Water for Agriculture in Zimbabwe

Policy and Management Options for the Smallholder Sector

Edited by

Emmanuel Manzungu, Aidan Senzanje and Pieter van der Zaag

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UNIVERSITY OF
ZIMBABWE
Publications

First published in 1999 by
University of Zimbabwe Publications
P.O. Box MP 203
Mount Pleasant
Harare
Zimbabwe
Reprinted 2000
ISBN 0–908307–63–2

Printed by Mazongororo Paper Converters
Typeset by the University of Zimbabwe Publications.

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Acknowledgements

Special thanks are due to the Netherlands Organization for International Cooperation in Higher Education (NUFFIC), The Hague, for providing financial support towards the hosting of the workshop upon which this book is based. NUFFIC also met part of the publication costs. The two coordinating committees of the Zimbabwe Programme on Women, Extension, Sociology and Irrigation (ZIMWESI), a NUFFIC-funded inter-university exchange programme in research and training between the University of Zimbabwe and Wageningen Agricultural University deserve special mention for the moral support they gave us.

We also wish to thank Dr Dayo Ogunmokun and Mr Edward Chuma of the Department of Soil Science and Agricultural Engineering, University of Zimbabwe, for their comments on the draft of this book. Dr Ogunmokun has, however, left the University of Zimbabwe.

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September 1998

CHAPTER 2

Do land-use induced changes of evaporation affect rainfall?

M. DE GROEN AND H. SAVENIJE[1]

INTRODUCTION

The area comprising Zimbabwe and Zambia, referred in this chapter as Southeastern Central Africa, suffered from extremely dry years in the past decade. Two recent seasons (1995/1996 and 1996/1997) have generally been good, which shows just how large the variance in seasonal rainfall is. Nevertheless there is concern, as expressed in Chapter 1, that there is a trend towards a drier climate. Investigations on the factors influencing the climate of Southeastern Central Africa have mainly been restricted to global influences like the greenhouse effect. As explained in Chapter 1, an explanation for the large variance in seasonal rainfall is sought in correlations with large scale phenomena like the El Niño, the Southern Oscillation and sea surface temperatures in the Indian Ocean. When we explain to people that we are trying to investigate if drastic land cover changes have influenced rainfall patterns, the most frequent response is: Has this not been proved already? The answer, in our view, is still negative. To our knowledge, neither in international publications nor in local or grey literature, are there any published results of a research on the feedback of land cover on rainfall in Southeastern Central Africa. However, the idea that land cover changes influence climate is so lively that the Zimbabwean Meteorological Department published this view on the front page of the national newspaper (*The Sunday Mail*, 1995). Although we share the concern, we want to find a scientific basis for these perceptions.

The amount of rainfall depends on the amount of moisture in the atmosphere and the energy available for condensation. Land cover changes can influence the energy balance via albedo — the reflectivity of the surface for solar input — and surface roughness. Land cover changes also affect evaporation, which influences the energy balance (evaporation converts sensible heat into latent

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[1] The authors wish to thank the Department of Water Resources in the Zimbabwean Ministry of Lands and Water Resources for their hospitality and support. The study on moisture feedback is part of the PhD/MSc research project 'Sharing Scarce Resources — Zambezi', a co-operation between four Dutch international institutes and various local institutes for research on the management of natural resources in Zambia and Zimbabwe.

heat) and the amount of atmospheric moisture (evaporation determines the amount of water returned to the atmosphere). Thus, in several ways, land cover has a feedback on rainfall, both locally and regionally. In this chapter, we restrict ourselves to the feedback of land cover on rainfall through the water balance effects of evaporation, called the "moisture feedback". In this chapter the term evaporation refers to the sum of evaporation and transpiration. The availability of atmospheric moisture is expressed using the term "precipitable water". Precipitable water is the total amount of water vapour in a column of air, expressed as the depth of liquid water in millimetres over the base of the column.

