REPORT ON A REVIEW OF EVAPORATION ESTIMATION FOR THE OKAVANGO DELTA

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April 1990

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Report by staff of the Institute of Hydrology, Wallingford, UK.

1. INTRODUCTION

At the request of the Department of Water Affairs, three senior members of staff of the Institute of Hydrology, Wallingford, UK, visited Botswana from 19 February to 2 March 1990. The staff were F.A.K.Farquharson, Head of Consulting Services, Dr J.H.C.Gash, Head of Evaporation Physics and Dr J.M Roberts, Head of Plant Physiology. The purpose of the visit was twofold, firstly to review existing work on evaporation in Botswana, and secondly to determine whether or not modern, sophisticated micro-meteorological techniques could usefully be employed over the Okavango to measure evapotranspiration losses directly.(See footnote 1)

The first objective, the review of previous work on evaporation, relates largely to the recent studies undertaken by the Snowy Mountain Engineering Corporation (SMEC) on open water evaporation and on ecological zoning of the Okavango.

Annual average rainfall in Botswana varies from less than 400 mm over half the country rising to no more than 550 to 650 mm in the more populated eastern and northern areas. Annual evaporation from open water is of the order of 1900 to 2000 mm and is thus an extremely important component of the hydrological cycle in the semi-arid environment of Botswana. The principal source of water to the major areas of population is from major surface storage reservoirs, particularly Gaborone and Shashe reservoirs. Inflows to these reservoirs are infrequent due to the highly skewed nature of annual rainfall and runoff. The reservoirs have therefore been constructed to store several years' supply, and significant loss of stored water is experienced through evaporation.

The second objective of the visit was to consider the process of evapotranspiration from the Okavango swamp and delta area. This region of Botswana is important from the point of view of wildlife and tourism, and may be an important potential source of water for agriculture and for the growing tourism industry.

Evaporation from the swamp is of considerable importance as, of the average annual inflow of 1100 million m^3 to Botswana, some 95 to 98% is lost as evapotranspiration and seepage within the Okavango delta. A number of attempts have been made to quantify the magnitude of this evapotranspiration loss over the years, and deriving accurate estimates of evaporation is the vital first step in development of a successful mathematical model of the Okavango system.

(1) A distinction is drawn in this report between evaporation, the loss of water from a free water surface, either open water or a wet surface such as soil or wet vegetation, and evapotranspiration, loss of water through transpiring vegetation. This latter process involves movement of water through the stomata of plant leaves, which can be employed by the plants as a water conservation measure to suppress actual water loss during periods of water scarcity. Evapotranspiration is used in this report to mean water loss to the atmosphere through both direct evaporation from either open water or wet surfaces and also through transpiring vegetation. Thus the process is of particular relevance to the consideration of water losses from the Okavango swamp and delta region of Botswana.

Recent advances in micro-meteorological research would permit direct measurement of the evapotranspiration flux from various vegetation types within the Okavango ecosystem. The Institute of Hydrology are acknowledged world leaders in this field, and have developed one of the most advanced direct evaporation measurement systems in the form of their Hydra equipment. This equipment would be deployed at a number of representative sites throughout the swamp and delta and combined with measurements of various indicators of plant physiology which can assist in estimation of direct evapotranspiration. Details of the Hydra equipment are given in Appendix II.

This current report will start by reviewing previous studies of evaporation in Botswana, with particular emphasis on studies relating to evapotranspiration from the Okavango. The report will then discuss the type of additional work that is required to define fully the actual evapotranspiration losses from the Okavango swamp and delta system. Details of the itinary of the IH staff and a record of people met is provided in Appendix I.

2. REVIEW OF PREVIOUS EVAPORATION STUDIES

2.1 Early studies

The first study of evaporation in Botswana was undertaken in the late nineteen sixties by an FAO team and reported on by Pike (1971). The Penman formula was applied to data from Gaborone, Mahalapye, Francistown and Maun. These estimates of open water evaporation, Eo, formed the basis of most engineering studies in Botswana until the mid 1980's when the Institute of Hydrology (IH), working with Sir Alexander Gibb and Partners on increasing water supplies to Gaborone and the south east, undertook a detailed water balance study of Gaborone reservoir in an attempt to measure open water evaporation directly. ?

At about the same time the Department of Meteorological Studies (DWS) applied the Doorenbos and Pruitt (1977) version of the Penman formula to data from nine stations throughout Botswana, and the DWA also carried out a water balance study of Gaborone reservoir. The recent report by the Snowy Mountain Engineering Corporation (SMEC 1987) discusses and presents results of this earlier work.

The Pike estimates are now believed to be rather low, a fact that was recognised by DWA and IH some years ago and it was this concern that led to the reservoir water balance studies and to the recent DMS work. However, the DMS estimates were between 20 and 30% higher than the earlier Pike values, the increase being relatively uniform from month to month. This difference is fully discussed in the SMEC report. Similarly, the DWA water balance estimate of Eo for Gaborone reservoir was 25% higher than Pike's earlier Penman estimate. By comparison, the IH water balance estimate of Eo from Gaborone reservoir was only 5% higher than Pike.

The DWA water balance estimate was high because evaporation had been calculated for all months, and not just from months when inflows could be assumed to be zero as applied by IH. Thus evaporation is calculated using the equation;

$$Eo = (I + P.A_{av} - Abs - S - dV) / A_{av}$$

where Eo = evaporation in mm from the reservoir surface
I = inflows to the reservoir
P = rainfall onto the reservoir in mm
A_{av} = average reservoir area during the month
S = seepage loss from the reservoir
dV = change in reservoir storage during the month

Both IH and DWA assumed that the seepage loss was negligible, which a recent report by Rofe, Kennard and Lapworth (1986) has essentially confirmed. Because DWA did not exclude periods of inflow from their analysis, the inflow, I, would only equal the increase in storage if $E.A_{av}$, $P.A_{av}$ and Abs were small during the inflow, which would only be true when large inflows occur over a short period of time. Thus the DWA formulation would tend to overestimated evaporation loss from the reservoir.

The results of the IH and DWA water balance calculations are shown in Table 1 and in Figure 1. It is apparent that the DWA estimates are more variable from month to month than would be expected and are generally higher than the IH estimates.

