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The impact of small farm reservoirs on urban water supplies in Botswana

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In eastern Botswana there are many small farm reservoirs within the catchments of the major water supply reservoirs, and there is increasing demand for more small reservoirs. The increasing development of farm reservoirs has an impact on the availability of water from the major reservoirs, which supply urban and industrial users, and this creates a conflict between the needs of the rural water users and the urban and industrial users. This paper describes a model which has been developed to allow the effects of the existing small reservoirs and the possible impacts of future proposed ones on the water resources of the major reservoirs to be quantified. The model provides a planning tool, enabling guidelines for future small reservoir development to be determined. The model is a general one which could also be calibrated and applied in other areas with a broadly similar climate. The results of a series of model runs indicate the rate of decline of runoff and yield from the major reservoirs as the total capacity of small reservoirs within the catchment increases. It also shows how this decline is affected by secondary factors such as the relative location of the small reservoirs within the catchment, the typical size of small reservoirs and the type of use to which they are put. The results clearly indicate the adverse effect which uncontrolled development of farm reservoirs would have on the water supplies from the major reservoirs. By quantifying these effects, planners have some of the necessary information to determine the optimum balance between development of small-scale rural water supplies and large-scale urban supplies.

Urban water supply in Botswana is largely dependent on surface water sources and three major reservoirs have been constructed to supply the urban centres. However, within the catchments of these reservoirs there is also considerable demand for agricultural water supply, and over the years large numbers of small dams have been constructed.[1] Clearly the small dams have some impact on the flows into and the yields from the major reservoirs, but the size of this impact is unknown. There is increasing demand for more small dams in the catchments, leading to a conflict of interest between the rural communities and the urban users. In order to quantify both the effects of the existing small dams and the possible impacts of future proposed dams, a model of the system has been developed which allows these effects to be simulated. The model provides a planning tool, enabling guidelines for future small dam development to be determined which provide the maximum benefit to rural users of small dams while safeguarding the urban supplies from the major reservoirs.

This paper briefly outlines the methodology behind the model structure and its calibration, but its main purpose is to present some of the results obtained from applying the model and to discuss the implications for rural water resources development.

The model was developed for the Botswana Department of Water Affairs (DWA) by the Institute of Hydrology in cooperation with Sir Alexander Gibb and Partners (Gibb/Institute of Hydrology, 1992). It was

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[1] In Botswana the word dam refers to the reservoir itself rather than just the water-retaining wall, and it is used with this meaning in this paper.

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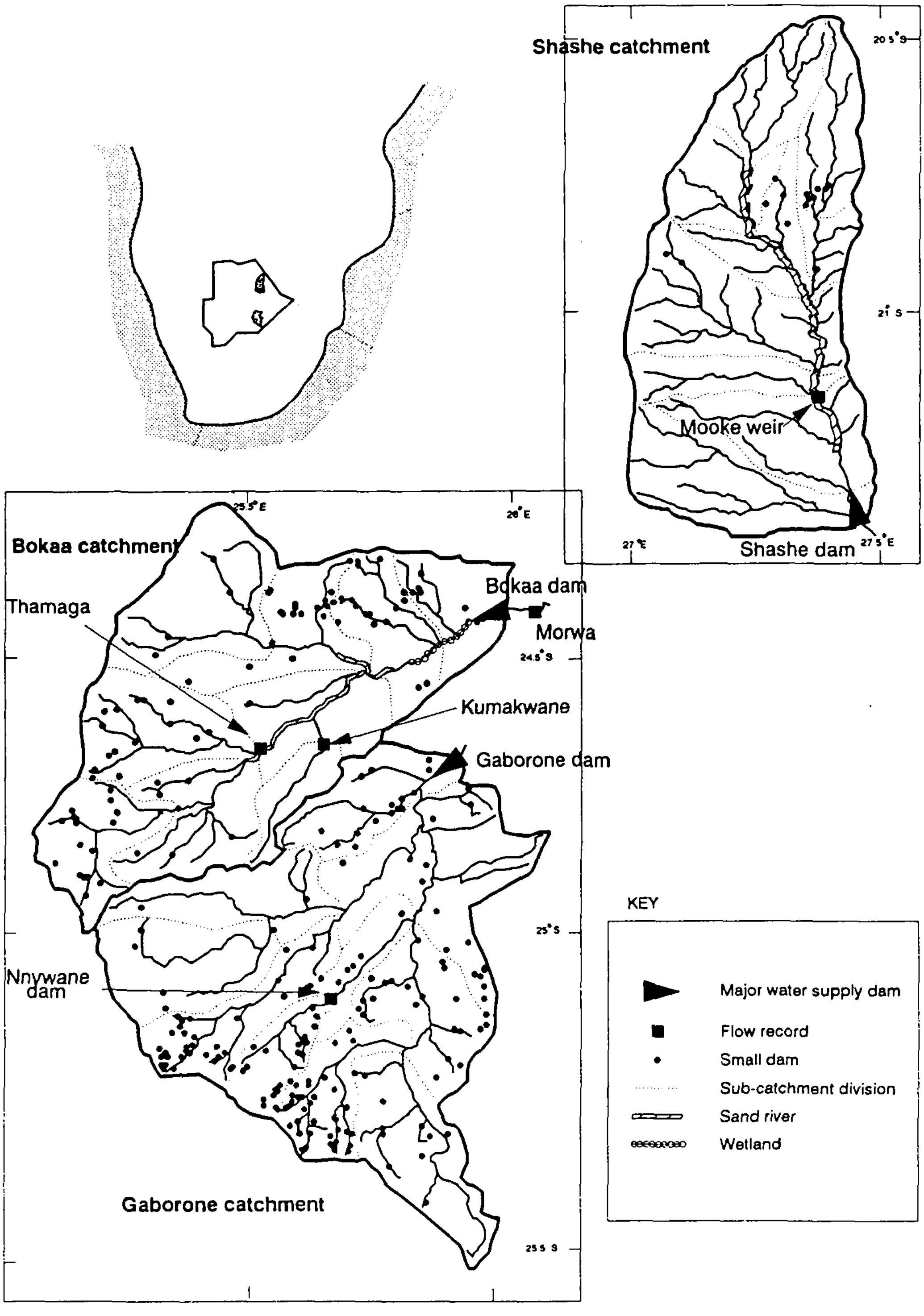

Figure 1 Location plan

constructed and calibrated for the catchments of the three existing major water supply reservoirs in Botswana (Figure 1), but provision has been made for it to be easily reconfigured to run for additional catchments when more major dams are developed. It has been designed as a user-friendly piece of software, running under Windows 3.1, and has been installed in DWA's offices in Gaborone.

