through integrated water and soil management, where water as the entry point. Water supply to mitigate dry spells has to be secured before investments in fertilisation become interesting for the farmer. This hypothesis can then be broadened to include all components of farming systems research, regarding investments in pest management, improved varieties, crop rotations, timing of operations etc..

Farming systems research, where water harvesting forms an integral part, must also bring out institutional and land tenure issues. Water harvesting operates at both household/farm scale and community/watershed scale. As soon as external water is harvested issues regarding land tenure (of the catchment area) may be of importance. Institutions, traditional and formal, may be crucial in the management of runoff and water harvesting on community and water shed scale. Very little research has been carried out regarding institutional issues related to water harvesting.

### ***Dry spell occurrence and mitigation***

Conventional assessments of agricultural potential in semi-arid areas tend to focus on cumulative rainfall/PET ratios, either annual or seasonal. This is of little interest for farming systems development, as inadequate rain/PET ratios on a seasonal basis rarely constitutes the limiting factor to produce say 2 t grain ha<sup>-1</sup> yields, but rather (i) the occurrence of dry spells (due to extremely unreliable rains) and (ii) the poor rainfall partitioning (resulting in < 30 % of the rain used productively).

Most planning tools for the assessment of crop water requirements (ET flow) and the needs of additional crop water supply are based on seasonal data. Furthermore, the developed approaches are designed for conventional irrigation systems (which require close to full irrigation) (e.g. the FAO CROPWAT method).

The above conventional approaches are not very useful in efforts of upgrading rainfed farming systems, and especially in assessing and designing water harvesting systems. The reason is that the conventional methods tend to be, if anything, biased toward the management of meteorological droughts. But, droughts are not very interesting for the small-scale farmer. They occur, have and will always occur, and always lead to complete crop failure or very serious crop yield reductions. No water harvesting system can cope with severe meteorological droughts. Conventional dam reservoirs dry out during meteorological droughts, and the impact on society as a whole is often devastating, as, e.g. illustrated by the drought related famine, loss of livestock, power failures, and severe water supply rationing recently experienced in Kenya due to meteorological drought (March - June 2000).

The manageable challenge for the farmer is to mitigate the effects dry spells, which occurs very frequently (often >every 2<sup>nd</sup> rainy season) in semi-arid farming systems in Eastern and Western Africa. There is very little research carried out studying the occurrence of dry spells from a management perspective, and the potential of planning for dry spell mitigation using water harvesting. Planning tools have to be developed from fundamental science that enables the assessment of water requirements to mitigate dry spells, and the potential of harvesting the required water.



### ***Integration with infrastructural development***

Rains in semi-arid tropics are not only unreliable over time, but are erratic and often fall as large intensive storms, resulting in severe floods. It has been estimated, floods caused e.g. that 38 % of the disasters in Tanzania 1872-1990, while 33 % were caused by droughts. Too much and too little water in water scarce areas seem to account for 71 % of the natural disasters. Floods are common phenomena in semi-arid areas. Floodwater harvesting could have a potential, which at present is largely untapped. Comparative research, studying the processes, design, and pre-conditions, involved in the functioning of well established flood water harvesting systems in, e.g. Eritrea, Sudan, Ethiopia, would be very valuable in assessing the potential in other agro-ecosystems. Floodwater harvesting is particularly sensitive when it comes to dissemination and adoption, due to the large volumes of water involved. Diverting gully storm flow onto cropland can - if wrongly designed - result in very severe soil erosion. Therefore, research on storm flood management for crop production, has to be closely taking into account the capacities of the service giving institutions into account.

As mentioned in Chapter 4, there are a few attempts, often by communities themselves, to use, often un-intentional side effects, of infrastructural developments like roads and railroads, for water harvesting purposes. Culverts and borrow-pits constitute a couple of examples. An un-tapped potential would be to link the building of especially small bridges over ephemeral rivers in semi-arid areas with subsurface and sand dams. This is very rarely done. Instead roads are built with the objective of getting rid of the runoff, instead of integrating a water harvesting component as an extra benefit from the construction.