Table 1 Comparison of Eo estimates for Gaborone reservoir

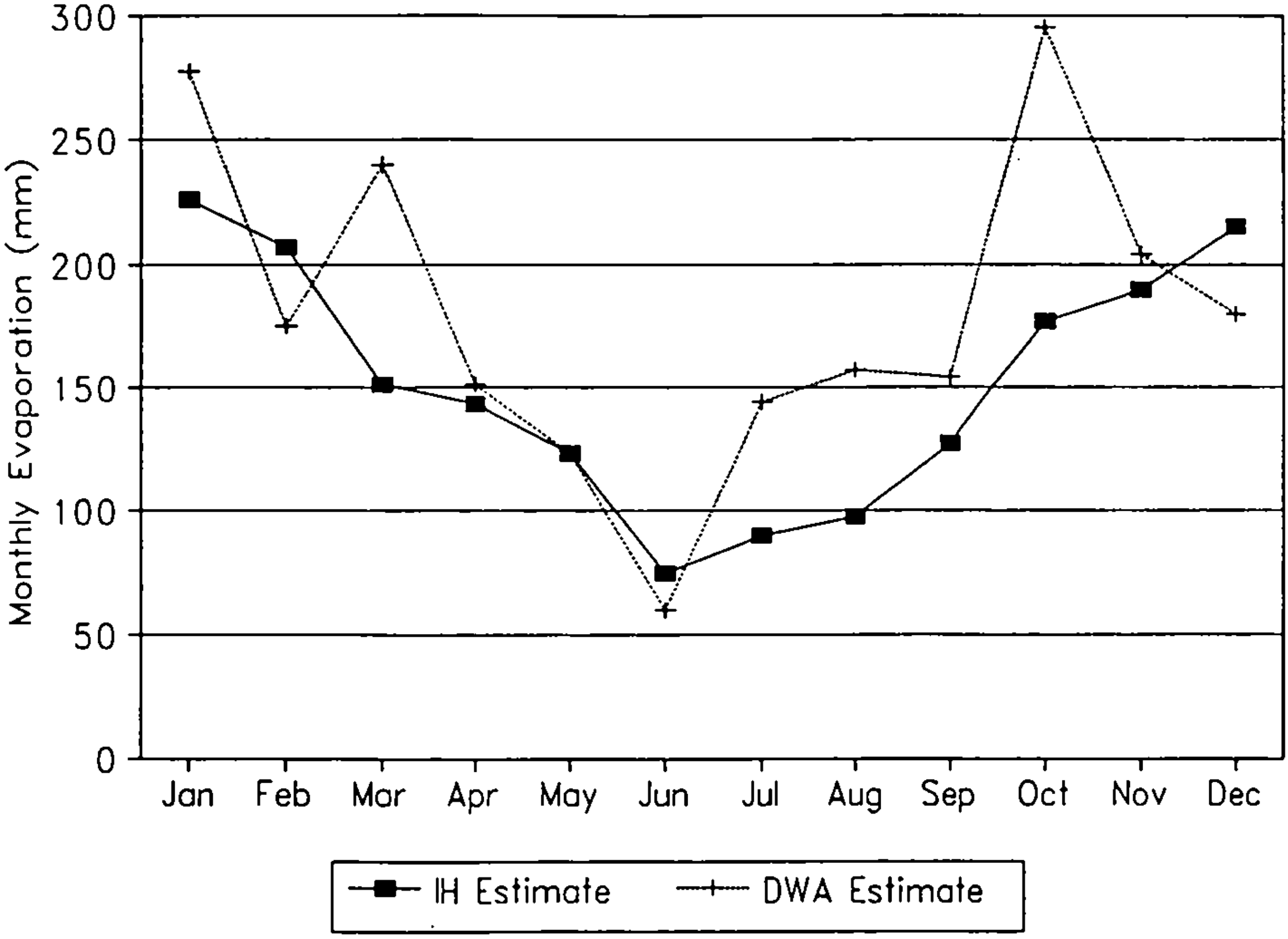
Mean monthly evaporation losses from reservoir (mm)

Month	IH	DWA
Jan	226	277
Feb	207	175
Mar	151	240
Apr	143	151
May	123	123
Jun	75	60
Jul	90	144
Aug	98	157
Sep	127	154
Oct	177	295
Nov	190	204
Dec	215	180
Annual Total	1,822	2,158

Because of the uncertainty as to the true magnitude of open water evaporation in Botswana, the DWA commissioned a thorough study of all data by consultants, the Snowy Mountain Engineering Corporation, who reported in 1987. Comments on this report are presented below.

2.2 Comments on "Study of open water evaporation in Botswana", SMEC, 1987

FIGURE 1 Comparison of Water Balance
Estimates of Evaporation from Gaborone



This report is clearly a very thorough review of the process of evaporation from open water in Botswana. The study used three main methods to assess Eo, which were;

(i) Penman's formula
(ii) a reservoir water balance
(iii) use of evaporation pans with a coefficient

Considering the evaporation pans first, SMEC correctly point out that pans rarely provide a useful estimate of evaporation as a coefficient must be applied to the pan data, the coefficient often being estimated from other estimates of evaporation within the region. The pan coefficient varies from 0.6 to 0.8 in general throughout the world, and SMEC calculated that for Botswana it varied from 0.6 to over 0.9 on a monthly basis, and that the mean annual value was 0.78 over the seven pan sites with data.

SMEC concluded that for water resources purposes it would always be preferable to use other data from the climatological stations in the country to estimate evaporation using the Penman formula. The Institute of Hydrology would agree with this conclusion.

The use of existing reservoir data to estimate Eo was pioneered in Botswana by IH and has been discussed above. SMEC have undertaken a careful reappraisal of the available data for Gaborone, Shashe, Nywane and Mopipi reservoirs. They agreed with earlier IH and DWA studies that seepage losses could be neglected. The SMEC studies adopted a similar approach to that used by IH and the results for the two reservoirs studied by both consultants are broadly similar as shown in Table 2.

Table 2 Comparison of Reservoir Water Balance Estimates of Eo

Reservoir	Estimated Annual Eo (mm)		
	IH	SMEC	DWA
Gaborone	1822	1901	2158
Shashe	1911	1928	

Estimation of Eo using the reservoir water balance approach is inherently simple to understand, and given good quality data, should provide accurate estimates of monthly Eo. However, as SMEC correctly point out, the data contain many inconsistencies and deficiencies which hamper the accurate estimation of Eo. However, the results from Gaborone, Shashe and Mopipi reservoir provide reasonably accurate estimates of Eo on an annual and mean monthly basis.

2.2.1 The Penman equation

The review of the Penman formula and its application to Botswana data is very well discussed by SMEC. The report presents a very clear and thorough analysis of all aspects of estimating open water evaporation using the Penman equation and IH generally agrees with their results and conclusions.

The recommendation to site the automatic weather station at the centre of the Gaborone reservoir, rather than on land, is sound. We would further suggest that if, or when, the automatic weather station can be reinstalled on the reservoir it should be modified to include a measurement of water temperature in the surface layer. This measurement allows the evaporation to be calculated by the mass balance approach, ie a diffusion equation with a windspeed dependent diffusion coefficient. Alternatively the gradients of temperature and humidity can be used in combination with the net radiation to derive the evaporation by the Bowen ratio method. Recent work at the Institute of Hydrology has shown that in a tropical lake with negligible seasonal change in water temperature all these methods give acceptable results. However if there is a substantial seasonal change in water temperature, and therefore energy going into or coming out of storage, the mass balance method may be expected to give better results.