There have been a number of previous studies of the effects of farm dams in semi-arid climates, for instance by Moolman and Maaren (1986) and Chunnet Fourie (1990) in South Africa, Mostert (1990) in Namibia and

Neil and Srikanthan (1986) in Australia. These studies were conducted on broadly similar principles and showed broadly similar results to the present one. All, however, were tied to a specific network of dams, and none went so far as to produce a generalized model which can be used to assess the impact of a range of proposed dams.

The study catchments

The location and some of the main features of the three catchments are shown in Figure 1; they lie close to the eastern borders of Botswana where the majority of the population is concentrated. The climate of the area is semi-arid, with annual rainfall of 450–550 mm, falling almost exclusively from October to April. Rain generally falls as short intense storms which are often highly localized. The soils of the catchments are mostly sandy, and it is usually only after several days of storms that any significant runoff occurs, the rivers being dry much of the time even in the rainy season. Runoff events typically occur as spates lasting two or three days up to a week, with 75% or more of annual runoff concentrated into the period December to March, but with very high variability in flows from year to year. Annual open water evaporation rates are about 2000 mm, greatly in excess of rainfall. This pattern of runoff and evaporation has significance when considering the effect of small dams. At the beginning of the rainy season almost all dams are dry. The dams have their greatest impact at this time as they fill up with the first few runoff events. If more runoff follows fairly soon afterwards it tends to pass through the dams little changed, but if as often happens there is a longer dry period, subsequent flows will again be considerably affected as the drawndown dams fill up once more.

The small dams are typically between 1000 and 100 000 m^3 in size, with a few considerably larger than this. This compares to the three major dams which range from 19 to 144 million cubic metres (Mm^3). A total of 320 small dams were identified in the catchments; the majority are used for stock watering, with a lesser number for small-scale irrigation schemes and other purposes.

Model development

There were three main stages in the development of the model: estimation of the dam characteristics (for which very few data are available); construction of the model itself; and model calibration. Each of these are outlined briefly here (for more detail, refer to Gibb/Institute of Hydrology, 1992).

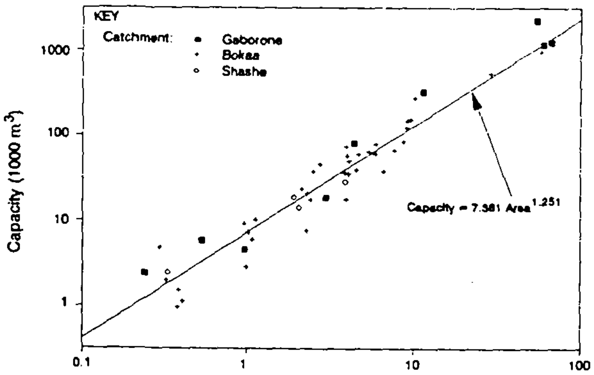

Figure 2 Dam capacity against surface area

Estimation of dam characteristics

For most of the small dams, no data were available on their physical characteristics, but to model them it was necessary to have estimates of at least the following for each: the surface area and capacity, the area/capacity relationship as the dam is drawn down, and the abstractions. The locations of the dams were identified from 1:50 000 scale mapping and from records held by government departments. For a small sample of the dams, physical surveys were carried out and additional information was sought on the usage of water by the local people. This information was used to derive methods to estimate the dam characteristics.

Surface areas and capacities

The surface areas of all the dams were estimated from the size of the blue area shown on the 1:50 000 maps. It might be expected that the area estimated from the maps would be a poor measure of the actual area because the aerial photography on which the maps are based is unlikely to correspond to times when the dams were full, and because many of the dams are very small and are indicated by symbols which may not be representative of the actual areas of the dams. However, when compared to the measured surface areas for the sample of dams surveyed, there appeared to be negligible bias, and it was concluded that it was adequate to use the map areas. This result was also confirmed by measurements made from satellite images of the region.

Having established the surface area of a dam, it is next necessary to estimate its capacity. Figure 2 shows the capacities plotted against area for the surveyed dams. The best fit relationship was

$$capacity = 7.381\ area^{1.251}\ (r^2 = 93.1\%)$$

where *capacity* is in thousand m^3 and *area* in hectares. This fairly strong relationship results because geology

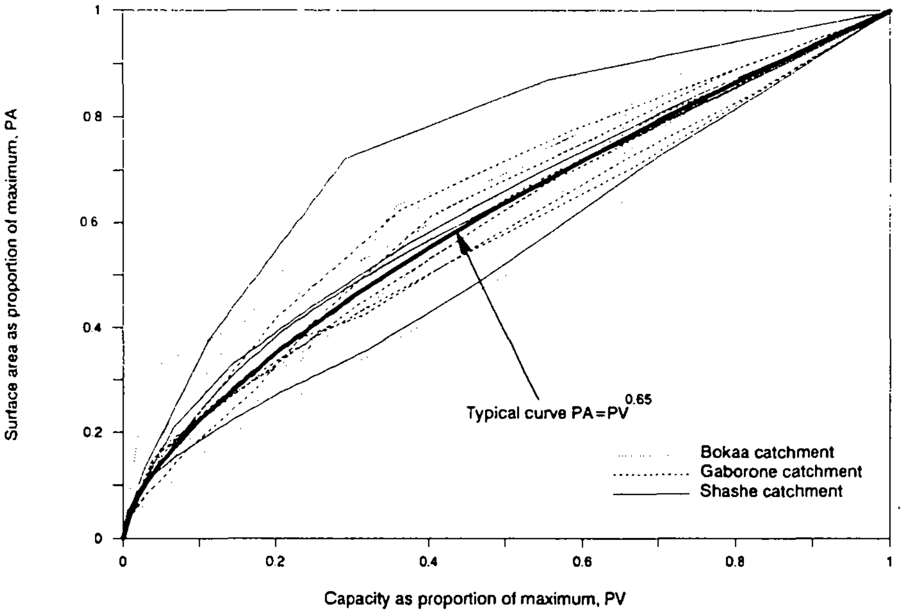

Figure 3 Typical dam area/capacity curves

and topography are generally uniform over the three catchments, with the great majority of the dams lying in similar relatively broad, flat valleys.