Applied research and pilot tests are required where rural, water and infrastructural authorities establish partnerships to develop synergistic water harvesting options for crop production from infrastructural developments.

## **More crop per drop - getting a larger proportion of the rain to produce crops**

### ***On-farm water partitioning***

The water balance is probably the most useful analytical tool to study the agro-hydrological potential and actual performance of rainfed farming systems in semi-arid tropics. Unfortunately very little research has been carried out on-farm, studying the partitioning of rainfall over relevant scales for farm management. From this, it is needless to say, that on-farm water balance research linking water harvesting and run-on flow of surface water from upstream catchment areas is close to none-existent. Still such research is the only basis for wise land management in semi-arid tropical areas where water harvesting may be an option for improved crop yields.

There is a need for hillslope or small-watershed scale research on rainfall partitioning on a system scale - studying run-on surface flow from catchment areas, the water balance of water harvesting structures, and the rainfall partitioning in the production systems linked to the water harvesting system. Such research will give important knowledge on how far water harvesting can go in improving crop production, and will form the basis for analysis of spatial up-scaling of water harvesting.

Vapour research is a well-established research field, primarily practiced by micro-meteorologists and scientists interested in the atmosphere-land interphase on various scales (from pot scale to GCM scale predicting weather patterns and climate change trends). Applied vapour research is urgently needed within the context of water harvesting development and farming systems improvement in semi-arid tropics. As biomass growth is approximately linearly proportional to vapour flow, every improvement in crop production will result in a larger proportion of rainfall being returned directly through evapotranspiration to the

atmosphere. However, this assumption is only valid under constant agro-meteorological conditions (basically related to the saturation deficit).

There are empirical and theoretical indications that more crop can be produced per unit vapour (i.e. increasing transpiration water use efficiency), by altering the microclimate under which the crop is grown. For example, shading by trees in agroforestry systems have been reported to reduce transpiration.

### ***To convert evaporation to transpiration***

An interesting win-win option is to convert non-productive evaporation to productive transpiration. Inter-cropping have in several trials not resulted in higher cumulative evapotranspiration than mono-crops, which may be a result of reduced evaporation in favour of productive transpiration (Ong et al., 1996). However, there is also research indicating that for warm tropical regions, in biomass scarce farming systems (systems with low leaf area) it may be difficult to reduce evaporation losses (Daamen et al., 1995).

The notion of maximising the "crop per drop", advocating the need of increasing water use efficiency in crop growth by producing more crop per unit water, was strongly advocated in the World Water Vision report prepared for the World Water Forum in March, 2000. For the individual farmer improving WUE may not be the most important issue, but rather to assure a stable supply of soil moisture throughout the crop growing season. However, from a water harvesting perspective, all possibilities of using water harvesting as a method of improving the crop environment in favour of (i) lower saturation deficit (VPD, vapour pressure deficit) (which reduces the atmospheric thirst for vapour) and (ii) increasing the T/ET ratio can be of large importance for the water availability on a watershed scale. Water harvesting could contribute to lower VPD and higher T/ET through several ways:

- improving canopy cover during the growth season (basically larger leaf area covering the ground), which would reduce evaporation flow in favour of transpiration flow.
- enable more densely grown mono-crops or inter-cropping, which would increase T/ET ratio.
- enable agroforestry systems (e.g. fruit orchards with cereal/legumes) through supplemental irrigation of trees, resulting in more shade, lower VPD and thereby lower transpiration flow per unit CO<sub>2</sub> uptake by the crop.
- enable a long-term build up of organic matter and mulch on the soil (through improved biomass productivity in general), which would reduce VPD at the soil surface.
- reduce evaporation losses early in the rainy season, and loss of carbon from soils during dry seasons, if more soil water is available to supplement crops at emergence (assuring quick emergence), and if water is available for off-season cultivation.