The greenhouse effect is hardly influenced by any human activities at the scale of Southeastern Central Africa. Sea surface temperatures in the Pacific Ocean (El Niño) and the Indian Ocean are hardly influenced by human activities at all. Investigations on both these large scale influences are done to predict the consequences, not to derive recommendations for regional measures to counteract regional climate change. Moisture feedback — on the other hand — is a mesoscale phenomenon with a length scale in the order of 1 000 kilometres, that is related to land cover, which, if sufficiently documented, can lead to recommendations for land use to restore the damage done.

Feedback of land cover on rainfall in other parts of the world has foremost been investigated in the Amazon and the Sahel. For the vast rain forests of the Amazon, moisture feedback has been generally accepted to be important (e.g. Salati *et al.*, 1983; Bruijnzeel, 1990). For the Sahel, with large areas of savanna similar to Southern Africa, moisture feedback is still a point of discussion among scientists (Druyan, 1989). Savenije (1995) contributed to this discussion with the introduction of a simple advection dispersion equation that reproduced fairly well the average annual rainfall on different distances from the coast. With this model as a base, we are investigating the more complex weather system of Southeastern Central Africa.

Influence of land cover changes on evapotranspiration

A denser vegetation cover intercepts a larger proportion of the rainfall, most of which will evaporate shortly after the rainfall event. A denser vegetation cover also decreases surface runoff, via its enhancing effect on infiltration. Thus, land cover changes due to deforestation, cultivation and grazing, affect the proportion of rainfall that is intercepted, infiltrated or becomes surface runoff. The difference between rainfall and runoff is equal to evaporation. Runoff is a measure of the depletion of atmospheric moisture flux by the difference between rainfall and evaporation. For large areas in Southeastern Central Africa, average runoff rates are less than 10%; in dry years the percentage is even less than in wet years. Thus, more than 90% of the rainfall is evaporated and only 10% of the rainfall is balanced by a depletion of atmospheric moisture content (Savenije, 1996a).

Although one would expect that a reduction of evaporation leads to higher runoff coefficients (the proportion of rainfall which comes to runoff), in most parts of Zimbabwe runoff coefficients tend to decrease instead of increase in comparison to similar amounts of rainfall in earlier years (Gunther, 1995). On an annual basis, evaporation seems to have increased. This evaporation increase is mainly due to the increase of storage works with time and other irrigation activities. However, these contribute primarily to evaporation in the dry season, while only wet season evaporation contributes to rainfall.

Natural forests are powerful evaporators during the wet season. In forested areas most of the rainfall evaporates shortly after falling due to interception by the leaves. Moreover, transpiration of vegetation is highest in the wet season when the leaf area index is highest. Thus vast deforestation in the past decades (Whitlow, 1988) has contributed negatively to moisture feedback to the atmosphere in the wet season.

The importance of investigating moisture feedback

The problem of land degradation and shortages of woodland products, especially firewood, are reasons to actively prevent deforestation. In comparison to moisture feedback, these reasons are more obvious at a local scale and the effect is, without doubt, more recognisable for most people. Although still difficult, it appears easier to find support for afforestation to prevent degradation and shortages of woodland products than for the enhancement of moisture feedback.

What practical use has it then to extend the knowledge on moisture feedback? If moisture feedback is proved important, the general idea that evaporation is a loss of water resources has to be revised. Moreover, downwind areas will realise the contribution of land cover in upwind areas to the rainfall they receive. For example, Mozambique, downstream in terms of rivers, is dependent for its surface water on what Zimbabwe and Zambia leave in the rivers. Yet from an atmospheric point of view, Mozambique is the upstream country. If moisture feedback is proved important, Zimbabwe may realize that Mozambique's land cover is of influence on the water that reaches them through the atmosphere. Similar implications play a role at a provincial scale.

Determining the influence of moisture feedback

To demonstrate that moisture feedback is important two things have to be proved:

- rainfall is related to the availability of moisture in the air, and
- the recycling of moisture is not negligible compared to the atmospheric moisture flux.

Weather systems are complicated. We have no intention to build models that can forecast weather. In our approach we intend to model the average rainfall in dry years — years drier than the average — as a function of land cover indicators. This chapter is only meant to open a discussion on the influence of moisture feedback on precipitation and does not go further into modelling of moisture feedback. The chapter gives a summary of past research in Zimbabwe that can contribute to insights in moisture feedback mechanism. It makes a few preliminary assessments on the importance of moisture feedback.