Area/capacity curves

The area/capacity curves for a selection of the surveyed dams were made non-dimensional by expressing both capacity and area as proportions of their values when the dams are full, and were then compared as shown in Figure 3. Although there is a fairly wide variety of different curves, many are quite similar and these are concentrated at the centre of the others. A mean curve was estimated by eye, and this was taken as the typical curve, used to represent all dams for which full survey data are not available. It is clear that in many cases the curve will represent actual sites poorly, but the area/capacity curve is of secondary importance compared to the estimates of dam capacity and surface area.

Abstractions

The majority of the dams are used for stock watering, and although it is likely that the amount abstracted is very much less than losses to evaporation, it was thought worthwhile to include some estimate of it. In the survey it was found that no systematic data are kept of the numbers of cattle using particular dams, and in any case numbers vary widely as stock are moved around according to the availability of water and grazing. However to make some allowance for abstractions a somewhat arbitrary assumption was made: that 10 cattle drink at a dam for each 1000 m^3 of capacity. Goats and other animals were ignored. Each head of cattle was assumed to consume 31.5 l/day (SMEC *et al*, 1991). This approach gave cattle numbers which were generally in accordance with the typical numbers thought to be in the area.

For dams used for irrigation, the monthly water use for a typical range of crops and typical irrigation efficiency was estimated from work carried out for other studies (SMEC *et al*, 1991; Arup Botswana, 1991; Chunnet Fourie, 1990). For testing the model with irrigation dams, yield estimates for the dams were also needed. Some curves relating yield to dam capacity, both expressed as proportion of mean annual runoff, were derived from detailed yield analyses which have been carried out in the past for a number of sites (eg Gibb, 1985).

Model construction

The model was required to simulate the daily flows into the major water supply reservoirs over a period of several years. This needed to be done for each of the three conditions of no small dams, the existing small dams only, and existing plus proposed dams in the upstream catchments. It was necessary to allow any combination of proposed small dams to be examined, and to provide facilities for comparisons with observed data to permit model calibration. The model was designed so that it could be easily reconfigured to run for other catchments.

Because of the large number of small dams and the need to allow new dams to be added, a fully distributed approach where the runoff into each dam would be estimated separately, was not practicable. But to model the

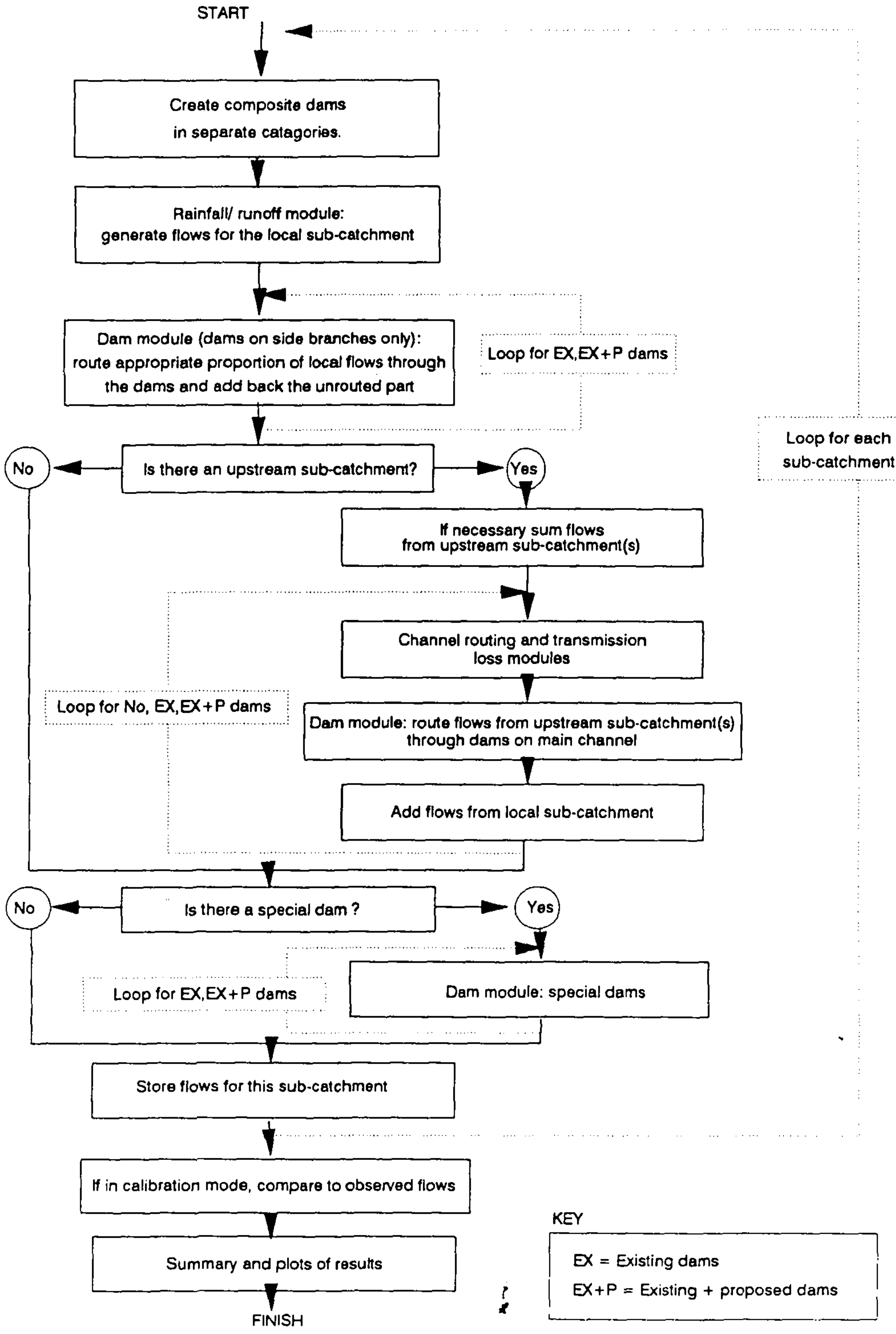

Figure 4 Simplified overall structure of the model

dams with some degree of realism and because of the temporal and spatial variability of rainfall in Botswana, treating the whole catchment as a lumped unit was also inadequate. Therefore a semidistributed approach was taken. Initially each catchment was divided into a number of subcatchments whose boundaries were then fixed; this choice of subcatchment divisions is a key initial decision in setting out to model a catchment. Each of the subcatchments is treated as a lumped system, within which it is assumed that hydrological processes are approximately uniform. The proportion of runoff which is routed through each dam is taken as the proportion of the subcatchment area controlled by that dam. To make some attempt to account for the spatial variability of rainfall, a separate rainfall input is used for each subcatchment.