2.2.2 Altitude correction in the Penman equation

The SMEC report on open-water evaporation advised that no correction for altitude should be made to the calculations of Penman open-water evaporation. The minutes of a meeting on this subject held in Gaborone also showed that there was some general doubt among the scientific community in Botswana on this point.

The derivation of the Penman equation given by Brutsaert (1982) shows that the altitude correction arises out of the pressure dependence of the so-called psychrometric "constant". This is not a constant but is a pressure dependent variable given theoretically as;

$$g = c_p p/0.622L$$

where cp is the specific heat of air at constant pressure, p is atmospheric pressure, L is the latent heat of vaporisation, a weak function of temperature, and the factor 0.622 is the ratio of the molecular weights of water vapour and dry air. Clearly as altitude increases and pressure decreases so the psychrometric "constant" will decrease.

The following formulae can be used to adjust for altitude;

$$p = 1013\,(1 - 0.0065A/288)^{5.2553} \quad \text{mbar}$$

where 1013 mbar is the average sea-level pressure, and A is altitude in metres.

$$L = 1000\,(2500 - 2.33T) \qquad \text{J kg}^{-1}$$

where T is temperature in deg C.

c_p is a weak function of humidity (see Brutsaert, 1982), but for applications of this type is normally taken as 1010 J kg^{-1} K^{-1}.

For the altitude of Maun, approximately 900m, with an average temperature of 22.5 deg C, the average atmospheric pressure should be 909 mbar. The psychrometric "constant" would be reduced from 0.66 to 0.60.

Although the value of the psychrometric "constant" should clearly be adjusted when used in evaporation estimation formulae, there is some room for argument over whether this applies to the value of the parameter used for calculating humidity from dry and wet bulb temperature. This is sometimes differentiated from the theoretical psychrometric "constant", by calling it the wet bulb psychrometric "constant". It can be argued that the wet bulb psychrometric "constant" is an empirical parameter which, for a well ventilated wet bulb, is observed to have the same value as the theoretical psychrometric "constant", ie 0.66

at sea level (note: for unventilated screens this is normally increased by the factor 1.22). However the standard work on matters of this type, which is usually taken as the Smithsonian Meteorological Tables (List, 1966), states that;

"in agreement with theory many empirical workers have verified, for the system water-air, the validity in restricted range of air velocities of the expression;

$$A = (e' - e)/p(t - t')$$

where;

t = air temperature
t' = wet bulb temperature
p = barometric pressure
e = vapour pressure
e' = saturation vapour pressure at temperature t'
A = proportionality constant which for a given ventilation and instrument varies slightly with t'."

In the above expression the equivalent of the psychrometric "constant" is Ap. Whether A is derived theoretically or empirically clearly the combination, Ap, depends on pressure.

For the altitude of the Okavango the empirical wet bulb psychrometric "constant" would be reduced from 0.66 to 0.59 for an aspirated instrument. As an example: for the readings observed by the Institute of Hydrology team at 1330 on 24th February 1990 in the centre of the delta, ie dry bulb temperature 33.0 and wet bulb temperature 17.7 deg C, the calculated vapour pressure changes from 10.0 to 11.1 mbar. These differences could give systematic errors, which are not negligible.

2.2.3 Evaporation from the Okavango delta

The evaporation from the Okavango swamp was estimated by applying correction factors to the calculated open-water evaporation. The open-water evaporation was calculated from the meteorological data collected at the synoptic stations situated outside the delta, the possible effects of advection were not therefore considered. Advection may reduce evaporation by cooling the air and increasing its humidity as it flows over an evaporating surface. The limited analysis possible with the existing data from the automatic weather stations indicated that this effect might be acting to reduce the evaporation from the delta. It needs to established whether this in fact the case.

Given the lack of previous data on the transpiration rates from swamp vegetation the approach of applying corrections is reasonable, but it would have been preferable to use a reference crop evaporation as the starting point rather than Eo. The albedo, the reflection coefficient for solar radiation, of vegetation is normally in the range 0.10 to 0.30, whereas for open-water it is taken as 0.05. Treating the swamp as a vegetated surface would have allowed better account to be taken of the different energy balances which should be expected from the different vegetation types.

However, as the report points out, the over-riding need is for direct measurements of actual evaporation which can be used to derive real calibrations based on a sound understanding of the energy balances of the component vegetation types. Without such understanding, estimates of the evaporation from the swamp are really no more than experienced guesswork. The only feasible way of obtaining these measurements is by the application of micrometeorological and plant physiological techniques in the field.

2.2.4 Discussion on transpiration from vegetation within the swamp

What information that is available on the transpiration of wetland species especially in tropical regions is well covered in the SMEC report. However, the amount of this information and the ability to draw consistent trends from it at the present time are very much wanting. The range of variation in evapotranspiration of wetland species is not well-understood and at present the use of ratios of vegetation to open water evaporation is based on only fragmentary evidence and considerable extrapolation for plant species and locality is required.

This seems to be especially so for natural swamps such as in the Okavango Delta. Apart from some studies on Phragmites and papyrus transpiration elsewhere and quoted in the SMEC report, other important species of the Okavango flora have received no study. The SMEC report refers to the study by Jones and Muthuri (1984) of transpiration by papyrus at Lake Naivasha (Kenya). A very high daily rate of transpiration (exceeding 12 mm) and probably far exceeding Eo was reported. This is called into question in the SMEC report largely because it is a single daily value. The exact conditions under which Jones and Muthuri made their study are not yet known but the enhancement of transpiration by advected energy is possible. Clearly there is much to be done to investigate the influence of advected energy on swamp evaporation and studies should be directed at the distance scale into swamps for which advection is important.

The Jones and Muthuri paper does however give an elegant example of how plant physiological techniques can be utilised to quantify transpiration. Another paper by these same authors (Jones and Muthuri, 1985) gives information on the leaf area index and productivity of papyrus at two contrasting wetland sites in Kenya and Rwanda which offer themselves as sites against which the gross and net production and nutrient relationships of papyrus in the Okavango might be compared. No information seems to be available on other important constituent species of perennial swamp, semi-permanent swamp and grassland and drylands.