Research is required to study the actual potential of water harvesting to affect VPD, WUE<sub>ET</sub>, WUE<sub>T</sub> and T/ET ratio.

## **Finding affordable and accessible technical solutions**

### ***Water surface losses***

In the semi-arid tropics with potential evaporation rates of 5-8 mm d<sup>-1</sup>, water losses through open water evaporation are very substantial. Over a 6-month dry season the water loss due to evaporation can amount to 0.9 - 1.4 m. Investments in the extra storage depth to cater for such losses can be substantial. Several options of reducing evaporation through various floating materials (oils, foams etc.) have been studied. These are generally successful in reducing evaporation, but are not adopted by small-scale farmers due to the high cost. Instead, it is

worth investigate various low-cost, and potentially income generating alternatives. In Kenya trials are presently carried out testing whether passion fruit can be used to shade farm ponds in semi-arid areas and at the same time generate cash income from the fruits. An alternative "living" roof is the drought tolerant "lupher" plant, with large crawling leaves that produce a cucumber-like fruit. This fruit is dried and used as a cleaning sponge in, e.g. Uganda, Kenya and Tanzania (and exported to, e.g. Europe). Shading is reported to reduce open water evaporation with approximately 30 %. There are still unanswered questions regarding what species can be used as shades over farm ponds, what options are technically and economically viable for resource poor farmers, and how are such "living" roofs managed?

Finally, there are several technical storage options without exposing a free water surface to the atmosphere. Underground tanks are used in China and experimented in Machakos district, Kenya. These tanks are dug and installed in crop fields at such a depth that crops still can be cultivated next to the manholes of the tank structures. However such tanks require deep soil profiles, and relatively good design and construction skills. An inventory of different subsurface storage systems is required, followed by applied research on site-specific adaptation of techniques and approaches.

### **Seepage**

The 2nd largest water loss in storage systems is from seepage. Small-scale farmers generally do not afford expensive lining of, e.g. earth dam reservoirs with cement/sand mixtures or plastic sheeting. Instead the reservoirs generally are left to self-seal from suspended sediment in the runoff. Such a strategy may be successful in certain soils, but certainly unsuccessful in soils with highly permeable layers or fractured bedrock within the storage depth of the reservoir. There seems to be an interesting scope of using different "light" (low concentration) cement mixtures with soil to seal reservoirs (Shone, pers. comm.), and to use "light" cement mixtures with lime and soil from termite-mounds (Erik Nissen-Petersen, pers. comm.). Such applications can save a lot of money for the farmers, and use locally available resources. Successful experiments have likewise been carried out on sealing tanks using burned clay lining. The technique is essentially the same as used in pottery production. Asphalt layers lining reservoir walls also produce impermeable layers. However, water quality is an issue that needs to be studied as oil products are applied in this form.

### **Irrigation application**

At present there are good opportunities to link water harvesting systems with efficient and appropriate application methods (compared to the conventional open surface water application of irrigation water). Drip irrigation, developed in Israel during the 1950s and until recently used only in capital-intensive commercial farming, has recently become accessible on local markets for small-scale farmers. These include a broad variety of techniques, from perforated rubber hoses, hoses with cheap nipples, to sophisticated low-pressure drip tapes.

Traditional furrow and overland (inundation) irrigation practised in many countries release large volumes of water to infiltration and evaporation even before the water reaches the field. Such losses can easily surpass 25%, and even though it is often argued that seepage losses in irrigation systems are recycled downstream, there is a need for further studies on efficient application methods of harvested water. Other issues such as irrigation scheduling, and alternative irrigation methods including sprinkler and subsurface irrigation need further study for performance enhancement.

### **Catchment treatment**

Substantial research has been carried out investigating the technical performance and economic viability of treating catchment areas for improved runoff production including earth compaction, asphalt layers, plastic sheeting, cementing etc. (Frasier, 1994; Li and Zhu, 2000).