PRECIPITABLE WATER AS A MEASURE FOR RAINFALL

Before clouds can form, air has to be cooled so that condensation of its water vapour can take place. This can be done in several ways:

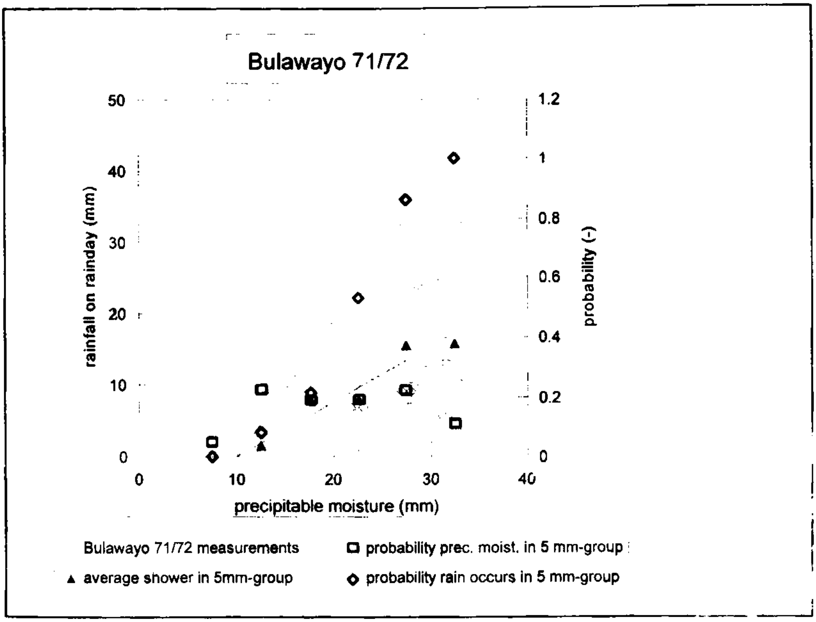
- Orography Mountains force the air to rise; the comparatively high rainfall in the Eastern Highlands is the most obvious example, but also less hilly areas are involved (Laing, 1973).
- Convection The heat of the sun generates rising air mostly resulting in thunderstorms. On an average day in the rainy season the temperature will reach 25°C before showers or storms commence.
- Convergence Surface airstreams from different directions merge; the Inter Tropical Convergence Zone (ITCZ), is a zone in which rain is especially liable to occur because of convergence. Average annual rainfall decreases from north to south partly because the southeast position of the ITCZ differs every year. Thus, despite that a large part of the moisture comes from the southeast (Torrance, 1976), the isohyets (lines of equal amounts of rainfall) decrease from north to south.

Convection is considered the dominant rain-inducing mechanism, accounting for perhaps about 90% of the rainfall (Torrance, 1981). Orography and convergence are considered supplementary but are often conditional. Dependent on the mechanism and the circumstances, rain may, or may not occur, the shower may be long or short and the intensity may be large or small.

As mentioned before, no prior investigations have been carried out on the importance of moisture feedback in the study area. However, related subjects have been studied by the Meteorological Department in Zimbabwe. In the beginning of the seventies, cloudseeding was practised in Zimbabwe. Climatic data were studied to find out if cloudseeding in a certain area would result in less rainfall in other areas. Moreover, to improve weather forecasts, the relations between precipitable moisture, dewpoint and rainfall were studied as well as upper air wind patterns.

The frequency distributions of the percentages that raindays with a certain amount of rainfall occur differ little between different stations. The frequency distributions also remain nearly steady over the years (Kreft, 1972; Torrance, 1981). This points to a similar rain-inducing mechanism over the country and implies that wetter years have been more frequent instead of heavier showers.

Figure 2.1: Rainfall and precipitable moisture as measured in Bulawayo, 1971/72



Source: Derived from data in Torrance, 1973.