2.3 Comments on "Ecological zoning, Okavango delta", SMEC 1989

The immediately relevant sections of this report are Section 5, (Vegetation) in the main report and Appendix F, in Volume 2. A major objective of this report is to provide a floristic list for the Delta, which on a unit area basis is shown to be relatively rich in species when comparisons are made with other southern African habitats and with other major regions in the World. Nearly 1100 plant species have been recorded as occurring in the Okavango Delta, although no species are endemic to the Delta. There are a range of habitats on which small differences in factors, such as topography, soil and hydrology are superimposed, which favour particular plant species. These complex, small variations probably contribute largely to the relative richness of species.

It is clear from the report on the vegetation that the information on the presence of plant species in the Delta is good, although the point is made that revision of some key plant taxa is necessary. The report and its appendix contains a large amount of information on the species present and their distribution in habitats. It would be unfortunate if this fund of information could not be published in a more readily available form.

Overall, the Ecological Zoning Report has defined five mapping units and these units correspond to categories identified as significant in separate descriptions of the Delta with respect to a) Geomorphology/Soils b) Hydrology and c) Vegetation. There is coincidence of the mapping units for soils, vegetation and hydrology in Ecological Zones I, permanently flooded, and V, dryland. There are some overlaps in Zones II, III and IV, the seasonal swamp. These correspond to regions which receive floods on a decreasingly frequent basis. The first two are combined in vegetation mapping units as seasonally inundated areas with Ecological Zone IV defined hydrologically as 'high flood only' and as a vegetation category as 'intermittently flooded'.

It is clear from the vegetation section of the report that accurate mapping of these intermediate zones has caused considerable difficulties, reflecting a dominant but very variable feature of the Delta: the seasonal and annual level of flooding.

The mapping of the vegetation in the Delta using Landsat MSS data has been undertaken (Ringrose, Mattheson and Royle, 1988) for two contrasting times of year. This excellent initiative should be followed up and extended to many more views at different seasons. This should be done in conjunction with ground-based measurements of spectral properties of dominant vegetation types. Particular emphasis should be placed on mapping the boundaries between permanent swamp and semi-permanent swamp and flooded grassland. Further discussion on the work by Ringrose is presented in Section 2.4.

Some reference is also made in the report of vegetation changes and it is suggested that the study of vegetation boundaries can provide useful indicators of where change is taking place. This point is made more fully in Smith (1976) where particular attention is drawn to the distribution of papyrus (Cyperus papyrus) and the wild date palm (Pheonix reclinata). Papyrus is thought to respond dynamically to changing channel conditions, responding to a lower water status by disappearing quite rapidly. In contrast the date palm remains for a much longer period indicating clearly places where conditions were previously wetter. There are now available physiological techniques which can monitor plant water stress in field conditions and which might confirm zones where recession or advancement of swamp areas are thought to be occurring.

2.4 Comments on Remote Sensing Analysis reports of Southern Okavango Integrated Water Development - Phase I, SMEC, 1986.

The studies by Dr Ringrose were primarily based on the analysis of data from Landsat MSS. Five sets of photographic products and two sets of digital data were used. The initial interpretations were made by examining the photographic products and defining units which were thought to be distinct ecological zones. The analysis of the digital data was carried out using two of the four MSS bands, these were the red and near infra-red bands. The analysis was done by plotting the red radiances from the data against the near infra-red radiances and then manually defining areas where the points 'clumped' together. Field work to check the results was carried out by aerial reconnaissance, on foot and by boat. In addition ground radiometer measurements were made to validate the remotely sensed data.

Significant differences were obtained between the visual and computer interpretations. These were attributed partly to an inability of visual interpretation to distinguish subtle differences in the radiance values, and to the computer analysis being unable to take into account contextural information. Nevertheless, the analysis did distinguish ecological zones of the Okavango that seem to correspond reasonably with ground truth.

3. COMMENTS ON THE AUTOMATIC WEATHER STATIONS OPERATED BY DWA

The automatic weather station at Xugana and Kwihum were visited. Both stations were adequately exposed and apparently well maintained.

The wet bulb wick on the Xugana station was however in need of replacement. Experience at IH is that these wicks should be changed at each visit, regardless of whether or not they appear to need replacing. Our experience is that field operators (whether they be PhD level researchers or meteorological observers) should not, if possible, need to make subjective decisions in the field. Similarly the silica gel in both net radiometers inspected was in need of replacement. Our experience is that the high ultra-violet levels in the tropics can destroy the domes of net radiometers more rapidly than in temperate latitudes and both domes and silica gel are best replaced at three monthly intervals. Silica gel can be recycled after drying in an oven at about 80 deg C for 24 hours. The costs of the other components are small in comparison to the overall cost of maintaining an automatic weather station.

The cassette tape loggers in use on these stations are now obsolete and it is recommended that they be replaced by solid state loggers. The Campbell Scientific loggers, which may be purchased ready programmed through Didcot Instruments or directly from Campbell Scientific, Sutton Bonnington, are proving reliable and robust field instruments. The logger is programmed with the calibrations of the individual sensors and the data are therefore recorded in engineering units, the output from each of the sensors can be inspected in the field. Each line of data is labelled with the time and date thus eliminating synchronisation problems. It is possible for the Penman equation to be calculated in real time and recorded each day as part of the data. At each service visit the data are transferred to a portable data bank and are then down-loaded to an IBM compatible PC in the laboratory. The data are transferred to a file as ASCII characters for listing or processing. Although there is a high overhead in setting up these systems in terms of skilled programming, once set up our experience is that they are easier and more reliable to operate by relatively unskilled technicians. There is also the considerable advantage that faults can be identified either on the spot during a service visit, or within a matter of hours of data collection.

The use of Data Collection Platforms (DCP) to transmit the data directly from remote field sites (via Meteosat) to the laboratory, is an attractive, fast developing technique. Its major advantage is the speed at which the data are transferred from the field to the laboratory making it especially attractive for operational forecasting. However the experience of IH is that this method of data transfer is not - at the moment - 100 per cent reliable and should be backed up by conventional data logging. Faults with the satellite management system can sometimes mean that data are not transferred - through no fault of your own. With some variables such as rainfall this could have serious consequences. However these effects can be mitigated by designing the system with this in mind - for example by transmitting accumulated rainfall, rather than rainfall in the last hour. It must also be emphasised that this is a very fast developing field and the reliability of the method may improve.

4. CONCLUSIONS

The SMEC report presents a very thorough discussion of open water evaporation estimation in Botswana and is to be welcomed. It is believed that this report are represents the best currently available statement on evaporation estimation in Botswana and should be adopted as the national standard until such time as sufficient data are available from automatic weather stations to permit revision.

However, there are a number of minor points on which the SMEC work is believed to be deficient and these have been discussed above. The main problem with the report is that the important topic of evaporation estimation from the Okavango delta was only a minor component of the main study and hence the estimated evaporation losses from the swamp and delta area can only be thought of as provisional. More work is certainly required on this topic, a point recognised and commented on by SMEC in their report.