The model runs with a daily time step because it was required that the effects of the dams on short-period flows could be examined as well as on monthly totals. This choice was a compromise: to represent the temporal variability of the processes as fully as possible, hourly or even shorter time intervals would be required, but considerations such as the computation time and lack of suitable data, mean that a daily time step was the shortest practicable.

The model consists of a number of modules for rainfall/runoff transformation, for routeing through dams, and for channel routeing and transmission losses; these are described in the following sections. The overall structure (illustrated in Figure 4) can best be understood by following the processes involved in a typical model run. Each subcatchment is processed in turn, working in the downstream direction. For each, the steps are as follows:

1. The dams in the subcatchment are divided into a number of different categories, and within these they are amalgamated into composite dams.
2. A rainfall/runoff model generates a flow series for the local subcatchment.
3. A proportion of these flows is routed through the composite dams which are on side branches of the main channel and the unrouted portion of the flows is added back to the routed part.
4. The next part of the process is only carried out when there are other subcatchments upstream of the current one. The summed flows from the upstream subcatchments are passed through a channel routeing and transmission loss model to account for time delay and attenuation of the flood wave and for any significant transmission losses.
5. The flows are routed through the dams on the main channel. Again, this is only when there are upstream subcatchments.
6. Dams can also be defined as special dams which can only be at the downstream end of a subcatchment. The total flow from upstream plus the local subcatchment runoff are routed through this if there is a special dam.

At this point the processing for a single subcatchment is complete and the flows are saved to provide the inputs to other subcatchments further downstream. Each remaining subcatchment is processed in the same manner.

The processing of the appropriate parts of the system is carried out for the three cases of no dams, existing dams only and existing plus proposed dams. Thus, the final results are the flow series for these three cases: summary statistics are then calculated and a range of plotting options are available to allow the flow series to be compared. An additional option allows the model to be run in calibration mode. In this case the flow series for existing plus proposed dams is not computed: instead the flows for no dams and for existing dams only are compared to the observed flows at a river gauge.

Within the overall model, there are three separate modules (to describe the processes of rainfall/run off conversion, dam routeing, and channel routeing/transmission losses). These modules are not described in detail here, but a very brief outline is given of each.

Rainfall/run off module

The rainfall/runoff module used was the Pitman daily model (Pitman, 1976). This is a physically based model which, for each subcatchment, converts the rainfall input from a single raingauge into the runoff from that subcatchment. The Pitman model was chosen because there is a monthly version of it (Pitman, 1973) which has been used on most water resources studies in Botswana and is known to give generally good performance for the conditions there. The daily model has essentially the same structure as the monthly model, and would therefore be expected to do likewise.

Dam module

The dam module carries out the function of determining how much water is lost from the dams (by evaporation and abstraction) and how much continues downstream. To make the modelling practicable, and because there are a large number of dams, they were combined into composite dams within each subcatchment. Because of the different behaviour of dams in different locations and with different uses, the dams were divided into a number of categories before creating the composite dams. The categories used were, first, whether the dam is on a main branch of the river (which receives flow from an upstream subcatchment), or on a side branch (which does not receive flow from an upstream subcatchment). And, secondly whether the dam is used for stock watering or for irrigation. An additional category of special dams was also used to deal with the few much larger dams which behave rather differently to the typical small dams. The assumption, which is believed to be a reasonable one, in treating the dams as composites of many small dams is that all the dams in a particular category behave in the same way: each is filled and drawn down at the same rate in relation to its own capacity.

Within each category the lumped or composite dam is created by summing the capacities, surface areas and abstractions of each, and a composite area/capacity