Torrance (1973) directly compared the amount of precipitable water measured by radiosonde with measurements of rainfall on the same day. He did this for areas around Bulawayo (see Figure 2.1) and Harare. Both areas have similar frequency distributions of precipitable water. In Harare, however, the proportion of raindays is always greater than in Bulawayo. The explanation lies partly in the fact that Harare is more often under the influence of the Intertropical Convergence Zone (ITCZ) while Bulawayo is far more subject to the rain-inhibiting stability of the Botswana Upper High. This underlies the need to use different parameters for different places while modelling rainfall mechanisms of the Southeastern Central African atmosphere. On the use of cloudseeding methods, Torrance concluded that they would not decrease rainfall at another time or at another location. His argument was that after a heavy shower, even in case of a widespread heavy shower, there was no considerable difference in the precipitable water measured the next day. Torrance concluded that advection was so large that rainfall hardly depleted the moisture flux. But Torrance did not recognize the fact that a considerable part of the rainfall may already have returned to the atmosphere via evaporation.

The Department of Meteorological Services (Watts, 1970) tried to find methods to forecast the weather for Bulawayo Airport. Correlation was sought between rainfall and wind, temperature, thickness and showalter (a measure for instability) and moisture terms of various sorts. The moisture terms overshadowed all other terms. In the evaluation, an Effective Moisture Term was devised, comprising the sum of the dewpoint measurements at 700, 600 and 500 mbar with the 700 mbar level multiplied by four. Although Watts does not present any data that can confirm this, the importance of the 700 mbar level is probably because it represents the levels below which the larger part of precipitable water occurs. This research clearly shows the relation between precipitable water and rainfall.

A method to include an instability factor in the daily forecast was also developed (Watts, 1970). The underlying assumption that mixing of surface and upper air takes place each day can be used to support our assumption of modelling without a vertical dimension.

PRELIMINARY EXERCISES

To get some idea of the importance of moisture feedback some "back of the-envelope" computations are done with some representative climatic data from Zimbabwe:

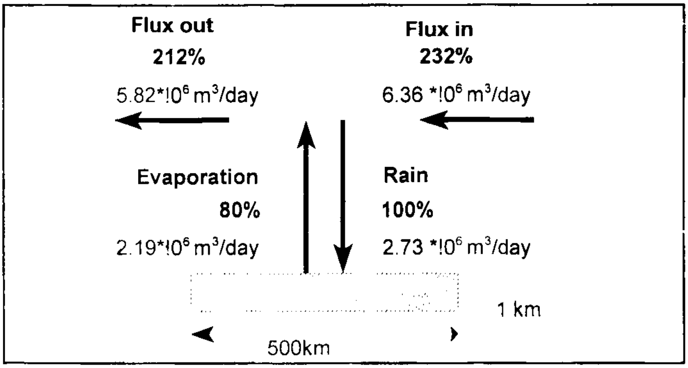
- annual rainfall amount of 700 mm (Torrance, 1981) of which 90% is in the wet season (Griffiths, 1972);
- the wet season lasts 115 days (Torrance, 1981);
- 80% of the rainfall in the wet season evaporates in the same season: assumption based on influence of soil moisture and leaf area index and greenness of trees on evaporation;
- the average amount of precipitable moisture in the atmosphere is 23 mm (Bulawayo in the wet season, derived from Torrance, 1973);
- the average velocity over the height weighted for the moisture content is 3.2 m/s (derived from Bulawayo data in January, Torrance, 1976 and 1981); and
- overall runoff is about 7% of the rainfall (DWR — personal communication)

Using these data, 72% (= 80%*90%) of the total annual rainfall is evaporated in the wet season and 21% in the dry season (= 100%-72%-7%). With the smaller length of the wet season (115 days) in comparison to the dry season (365-115 = 250 days) this means that on an average day in the wet season, 7.5 times more water is evaporated than on an average day in the dry season [(72% / 115 days)/(21% / 250 days)].