In summary, when considering evapotranspiration from the Okavango swamp and delta, there are three important unknowns which were not taken into account in the SMEC report, these can only be established by direct measurement;

i) The effects of advection, that is how the temperature and the humidity of the air - and therefore the evaporation - is modified by the water vapour which is being evaporated into it as it passes from the arid areas outside the delta to the moist conditions within.

ii) The albedo of the different component vegetation types.

iii) The actual evaporation itself and how it is controlled by the vegetation and the atmospheric boundary layer in which it is growing (ie the surface and aerodynamic resistance).

The need for a thorough investigation of evaporation from the Okavango swamp is discussed in the provisional project proposal included as Appendix II of this current report. Details of the studies proposed are presented together with cost estimates for such work.

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APPENDIX I

ITINARY AND PEOPLE MET

Visit to Botswana by F.A.K.Farquharson, Dr J.H.C.Gash and Dr J.M. Roberts of the Institute of Hydrology, Wallingford, UK 19th February to 2nd March 1990

19 February

Arrived Gaborone 20.00 hrs and met by Stewart Child

20 February

<u>Morning;</u>
Meeting at DWA to discuss the purpose of the Wallingford staff's visit. Discussions with;

Stewart Child	DWA
Isaac Muzila	DWA
Bridget Thorne	DWA
Jack Mathambo	DWA
Miss G.K. Ramothwa	Director,Botswana Meteorological Service
Jak Adringa	University of Botswana

<u>Afternoon;</u>
Visit to Dept of Meteorology to collect data. Discussions with;

Miss G.K. Ramothwa	Director, BMS
Donald Dambe	BMS
Russel Mothupi	BMS

21 February

<u>Morning;</u>
Flew to Maun.
Accompanied by Stewart Child and Isaac Muzila of DWA and Dr Paul Shaw of the University of Botswana.

<u>Afternoon;</u>
Visit DWA offices in Maun. Discussions with the DWA water chemist, Mrs Jane ?(Surname not noted; very many apologies).

22 February

<u>Morning;</u>
Flight in light aircraft with Isaac Muzila of DWA to Automatic Weather Station at Xugana.

<u>Afternoon;</u>
Visited Maun meteorological station. Showed round by Miss Floridah Butale.
Discussions with Pete Smith of DWA, Maun about the swamp vegetation.

23 February

Flight by helicopter with Isaac Muzila to Kwikhum island, site of another AWS. Met up with boats and Stewart Child and Paul Shaw. Began descent of the Boro river by boat, initially through permanent swamp. Camped for the night at Xaraxwa island.

24 February

Continued down the Boro river, moving from the permanent to seasonal swamp. Camped for the night at Xakue island.

25 February

Continued down the Boro river through the lower swamp to the buffalo fence and met by DWA vehicles. Taken back to Island Safari.

26 February

Morning;
Discussions about the boat trip with Pete Smith of DWA and with Jane ?.

Afternoon;
Return flight to Gaborone with Stewart Child, Isaac Muzila and Paul Shaw.

27 February

Worked in MacDonald's mess reviewing reports of previous studies. Visited Dept of Meteorology to collect meteorological data for Maun and Shakawe.

28 February

Morning;
Continued review of previous studies.
Visited offices of the Snowy Mountain Engineering Corporation. Met John Brown and Peter Fleming of SMEC and discussed both their earlier studies of evaporation in Botswana and the proposed additional studies of evaporation from the Okavango delta to be undertaken by IH.

Afternoon;
Demonstration of the HYDATA software at DWA by Frank Farquharson. Continued review of earlier studies by John Gash and John Roberts.

1 March

Morning;
John Gash and John Roberts visit Sabeele research station to discuss evaporation with David Harris and Graham Fry. Frank Farquharson types outline proposal on possible IH studies.

Afternoon;
Discussions with Stewart Child of DWA about possible future studies of evaporation from the Okavango delta.

2 March

Morning;
Visit to the British High Commission to discuss the visit with;

Brian Smith	High Commissioner
Peter Newman	Deputy High Commisioner

Discussed the possibility of the British Government funding the main field studies through ODA. It was suggested that EEC funding might be more appropriate.

Final meeting at DWA to discuss the visit by IH staff. Those present were;

Stewart Child	DWA
Isaac Muzila	DWA

Jack Mathambo	DWA
Donald Dambe	BMS
Russel Mothupi	DWA
Jak Adinga	University of Botswana

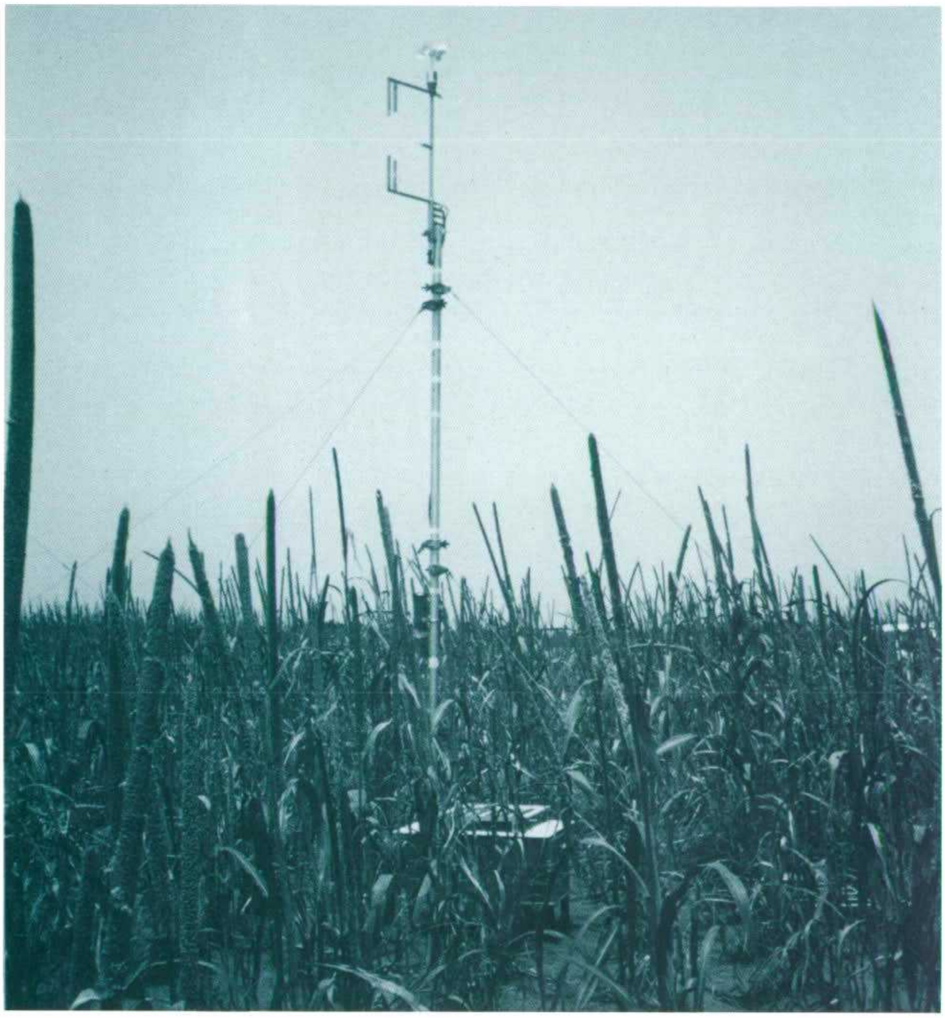
Afternoon:
IH group return to UK.