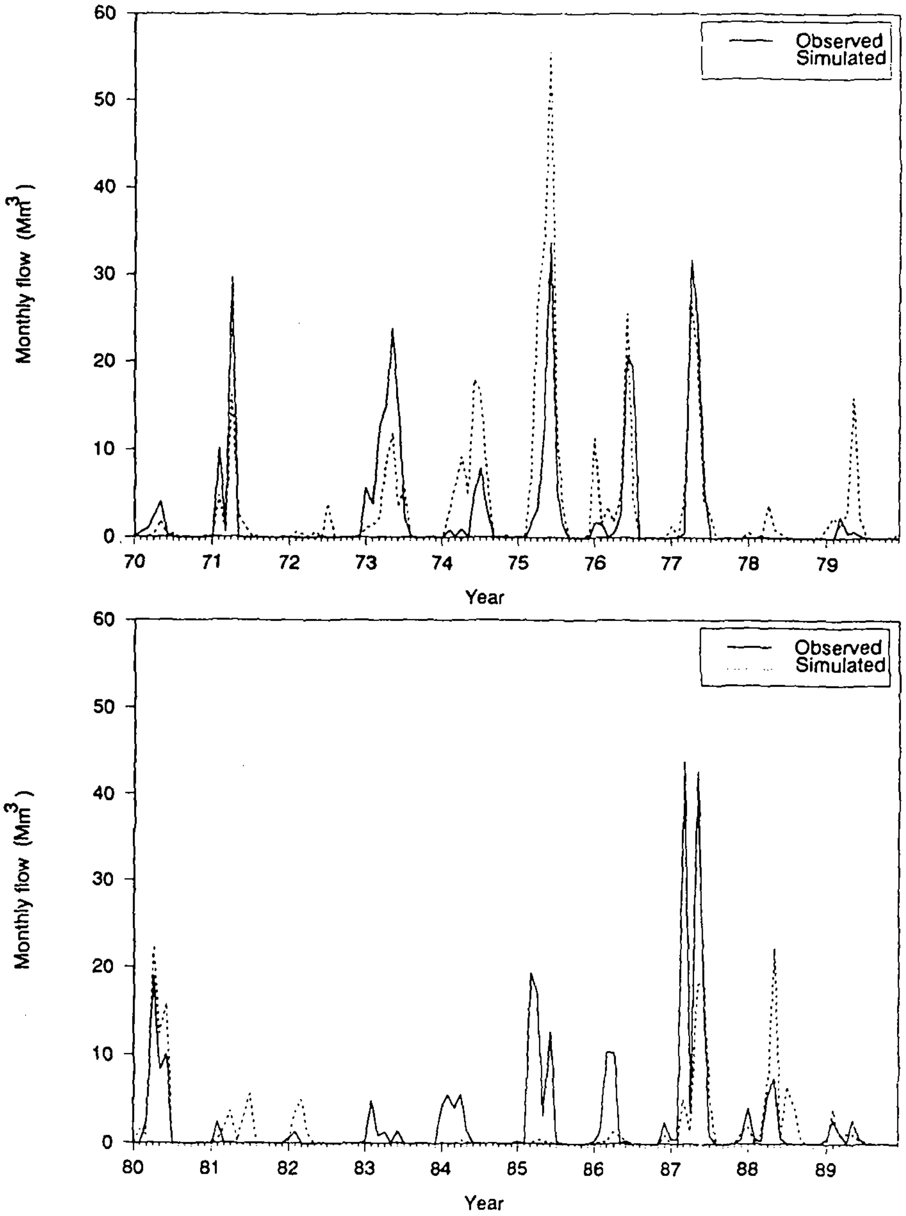

Figure 5 Model calibration for Gaborone catchment: comparison of monthly flows

curve is created as a weighted average of the individual area/capacity curves for each dam.

To determine the proportion of the runoff from the subcatchment which is routed through the dam, the proportion of the subcatchment controlled, *AC*, is used. This assumes that the runoff generated for a subcatchment is uniformly distributed over it. A composite value of *AC* is found by summing the values for each dam. This is satisfactory provided that no dam is upstream of any other dam, but when dams lie within the area which is controlled by a downstream dam, *AC* is set to zero for the upstream dams. If this were not done, the flows to be routed through the dams and thus their impact, would be overestimated. This approach will still cause a loss of accuracy as the upstream dams are effectively transferred to the location of the downstream dam in the lumping procedure, altering the ratio of the dam capacity to its mean annual runoff. However, this occurred for a relatively small number of dams and its effect should be relatively minor.

Channel routeing and transmission loss module

Channel routeing and transmission loss models are required for the subcatchments which have others upstream to provide a time delay and some attenuation of the upstream flows, and to account for significant transmission losses in some of the main channels. It is important to model the losses as in some cases they have a very considerable impact on total catchment runoff

Table 1 Model calibration: comparison of annual statistics

	Catchment area (km^2)	Period (years)		MAR (Mm^3)	Mean(log)	SD(log)
Whole catchments						
Gaborone	3983	20	Obs	30.2	1.096	0.790
			Sim	30.3	1.076	0.780
Bokaa	3570	15	Obs	13.1	0.848	0.557
			Sim	13.1	0.838	0.529
Shashe	3650	20	Obs	106.0	1.854	0.410
			Sim	106.2	1.840	0.413
Parts of catchments						
Nnywane	238	20	Obs	2.21	0.005	0.638
			Sim	2.27	0.030	0.592
Thamaga	1320	4	Obs	14.6	1.016	0.391
			Sim	14.7	0.947	0.537
Kumakwane	166	9	Obs	1.19	−0.223	0.565
			Sim	1.05	−0.250	0.514
Mooke weir	2460	11	Obs	48.8	1.587	0.350
			Sim	47.7	1.590	0.276

(approximately 50% of the total runoff in the Bokaa catchment).

Channel routeing was carried out by the simple Muskingum procedure using hourly flows, estimated from the daily values.

There are two main sorts of transmission losses occurring in Botswana. One is losses into the bed of sand rivers, where the sand bed stores significant quantities of water through the dry season and is recharged when the river flows. The second, which is found in the Bokaa catchment, is a wetland area beside the Metsemotlhaba river which again is recharged by river flows and loses water by evapotranspiration through the dry season. The main areas where these two types of losses occur are indicated in Figure 1. Both types of loss were modelled in a fairly simplistic manner by treating them as storages. These absorb a proportion of the river flow until the store becomes full. After this point, all flow is passed downstream. In periods of no flow, the store is gradually depleted, and this was treated as if it is caused solely by evaporation. Although other processes such as seepage losses and downstream flow within the sand bed also occur, these are probably much less important, and for simplicity they are included with the evaporation. The determination and initial calibration of these models was assisted by survey data on the size and storage capacity of the sand beds, and, for the wetland, a satellite image of the region helped to determine its overall extent (about 12 km^2).

In the Bokaa catchment where both sand rivers and wetlands occur, there are some periods of simultaneous data at flow gauges upstream and downstream of these areas (see Figure 1), and these were used to test the transmission loss model. The results indicated that the simple storage approach performs reasonably well. It was found that the wetland was a major cause of water loss from the Bokaa catchment, losing about 12 Mm^3/year compared to a downstream annual runoff of about 13 Mm^3. The sand rivers both in this case and in the Shashe catchment were relatively insignificant, losing about 1 Mm^3 each.

Model calibration

The model was calibrated for the three study catchments upstream of Gaborone, Bokaa and Shashe reservoirs, using the subcatchments as indicated in Figure 1. A problem arises with the calibration because the observed river flows include the effects of the existing dams, but the number of dams in use must have varied during the calibration period. Ideally, the date of construction of each dam should be known so that its effect can be included in the simulation at the appropriate time. However, very little data on construction dates were available, but it did appear that the majority were already in existence before the start of the calibration. For the purposes of calibration therefore, it was assumed that all the dams existed for the whole period. Generally, the model tended to overestimate observed flows in the earlier part of the calibration and underestimate in the later period (Figure 5), whereas if significant numbers of small dams had come into use during this period the opposite would have been expected. Thus this assumption does not appear to cause any inconsistencies, indicating that the change in the number of dams during the calibration period must have been small.