In many semi-arid areas the problem in designing water harvesting systems is the lack of a good catchment area. For example, in many rural societies in sub-Saharan Africa roofs are thatched, and most land surrounding the villages are either crop fields or grazing land. The possibility of treating small catchment areas for runoff harvesting has not been thoroughly investigated. The challenge is to find affordable and accessible solutions. This is an area where cross-regional experiences could be tapped. Li and Zhu (2000) present designed dwelling grounds for the purpose of harvesting water for domestic use parallel to garden and greenhouse production. Attention is required to roof materials for runoff generation, and surface runoff characteristics of courtyards, schoolyards, roads etc. A serious matter that needs to be further addressed is the water quality derived from these surfaces being a source for contamination.

## **Legal and institutional issues related to the use of surface runoff and storm floods**

Water harvesting as discussed in this report is based on the conversion of sheet, rill and storm gully flow for productive purposes in, primarily, upstream locations of catchments. None of these flows are regulated in laws or water acts. Legislation and policies regulating water resource utilisation covers only permanent/semi permanent streams/rivers and groundwater resources. In semi-arid areas largely all runoff flows occur as storm flows originating from sheet, rill or gully flow, and from storm flow in ephemeral streams. The reason why these flows are not legally regulated is probably related to the inherent perception that surface runoff is not a resource, but rather a nuisance. If farmers successfully adopt water harvesting, surface runoff is turned into an important natural resource, at the spot where it occurs, and will affect the recharge of perennial (and regulated) streams downstream.

Research is needed that investigates the legal and institutional issues related to the use of surface runoff and storm floods in gullies and ephemeral streams for productive purposes.

### ***Land tenure - a central issue***

In many developing countries, land tenure is a central issue of concern for socio-economic development in general. Water harvesting adds a dimension to this sensitive and crucial issue. Water harvesting systems depend on runoff production from either state/communal land (like roads, most grazing land etc.), or from private land owned by neighbours (e.g. when sheet and rill flow is harvested from other farmland and household compounds upstream). As long as water harvesting is an exception in a rural community, there may not be any problems with the ownership of runoff production and runoff producing land. But as soon as the demand for runoff water rises, and especially when upstream farmers tap runoff that otherwise would reach downstream water harvesters, the issue of ownership of runoff catchment areas will have to be addressed. The issue of ownership of runoff relates closely back to the issue of who actually owns the rain? This is often seen as a philosophical question, basically because conventional water resource management does not perceive rain as water until it reaches a stream or the water table. Water harvesting pushes the attention on water as a natural resource, upwards in the watershed and closer to the source (rain, forming sheet runoff resulting in rill flow, recharging gullies) instead of the conventional focus on the high-order flow form (perennial stream and groundwater flow).

An interesting example of water tenure was developed in the Naigaon water harvesting project in India referred to in Ch 1 (Pangare & Lokur 1996). In this water harvesting project, the idea was that, since water is a common property resource, all villagers - irrespective of land ownership - should have equal rights for and access to the utilisation of water in the village area. The water rights were therefore detached from land ownership, and when the land was sold, the water rights were reverted back to the village group. The new owner did not automatically gain the rights to the water. Mr Salunke - the initiator of the Naigaon

project - translated this principle into practise by offering membership to the water harvesting based lift-irrigation scheme also to landless villagers. By this arrangement, the landless became share cultivators to farmers having more land than water needed to cultivate that land.

Perhaps there is a need of a water tenure system, giving title deeds for the use of certain land areas as runoff harvesting zones. Definitely, this together with the legal issues outlined above, requires further investigation.