APPENDIX II

DETAILS OF THE HYDRA EQUIPMENT AND SUPPORTING MATERIAL

Direct measurement of evaporation using the Hydra

Evaporation estimation techniques can on a yearly time scale, be reasonably accurate for short vegetation plentifully supplied with water. On a shorter time scale, or for vegetation, where evaporation is less than potential, satisfactory results can only be obtained by modifying the estimation techniques. Confidence in these modifications is only justified by the use of direct evaporation measurements. Methods of measuring natural evaporation have been available for some time, but the effort and cost involved in collecting and analysing the data have restricted their use to a few research studies. The Hydra, an instrument developed at the Institute of Hydrology, now makes the routine measurement of actual evaporation a practical possibility.



Advantages of the Hydra.
The Hydra is a compact portable instrument incorporating a digital microprocessor to analyse the measurements as they are being made. The ability to run under battery power at remote sites makes the Hydra very attractive for both hydrological and agricultural applications. A prototype version has been used successfully in Britain for measurements over heather and forest and also as part of a hydrological study of the Amazon rain forest in Brazil. The Mark 2 version has proved itself in agricultural studies in the extreme environment of the Sahel. It has also contributed ground truth measurements to international experiments in France (HAPEX) and U. S. A. (FIFE), designed to improve global climate models by calibrating remote sensing data.

Consultancy service.
Measurements of evaporation made using the Hydra are now being offered by Institute of Hydrology technical and scientific staff. They can provide the expertise in the selection of suitable applications, the necessary experience to install and operate the instrument and interpret the results.

HYDRA Specification.

To provide a direct measurement of evaporation, sensible heat flux and momentum flux by the eddy-correlation method.

Constituents.

1. An aerodynamic framework comprising. – an ultra sonic anemometer, an infra-red hygrometer, a thermocouple thermometer, and a fast response cup anemometer. These measure fluctuations in vertica windspeed, humidity, temperature and horizontal windspeed respectively. This multi-sensor head is mounted perpendicular to, and usually two to three metres above the surface of interest.

2. Below this a relative humidity sensor permits ambient absolute humidity to be calculated which is required for the calibration of the hygrometer. Available energy is also monitored by a net radiometer and soil heat flux plates. which allows a daily energy budget check to be done on the Hydra's performance

3. A module containing the sensor electronics, microcomputer and a removable solid state data store.

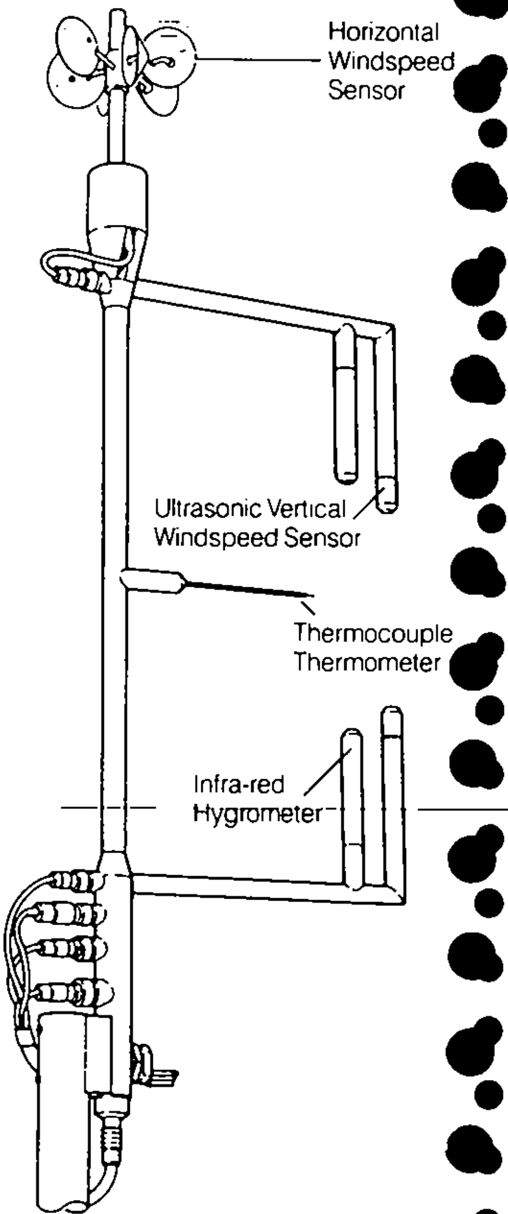
The whole system is designed such that it is protected from electrical storms by a contunuous Faraday cage

Operation.
The microprocessor interrogates the sensors at a frequency of 10Hz, producing variances, crosscorrelations and raw outputs which it averages and logs on a 48k byte by 4 bit solid state store. This will hold four week's data. This is removed during a site visit and the data subsequently unloaded onto a floppy disk after applying calibrations and corrections using a microcomputer.

Power Requirements.
300 milliamps at 12 volts. Depending on the situation this is usually maintained by car batteries charged with solar panels.

Accuracy and Limitations.
As with all micrometeorological measurements, the Hydra requires an undisturbed upwind fetch of uniform vegetation typically of 200 to 400 metres. Errors due to frequency limitations of sensors. drift, atmospheric stability and in extracting fluctuations from background changes in the variables, are corrected for in the software. With experienced installation, operation and quality control, the daily cumulative sum of the evaporation and sensible heat fluxes is normally within 5% of the measured available energy. Sensible measurements are not available during and immediately after significant rainfall when there is water on the sensors.

The Mk2 HYDRA Sensor Head



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APPENDIX III

PROPOSAL FOR A STUDY OF ACTUAL EVAPORATION FROM THE OKAVANGO DELTA AREA, BOTSWANA

1. Introduction

The Okavango delta and swamp region of north-western Botswana is a valuable resource to the country, both as a long term potential source of water, and because of the steadily increasing tourist trade.