The main emphasis in the calibration was on obtaining good agreement for statistics of annual runoff, and

Table 2 Summary of effects of existing small dams

	Existing dams		MAR (Mm^3) for		Percentage
	Number	Capacity (Mm^3)	No dams	Existing dams	change in MAR
Gaborone	203	26.09	40.43	30.28	–25.1
Bokaa (a)	103	3.58	15.01	13.07	–12.9
(b)	103	3.58	17.96	15.57	–13.3
Shashe	14	0.13	106.45	106.24	–0.2

(a) using calibration period; (b) using test period with reduced wetland area.

these results for each of the main catchments and for a number of locations within the catchments are given in Table 1. It can be seen that excellent agreement has been obtained, and this means that both the mean flow and its variability are reproduced by the model.

The seasonal distribution of flows was also examined, and this was not as good as hoped with a tendency for underprediction in December and overprediction in April, but this could not be improved without loss of agreement for the annual statistics which were considered to be the most important indicators of model performance. An example of the calibration is also indicated by the comparison of simulated and observed monthly flows for the Gaborone catchment (Figure 5). This shows that the model is not able to cope with the dry period of the mid-1980s, tending to underpredict at this time. One of the main factors contributing to this may be the general inadequacy of the rainfall data. Rainfall in Botswana is generally very localized and there is a great shortage of unbroken rainfall records, which means that rainfall records often do not give a good representation of the actual rain in any particular location. In these circumstances, the agreement between individual monthly flow values is as good as can reasonably be expected.

Model parameters were also needed for subcatchment areas which have no observed flow data, and generally, it was assumed that, lacking any better information, the same parameters should be applied to each subcatchment. In light of the broadly uniform topography, vegetation and soils over the catchments, this assumption is reasonable. The exception is the Bokaa catchment where observed data within the catchment did allow some differentiation between subcatchments.

Assessment of impact of small dams

A set of runs of the hydrological model over the 20 year period 1970–71 to 1989–90 was carried out to test the impact of small dams. The principal factor investigated was the total capacity of the small dams. In order to make the tests comparable between the different catchments, the total capacities expressed as a percentage of the mean annual runoff, *MAR*, of that catchment were approximately the same for each; small dams of about 2, 5, 10, 20 and 40% of *MAR* were used. Some secondary factors in determining the effects of small dams were also investigated. These were the size of the typical small dam tested; the proportion of the catchment controlled by the dams; and the type of abstraction from the dams. A typical small dam was taken as having a capacity of 50 000 m^3 as this is about the size that is commonly built, and smaller and larger dams of 5000 and 500 000 m^3 were compared to this. For the proportion of the catchment controlled by the small dams, *AC*, a value of 0.25 was taken as typical, but smaller and larger values of 0.1 and 0.5 were also examined. In effect, this is looking at the impact of the position of the dams in the catchment; as *AC* is increased the same total capacity of dams are placed further downstream. To look at the effect of abstractions from the dams, the tests were first carried out assuming that all proposed dams are used for stock watering, and then repeated assuming they are used for irrigation.

The results of the model runs are flow series with different combinations of proposed dams, which indicate the impact on *MAR*, runoff patterns and seasonal flow distribution.

Impact of existing dams

The effects of the existing dams on the runoff from the catchments were determined in the course of the model calibration work since simulated flows taking into account the existing dams were matched to the observed flows. The results are listed in Table 2: the effects vary from a negligible change in the Shashe catchment to a 25% decline in *MAR* for Gaborone which has 26 Mm^3 of existing dams.

In the case of Gaborone, 18 Mm^3 of this total capacity of small dams is contained in a single large dam which controls only a small part of the catchment, and because of this the decline in *MAR* is less than would otherwise be expected. The simplification inherent in the model means that the effect of small dams may be slightly