Overall water balance

Consider an airstream over a length of 500 km and 1 km wide strip of land located in Zimbabwe. The influx of precipitable water at the upstream side is about 6.36 * 10^6 (m^3/day) [= 23 (mm) * 3.2 (m/s) * 1(km) = 73.6 (m^3/s)]. The annual rainfall over the strip of land is about 700 mm of which 90% falls in the rain season that has a length of 115 days; 5.47 mm falls out per day, 2.73* 10^6 (m^3/day) over the whole strip. Of this 90% rainfall again 80% is assumed to evaporate in the same wet season, i.e. 2.19 * 10^6 (m^3/day) over the whole strip (see Figure 2.2). The relative importance of evaporation to the amount of advected moisture is 2.19/6.36 = 34%, which has a substantial influence on the rainfall itself, particularly in the most downwind part of such a strip.

Figure 2.2: Overall water balance over a strip of land



The water balance in the form of an advection equation

Figure 2.1 with Bulawayo data of the season 1971/72 shows that higher amounts of precipitable water in the morning result in linear increases in: the probability that rainfall occurs; the average shower size; and the variance in shower sizes. Both the function between the precipitable water and the probability that a shower occurs and the relation between the precipitable water and the shower size shows a clear threshold of about 10 mm precipitable water. In this sub-section it is assumed that the average annual rainfall (P) is proportional to the average annual precipitable water minus a certain threshold value (Savenije, 1996b):

$$P = p(W - D) \tag{1}$$

Additionally, it is assumed that the proportion of rainfall that does not evaporate back to the atmosphere is proportional to the amount of rainfall and that the net influence of dispersion can be neglected (Savenije, 1995). Thus, the advection equation reveals:

$$u\frac{dW}{dx} = -p\alpha(W-D) \tag{2}$$

with

W	the average amount of precipitable moisture in the air	(L)
D	a threshold value of precipitable water below which there is no rainfall	(L)
x	distance in the direction of the moisture transport	(L)
p	moisture depletion rate	(T^{-1})
α	loss coefficient; the percentage of rainfall that does not return to the atmosphere during the wet season	(-)

Integration yields:

$$P = P_0 \exp\left(-\frac{p}{u*\alpha}x\right) = P_0 \exp\left(-\frac{x}{\lambda}\right) \tag{3}$$

where

P_0	average amount of rainfall at upwind side of country	(L)
λ	length scale of the isohyet pattern	(L)

In Fig. 2.3 the consequent decrease in average rainfall in the dominant moisture transport direction is shown.

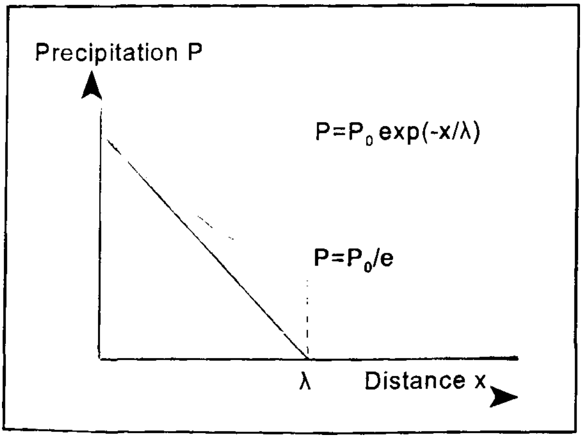


Figure 2.3: Exponential decrease in rainfall

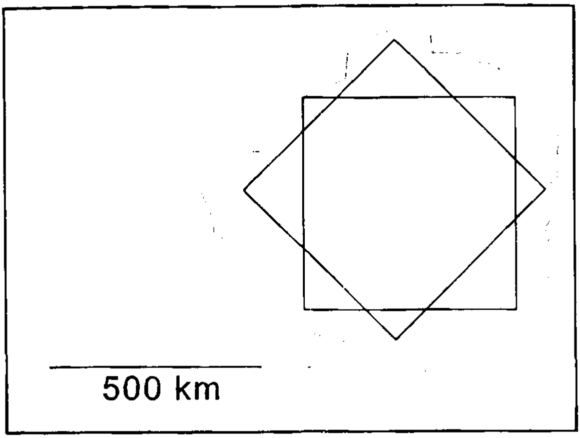


Figure 2.4: Square form model of Zimbabwe

Now let us model Zimbabwe to a square form area. With some manipulation a square of 500km*500km can be fitted into Zimbabwe in every direction (Figure 2.4). For different weather situations the square is in a different position with one side perpendicular to the moisture transport direction. Of course the moisture transport is not always coming from the same side, yet a varying direction would only enlarge the influence of local evaporation. The explained conceptual model above can give a rough estimate of the influence of evapotranspiration.