The successful long-term development and management of the region depends largely on understanding the complex hydrological behaviour of the Okavango river as it flows slowly through the swamps and lower delta area. The Department of Water Affairs monitor inflows to the swamps at Mohembo and outflows at Maun Bridge. On average some 98% of the inflow is lost through evaporation and groundwater seepage (Wilson and Dincer, 1976, SMEC, 1987). Of this loss, groundwater recharge is believed to be negligible and evaporation directly from open water or through transpiration of the varied vegetation throughout the area is by far the dominant hydrological process within the swamp and lower delta.

Very little firm information is available to permit accurate estimation of this evaporation loss, partly because of the problems of access within the swamp and partly due to operational difficulties with the recently installed automatic weather stations (AWS).

In a recent study of open water evaporation in Botswana, the Snowy Mountain Engineering Corporation (SMEC, 1987), carried out the most comprehensive study yet undertaken of available climatic data. They suggested that a more detailed study of evaporation within the Okavango area was necessary, and that such a study "would have to be very closely supervised, and indeed carried out by very competent atmospheric research scientists". They further suggested that the Institute of Hydrology's eddy correlation equipment, or Hydra, could provide one of the best methods of estimating evaporation over the swamp and delta. (Details of the Hydra equipment are given in Appendix III).

SMEC also suggested that the Bowen ratio method should be utilised and suggested that appropriate equipment was only available from research organisations and commented that "costs of such equipment are therefore largely notional but could be of the order of P 120,000". Recent work by the Institute of Hydrology has estimated evaporation over a large tropical lake in north Sumatra, Indonesia, using the Penman formula, the Hydra equipment, and using the Bowen ratio. Results will be presented in a paper to an International conference in May of this year and a paper has been submitted for publication in the scientific press.

It is suggested that the Institute of Hydrology is in a unique position to undertake the proposed detailed study of evaporation from the Okavango swamp system in view of its extensive international experience in this field. Details of the proposed study are given below.

2. Overall Objectives

To measure the evapotranspiration from the Okavango swamp and lower delta areas. To utilise these evapotranspiration estimates to develop a hydrological model of the Okavango system. This model should permit prediction of the hydrological effects of any proposed changes or developments within the system.

Evaporation rates would be established for the significant vegetation types within the swamp and delta at various representative times of year. The key vegetation zones are;

1 Perennial swamp
2A Seasonal swamp
2B Seasonally flooded grassland
3 Dryland sites and islands with trees

These evaporation estimates from key ecological zones would then be applied to existing ecological maps to enable total evaporation losses to be estimated. However, additional work on establishing the extent of the significant vegetation types would be required using satellite images, such as SPOT, which have better spatial resolution than the LANDSAT system used to date (Ringrose, 1988).

The detailed work proposed in each key vegetation zone is detailed below.

3. Zone 1 : Perennial Swamp

3.1 Objectives

a) To measure the evaporation from the perennial swamp in the upper and central delta, identifying the contributions resulting from the predominant plant species (papyrus and Phragmites)

b) To identify seasonal differences in evaporation

c) To produce simple models of evaporation in terms of routinely measured meteorological variables.

3.2 Methods

A series of suitable large areas of uniform perennial swamp will be identified by examination of aerial photographs and maps. Choice of a final site will be made by aerial survey and site inspection by boat.

An observation platform will be installed and instrumented with a Hydra eddy-correlation device and an automatic weather station (AWS). Additional instrumentation added to the standard AWS would be an inverted Kipp solarimeter to measure albedo directly.

After installation the Hydra equipment will be operated for a period of 3 weeks. A second measurement session would take place approximately six months later.
(NOTE; It would be better to measure at three different times as suggested by SMEC; but this would be more expensive).

In parallel with the meteorological measurements, plant physiological measurements would be undertaken from the same equipment platforms. These measurements would enable partition of the evaporative flux measured by the Hydra to the principal component vegetation species using a portable infra-red gas analyser (IRGA).

The fractional leaf area index (LAI) of each species would also be measured. Estimation of plant transpiration could then also be estimated as the product of vapour flux measured by the IRGA and the LAI.

The contribution of the open water surface beneath the vegetation would also be quantified.

The AWS would be left in place between the two (or three?) intensive measurement periods. A monthly visit to each site by staff of the DWA would be required to service the station and to extract and process the data.

3.3 Analysis

The measured climate of the experimental site would be compared with the synoptic climate stations at Maun and Shakawe outside the delta, and with the AWS stations operated within the delta by DWA. If systematic differences are identified, suitable relationships will be developed for incorporation into the Penman evaporation model. The radiation balance as measured over the perennial swamp will also be compared with that predicted using the coefficients and equations suggested by SMEC in their 1987 report, and if necessary, improved coefficients developed.

The Hydra and AWS data will be used to derive aerodynamic and surface conductances for application in a Penman-Monteith model. The data will also permit derivation of correction factors for Penman reference-crop evaporation estimates thereby converting them to actual rather than potential evaporation rates.

If the plant physiological studies show that it is necessary for the relative proportions of different vegetation species present in the perennial swamp to be taken account of, preliminary estimates of the vegetation distribution would be made. However, a detailed vegetation zoning survey may have to be made, which is outside of the present proposal; it is suggested that this problem be considered if and when it is shown to be important.

4. Zone 2 ; Seasonally flooded vegetation

It may be possible to treat this type of seasonal swamp as one zone, but it appears that there may be a distinction between seasonally flooded swamp vegetation and seasonally flooded grassland zones. Thus we propose to consider the seasonally flooded areas as two sub zones; 2A being seasonal swamp and 2B being seasonally flooded grassland.

This study would essentially repeat the studies undertaken in zone 1 described above. Access would be very much easier than to the perennial swamp, even during the flood season, as water levels are relatively shallow.

Two separate areas would be required, each having relatively uniform vegetation over an area of approximately 1 km by 1 km. Site identification would again be initially by analysis of maps and aerial photography followed by detailed air and boat surveys.

One set of measurements would be made close to the flood peak in June or July, and a second set of measurements would be made just before the onset of the following year's flood in March or April, to examine whether or not there is any reduction in transpiration as the soil dries out.

The seasonally flooded swamp will become inundated before the seasonally flooded grassland, which occupies higher elevation land and is more widespread in the lower swamp. Thus a Hydra would initially be installed over the seasonal swamp and would be operated for some three to four weeks. The equipment would then be moved to the seasonal grassland site for a similar measurement period.

During the flood recession period, the measurement order would be reversed as the grassland will be the first vegetation zone to dry out after the flood peak recedes.

Plant physiological measurements would again be made at each site during each measurement programme.