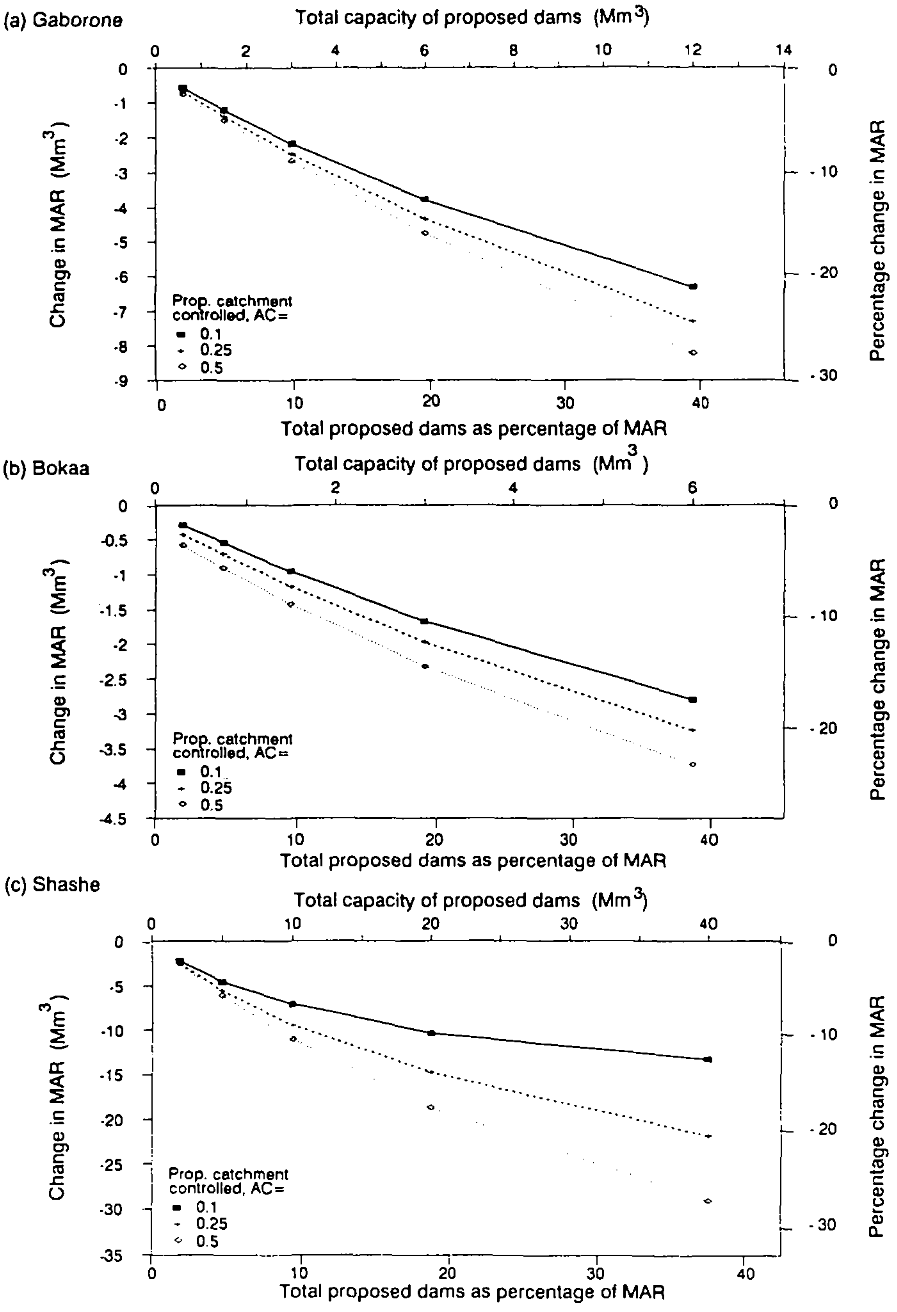

Figure 6 Change in catchment MAR with increasing small dams and varying proportion of catchment controlled: (a) Gaborone, (b) Bokaa, (c) Shashe catchment (stock-watering dams with a typical capacity of 50 000 m^3 are assumed)

overestimated when many dams are nested, so that these estimates of *MAR* for no dams should be thought of as upper limits for the undeveloped catchment *MAR*s.

Impact of proposed dams

The changes in *MAR*s for increasing total capacity of small dams in the three study catchments are plotted in Figure 6. This also shows the effect of varying the proportion of the catchment controlled by the dams, *AC*. In all cases it is assumed that each proposed dam has a capacity of 50 000 m^3 and is used for stock watering. The effects of small dams are basically similar in each of the three catchments; the total capacity of small dams is the overriding factor affecting the runoff. Broadly, dams having a total capacity of 10% of *MAR* cause roughly the same decline of between about 8 and 10% in catchment *MAR*. For greater total capacities of small dams the effect

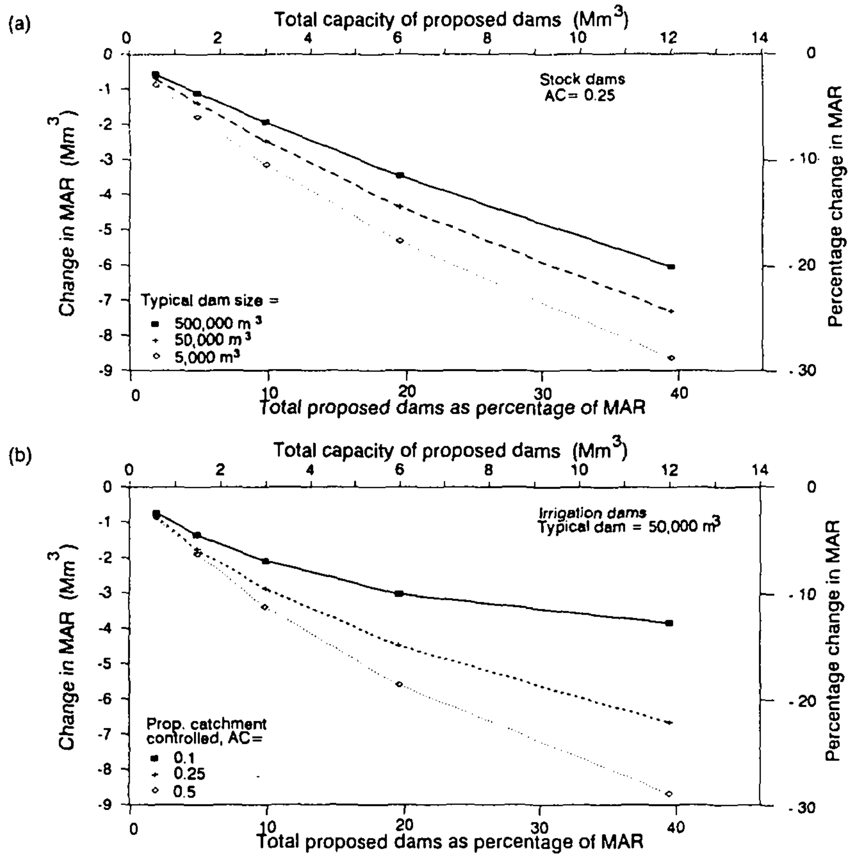

Figure 7 Change in catchment MAR with increasing small dams for Gaborone catchment: (a) showing the effect of varying typical dam size, (b) using irrigation dams rather than stock-watering (compare to Figure 6(a))

increases approximately linearly, but becomes relatively smaller with more small dams. An examination of the hydrographs showed that the effect was considerably more marked in dry years when the small dams absorb a greater proportion of the available flow. The same total capacity of small dams has a greater effect if they are placed further downstream (that is, if *AC* is increased). This is because the flows entering the dams are greater, and the dams are therefore likely to fill more frequently, and thus will tend to lose more water.

In addition, Figure 7a shows, for Gaborone catchment, the additional effects of varying the size of the typical proposed small dams, indicating that a small number of large dams has a relatively smaller effect than a large number of small dams with the same total capacity. This is because larger dams tend to have a more efficient shape which has lower evaporation losses.

Figure 7b, when compared to Figure 6a, shows the effect of the dams being used for irrigation rather than stock watering. In this example this difference is quite large, but this was found to be largely a result of the way the model was constructed. The proposed stock dams are treated as controlling a part of the catchment which has no existing dams. This is perhaps rather unrealistic considering the large numbers of existing dams in this case, and these results may have tended to overestimate the effects of stock dams for the Gaborone catchment. In other examples where there were few existing dams in the catchment, the difference between stock and irrigation dams was not great and this may be more typical of the general situation. Since water loss from dams is dominated by evaporation, differences in the abstractions would not generally be very significant.

An example of the effects of small dams on the seasonal distribution of flows is given in Figure 8. The effects were similar for each catchment but vary through the year. The reduction in flows is relatively greater early in the hydrological year, as at this time the dams will be dry so that a greater proportion of the runoff is trapped.