### ***What role can water harvesting play in poverty reduction?***

Poverty reduction for obvious and well-founded reasons ranks high on the international development agenda. Unfortunately rainwater management rarely ranks very high in the strategies suggested to actually battle poverty, despite the fact that the poorest of the poor depend for their livelihoods on rainfall-based land-use. Furthermore, semi-arid areas play an important role in the efforts of reducing poverty. This is amongst others related to the fact that land scarcity in high-potential areas (with higher and more reliable rainfall) pushes people to migrate to drier areas. The importance of semi-arid areas for socio-economic development was clearly stated by the late President Nyerere of Tanzania as follows; "The war against poverty in Tanzania will be won or lost in the semi-arid areas" (Tanzania being a country with relatively large proportion of sub-humid and humid land areas). Poverty reduction in semi-arid areas is closely linked to improved soil and water management. Domestic water supplies and sanitation have to be improved, and crop yields have to be doubled over the next generation.

What role can water harvesting play in poverty reduction in water scarcity prone areas in developing countries? This is an area in need of investigation.

### ***Cost benefit analysis***

At the end of the day, adoption of water harvesting systems by farmers will depend on (i) the cost-benefit relation and (ii) the capital flow needed at the investment stage. Cost-benefit analysis of water harvesting systems may also supply with additional information on the most attractive choice of production system. For example, it may not be economically advisable to invest in a supplemental irrigation system for staple food crops, while the same investment may be very beneficial for a cash crop.

Water harvesting alters water and sediment flow in the sub-catchment where the system operates. Every change in rainfall partitioning may affect, as mentioned above, the habitats for downstream flora and fauna, and/or the water availability for other water uses. Environmental impact assessments have to our knowledge not been carried out on water harvesting interventions, and may be a field in need of further studies.

### ***Cross-regional transferability of approaches and know-how***

As shown, water harvesting techniques are relatively widespread in the three studied regions (sub-Saharan Africa, India and China). Despite the generic similarities (the principle of using runoff for productive purposes on a small, from farm to watershed, scale) technologies have been developed differently. Emphasis is and has been on different types of water harvesting techniques, as does the approach to promotion, dissemination and adoption, and the emphasis. There is certainly a scope for cross-regional exchange of experiences, both regarding technologies and management approaches.

In India there is a long experience of promoting water harvesting as an integral part of watershed management. This experience can play an important role in efforts of upscaling the generally farm-level based emphasis found in the studied cases in sub-Saharan Africa. China has put relatively large emphasis on technology development, e.g. subsurface tanks, and on catchment treatment for runoff generation. These experiences can be interesting also for other

regions. In sub-Saharan Africa focus has been on in-situ water harvesting, to the extent that there is ample experience on indigenous and exogenous methodologies, which can have cross-regional relevance.

As shown in this study, appropriate technologies are not in themselves a guarantee for adoption among farmers. Management approach, institutional set-up, land and water ownership, socio-economic constraints, and capabilities, will also affect uptake of novel technologies. If there are differences in technological solutions between regions, these almost fade away compared to the differences in approaches used in promotion of water harvesting. Learning from the broad array of approaches used in management and dissemination in the three regions can assist in speeding up adoption in all three regions. At the same time research on conditions and approaches to adoption must distinguish between lessons-learned that can benefit from cross regional transfer and others that are out of cross regional context.

## **Water harvesting and climate change**

As mentioned earlier in this study, tropical soils may play an important role as carbon sinks in the efforts of reducing emissions of green house gases. All water harvesting systems have either the explicit (e.g. conservation tillage) or implicit (e.g. earth dam reservoirs) objective of significantly increasing carbon sequestration through a boost in biomass productivity. A reason why semi-arid tropical soils may be particularly interesting from a carbon sequestration perspective is that the opportunities of significant increases in organic matter contents in the soil should be high. There are large water losses in the water balance, and yield levels amount to merely 10 - 20 % of the on-farm potential. Water harvesting systems combined with improved farming practices and soil nutrient management can probably double or even triple on-farm crop yields, resulting in a significant rise in root production and above ground organic matter.