If we take the threshold of 10 mm in Bulawayo as a measure of the average threshold D, the depletion rate becomes 0.42 day $^{-1}$(=700/115/[23-10]). The loss coefficient α equals the percentage that does not return to the atmosphere in the same rain season. Thus α is assumed here to be 0.2 (100% -80%).

These estimates of the velocity μ (3.2 m/s), the depletion rate p (.42 day $^{-1}$) and the loss coefficient α (0.2) make the length scale l in the order of 3 000 kms. Consequently, after 500 km the average annual rainfall decreases 14% (630 mm to 540 mm in the rain season). Even in this conceptual model this value only applies to average annual rainfall in case of a clear dominant moisture bringing wind direction. The decrease is only 14% because evaporation replenishes the atmosphere. If no evaporation occurs ($\alpha = 1$) rainfall over the whole of the modelled Zimbabwe would on average be 25% less and at the most downwind end even 60% less.

The loss coefficient α is subject to land cover. The main reason for decrease of interception is deforestation or overgrazing. A decrease of the loss coefficient α from 0.2 to 0.1 would result in only 3.7% increase of the average rainfall over the whole square form, yet rainfall in the downwind would benefit with 7.4%. Locally the effect could be more substantial.

The abovementioned values should not be considered as absolutes, they are only meant to illustrate the conceptual model. In Zimbabwe in the rain season an air stream from southeast to northwest dominates, while there is more rainfall in the northwest than in the southeast. This can be explained by the more favourable rainfall mechanisms in the north and does not invalidate the conceptual model.

A STOCHASTICAL RAINFALL-GENERATING MODEL

The meteorological data show that the average seasonal rainfall has hardly any correlation with the average amount of precipitable water (Torrance, 1973). Apparently the threshold *D* is almost equal to the average amount of precipitable water *W*. The frequency with which the atmosphere is replenished with water will give a better measure for rainfall than the average amount of precipitable water. One could imagine the local atmosphere over an area as a bucket with the average amount of rainfall dependent on how frequent the bucket is emptied and not on the average content. The atmosphere produces rain whenever a certain amount of precipitable water, the bucket size, is reached. This carrying capacity of the atmosphere here compared with the bucket size, has a random component that can partly be explained by energetic conditions. Temperature lapse rate and moisture lapse rate play an important role. The influence of energetic conditions should be represented in the model through the probability distribution of the random component of the carrying capacity, the bucket size. If the bucket is full a proportion of the bucket size will fall out as rainfall. Precipitable water travels between neighbouring 'buckets' dependent on the airstreams. Of course this model is far too simplified. Yet as we only intend to reproduce the average annual rainfall, the exponential model described above or such a simple 'bucket' model could be sufficient. Model results for one location agree with the pattern of observations in Bulawayo as shown in Figure 2.1 (De Groen and Savenije, 1996) and show remarkable similarities with stochastical rainfall generators that have a less physical background (De Groen, 1997; De Groen and Savenije, 1997). In the one-dimensional variant, a similar exponential decrease as shown in Figure 2.3 can be noticed. As mentioned before, it is not the intention of this chapter to go into mathematical detail.

CONCLUSION

The above discussion indicates that moisture feedback is indeed important in Southeastern Central Africa. With this confidence we can start now to quantify influences by two-dimensional modelling of the area in GIS. The conceptual model will be elaborated in more detail and compared with historical data. One of the major problems will be to filter out normal anomalies from long term averages.

Once a mechanism for reproducing average annual rainfall is found, the influence of present and past canopy covers can be compared. The severity of droughts in certain areas can then possibly be partially explained by land cover changes in other areas. This is still to be accomplished. However, with this chapter we hope to have opened the discussion on the influence of land cover on rainfall in Southeastern Central Africa.

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