Implications for watershed development

There are considerable implications of these results for watershed development. They show clearly that development of small farm dams upstream of major reservoirs should never be allowed to proceed unplanned. Small dams can have significant effects on

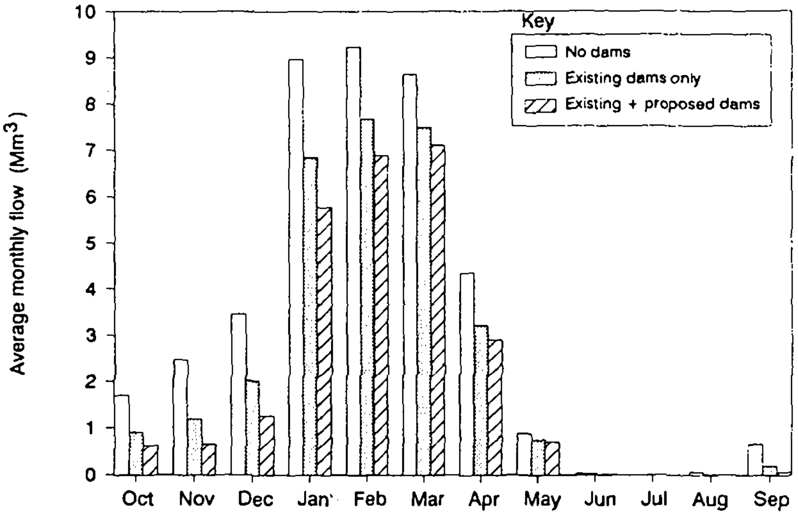

Figure 8 Impact of small dams on seasonal distribution of flows for Gaborone catchment

the run off into and the yield from the large reservoirs, and therefore it is necessary to assess these effects and weigh the benefits of rural developments against the adverse effects to urban water users.

Where development of small dams is to be carried out, the results of the study also help to show how the dams can be designed to minimize their impact. As far as possible, small dams should be located in the upper parts of the catchment, where they will have a smaller effect on downstream flows compared to placing them further downstream. Also the development of fewer somewhat larger dams, which minimizes evaporation losses, should be preferred to numerous smaller dams of the same total capacity, as it is found that this reduces the downstream impact. While this is the case when examined from a purely water resources point of view, there may well be environmental and socioeconomic factors which would favour the option of a greater number of smaller dams, and these factors will need to be balanced against the greater impact on downstream resources of smaller dams. These results relate to the particular catchments in Botswana, and they cannot be automatically extrapolated to other regions. However, the main conclusions are likely to remain valid in other similar semi-arid regions.

Conclusions

A model has been developed which allows the impacts of both existing small dams and of a range of proposed small dams within the catchments of major water supply reservoirs to be assessed. The model provides a planning tool, enabling guidelines for future small dam development to be determined. It is a generalized model which can be reconfigured to other catchments with a similar semi-arid climate. By using a semidistributed approach, the model tries to take account of the spatial variability of the hydrological processes, and, to a reasonable extent, allows the high temporal and spatial variability of rainfall in Botswana to be represented.

Methods have also been developed to estimate the physical characteristics of the small dams using only the surface area shown on maps. This means that the majority of dams, for which detailed information is lacking, can still be included in the model without the need to carry out extensive field surveys.

The results for the three study catchments show that the total capacity of small dams is the overriding factor causing decline in catchment runoff. Dams having a total capacity of 10% of mean annual runoff, *MAR*, cause roughly the same decline of between about 8 and 10% in catchment *MAR*.

This decline in *MAR* is affected by other factors which are of secondary importance but still significant. These are first the location of the dams; for instance, the same total capacity of small dams has a greater effect if they are placed further downstream. This is because the flows entering the dams are greater, and the dams are therefore likely to fill more frequently, and thus will tend to lose more water. The second factor is the size of the typical proposed small dams; a small number of large dams has a relatively smaller effect than a large number of small dams with the same total capacity. This is because larger dams tend to have a smaller surface area in relation to their capacity (from Figure 2, it can be seen that a dam which has a capacity twice that of another, has, on average, only about 70% larger surface area). Thus, larger dams have a more efficient shape which produces lower evaporation losses. The third factor, the type of use to which the dams are put, whether for stock watering or for irrigation, also has a minor effect. In addition, it was found that small dams have a greater impact in dry years and at the start of the hydrological year.

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References

Arup Botswana (1991) *Lotsane dam feasibility study* Report to Department of Water Affairs, Gaborone

Chunnet, Fourie and Partners (1990) *Lephalala river catchment water resources development study* Report to RSA/Lebowa Permanent Water Commission

Gibb, Sir Alexander and Partners (1985) *Feasibility study of Kolobeng and Metsemotlhaba dams* Report to Water Utilities Corporation, Gaborone

Gibb, Sir Alexander and Partners (Botswana)/Institute of Hydrology (1992) *A study of the impact of small dam construction on downstream water resources* Report to Department of Water Affairs, Gaborone

MacDonald, Sir M and Partners (1988) *Metsemotlhaba Transfer Scheme – Feasibility/ Preliminary Design Study* Report to Department of Water Affairs, Gaborone

Moolman, J and Maaren, H (1986) *The Effect of Farm Dams on the Hydrology of a Catchment* Hydrological Research Institute, Department of Water Affairs Scientific Services, Pretoria

Mostert, A C (1990) *The effect of farm dams in the Omatjenne dam catchment area on the yield of the Omatjenne dam* Hydrology Division, Department of Water Affairs, Windhoek, Namibia

Neil, D T and Srikanthan, R (1986) *Effect of farm dams on runoff from a rural catchment* Technical memorandum 86/18, CSIRO, Canberra, Australia

Pitman, W V (1973) *A mathematical model for generating monthly river flows from meteorological data in South Africa* Report No 2/73, Hydrological Research Unit, University of the Witwatersrand, Johannesburg

Pitman, W V (1976) *A mathematical model for generating daily river flows from meteorological data in South Africa* Report No 2/76, Hydrological Research Unit, University of the Witwatersrand, Johannesburg

SMEC, WLPU and SGAB (1991) *Botswana National Water Master Plan* (NWMP) Report to Department of Water Affairs, Gaborone