## **Research area of strategic interest for Sweden**

This chapter has summarized a number of research gaps that need to be addressed in a world heading for a food gap of 400 million tons of staple food grains per year only 20 years from now. The two particularly critical regions are semi-arid landscapes in sub-Saharan Africa and South Asia, which combine the lowest per capita nutrition level with the most rapid population growth. Some 75-90 % of the farmers depend on rainfed agriculture with low and extremely unreliable crop yields, often of the order of 1 ton/ha or lower. A strong contributing reason is that most of the rainfall escapes from root water uptake, basically due to soil permeability problems and plant damage caused by repeated dry spells even during good rainfall years. Often only 10-20 % of the rainfall is transformed into plant biomass while the rest constitutes losses from the perspective of the crops, either through soil evaporation, runoff formation or groundwater recharge.

In past research in the North (including Sweden!), the generated runoff has in fact been seen as an enemy of the farmer due to the erosion that it causes. However, looking closer into the problem reveals that this water could be turned into the farmer's best friend if it is harvested, stored locally, and used for protective irrigation during dry spells.

Such water harvesting techniques are in fact ancient, more than 4000 years old. They were not always well understood by colonial authorities with their climatic bias and worldviews originating from the temperate zone. The study suggests that there is a large window of opportunity, since research indicates that yields may double or even quadruple without very complicated action.

The regional overviews show not only that the technique is ancient in S Asia and China, but also nothing new in sub-Saharan Africa, as far as in situ conservation and runoff farming is concerned. The farmer has in that respect evidently seen water harvesting as a worthwhile

investment. The question is however why floodwater harvesting and especially storage systems are less common in sub-Saharan Africa.

Therefore interregional transferability and success criteria are essential to clarify. Interesting differences have been identified between India, China and sub-Saharan Africa. In India, the successful experiences of modern time have focused on the greening of villages, and been initiated by enthusiastic entrepreneurs. In China, water harvesting and “irrigating the crop and not the land“ is practised on a mega-scale with the aim to secure economic stability of a whole region and thereby to minimize rural exodus to already burgeoning cities. In the more scarcely inhabited sub-Saharan Africa, finally, the experiences are much more scattered and indications suggest that cultural factors affect adoption potential at least in the Sahel.

Research gaps refer mainly to four types of issues; water harvesting technique as such, the hydrology of on farm rainwater partitioning, issues related to system fit and transferability, and issues related to side effects downstream. Basically three different themes have been addressed:

- **why and on what scale** water harvesting for upgrading of semi-arid rainfed agriculture might be carried out is quite important to clarify. The whole issue evidently has existential dimensions. The potential identified will have fundamental consequences for inter-continental food transfer in the near future, and therefore also for temperate zone agriculture. This will include ethical aspects and even be of relevance for future European agricultural policies. Fundamental aspects relate both to possibilities for rural development in order to retard urban growth and to global food production and security. The fact that carbon sequestration will be a side product of an upgraded crop production is also quite interesting in view of the climate change problems ahead.
- **how to do it** both in terms of switching the approach to runoff management and seeing it as a friend rather than a foe; how to get a larger proportion of the rainfall to produce crops in an affordable and accessible way is a key issue, and how to integrate such systems with the infrastructure of roads, roofs etc..
- **what are the impacts** on community and catchment scale, regarding socio-economy, environment and water resources. This question relates especially to upstream/downstream linkages and impacts on downstream societal and ecosystem water dependence.
- **how to succeed** by implementing systems analysis to upgrading of rainfed agriculture applying an approach where water harvesting is seen as an integral component of the farming system as a whole, including the legal and tenure conditions that have to go with it. The possibility of developing water tenure as an alternative to land tenure, and the institutional system needed to make activities possible to implement and govern are other fundamental issues to be addressed.

### ***Final comment***

Water harvesting for upgrading of rainfed agriculture in semi-arid regions could be a strategic research area for Sweden. Research and development efforts would concur not only with the Swedish development agenda (to reduce poverty among the poorest and to improve environmental conditions by reducing desertification). The carbon sequestration perspective would also concur with the objectives of contributing to the reduction of human induced climate change.

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