The measurements over the seasonally flooded areas would be undertaken with one Hydra whilst the other instrument was deployed firstly over the perennial swamp and subsequently over the dryland site with trees. Thus two sets of Hydra would be used to measure evaporation over four separate vegetation zones, and staff would spend part of their time attending to each of two Hydra instruments and sets of plant physiological measurements. However, four AWS would be required, one for each vegetation zone.

5. Zone 3 : Dryland sites and islands with trees

Vegetation zones 1 and 2 cover the majority of the land area within the delta but a third zone, dryland sites and islands with significant tree cover, is also a very significant vegetation type, particularly in the lower delta. Although these islands are rarely, if ever, flooded, they are likely to make a significant contribution to the overall water loss from the delta system.

The physical size of trees and (with the exception of Chief's Island and the Sandveld and Moremi Tongues) the small size of islands present special problems of evaporation measurement. Several possible methods exist and it would be wise to attempt to apply several of these in order to quantify evaporation from such sites accurately.

5.1 Deployment of equipment from a tower

The first possible approach would be to erect a micro-meteorological tower on perhaps Chief's Island and to deploy the Hydra and AWS in a similar way to that recently employed to measure evaporation from forests in the Amazon basin. The tower would also be used to make plant physiological measurements.

In addition to the plant physiological measurements described earlier, given access to the top of the tree canopy, evaporation may be measured using Deuterium tracing. Late in the evening, when trees are no longer transpiring, known quantities of Deuterium are injected into a tree, or trees, and plastic bags placed over a representative sample of leaves and sealed. During the following evening samples of the transpired water would be collected from the inside of these bags as condensation. Analysis of the Deuterium concentration permits direct measurement of transpiration rates from particular trees.

Measurements of LAI would also be required for the trees being studied.

5.2 Heat pulse technique

The water use of individual trees may be measured using the heat pulse technique, which does not require access to the tree crowns using towers. The heat pulse technique involves inserting small heating probes and thermocouples into the trunk base of selected trees. Transpiration can be determined from the rate of heat transfer upwards in the stem which is measured continuously of several days.

5.3 Deployment of equipment from a tethered baloon

The flux of water vapour at the regional scale, 2 to 5 km, may also be measured using a temperature fluctuation technique and profiles of temperature and humidity over the 20-40 metre height range. Two tethered balloons and specially adapted radio-sonde equipment are required for this. These instruments exist as part of an IH boundary layer sounding facility but the method is still at the research stage and the risk of application correspondingly greater than the methods described above.

The method requires constant manning and is suitable for use only on a limited number of days. However, if deployed over the area of mixed swamp and small islands, it should be capable of measuring the evaporation from the landscape as a whole.

6. Use of Remotely sensed data

It is planned that remotely sensed data will be used to achieve a better classification of the Okavango delta into ecological zones that are significant to the hydrology. It is proposed that Landsat Thematic Mapper (TM) data will be used. This has two advantages over Landsat MSS data. Firstly it has higher spatial resolution, 30m compared to 80m, which will allow clearer differentiation of the ecological zones. Although SPOT XS data has even higher spatial resolution (20m) it lacks the additional spectral data and so is not so useful. The second advantage of TM data is that it has seven spectral bands compared to four. Two of these bands are further into the near infra-red than the MSS bands, and so are particularly sensitive to the presence of water, which is important in this context. In addition, there is a thermal band will be used to make direct estimates of evapotranspiration using methods we have been developing in Niger, Zimbabwe and USA.

Data will be acquired for the onset of the rainy season, February-March, and during the drying out period after the flood wave, September when the ecological zones should be most distinct.

Ground truth will be achieved by a short visit to make ground measurements of the radiance of the major vegetation, soil and water types.

Remotely sensed data will be analysed using the International Imaging Systems Model 75 processor, running System 600 software, at IH. Additional algorithms will also be used. One of the problems with existing classification techniques is that they assume that each element of the image belongs to only one class. An attempt will be made to use a new algorithm that allows each element to be a mixture of spectral types as this may allow a more 'natural' division of the system. Another technique that will be tried is contextural classification whereby the algorithm takes into account the spectral similarity of adjacent areas when attempting to classify an element of the image.

The combination of new data and the the application of new algorithms should allow a more detailed and accurate division of the Okavango delta system to be made.

The imagery needed will be from the periods February-April and September. There is no full coverage for these periods in the Landsat archives and so data will have to be obtained by special acquisition if a complete, contemporaneous data set is needed.

7. Ecological studies

In addition to the hydrological studies proposed above, there would seem to be merit in attempting to predict the ecological effects of any proposed changes in water distribution and/or flow regime in various regions of the delta and swamp. It is likely that there will over time, be a number of proposals to develop the water resources of the Okavango, either by utilising the water for agriculture or potable supply, or by changing the existing water distribution throughout the swamp and delta area.

Before any such development of the Okavango's water resources could be considered, there is a need to obtain basic data on, and an understanding of, the region's ecosystem. Whilst a considerable body of data exists on the animal, bird and fish populations throughout the swamp and delta, it is clear that considerable additional work remains to be done.

The Department of Wildlife is coordiating the data collection work currently underway throughout the area, but it is suggested that some input is required from internationally recognised experts in a number of key areas. It will be necessary in the medium to long term to develop models of wildlife and fish populations such that potential changes in the ecosystem may be both monitored, and ideally, predicted. Such changes may be brought about through man's activities, and these to a considerable extent may be controlled by legislative or political means. However, there may well be other factors, such as changing climatic patterns, natural geomorphological changes, and development of the upstream catchment outside of Botswana, that are more difficult to control.

Only by undertaking a major programme of research and modelling now can the effects of such potential future changes, either planned or uncontrolled, be predicted. The proposed hydrological studies aim to produce a powerful semi-distributed model of the swamp and delta area which would permit the hydrological impact of any change to be assessed. This would be an invaluable tool in the battle to manage and conserve the Okavango whilst striving to meet the aspirations of a growing local population and the demands of an increasing tourist industry.

It is suggested that a complementary ecological model is required which will permit the impact of any anticipated changes on wildlife and plant ecology to be assessed. The development work for such a study could most efficiently be undertaken in conjunction with the proposed hydrological studies as the ecological response of the Okavango is driven so firmly by water.

The Institute of Hydrology is part of the UK Natural Environment Research Council and has sister organisations who are international experts in the fields of fisheries and ecology. Senior staff of both the Institute of Terrestrial Ecology and Institute of Freshwater Ecology have relevant experience of working in countries similar to Botswana. This experience could with benefit to Botswana be combined with the obvious hydrological expertise of IH in provision of a co-ordinated hydrological and ecological modelling study of the Okavango.

Detailed costings have only been presented here for the hydrological component of such studies. Costings for the proposed ecological studies could be presented if it were felt that such studies would be beneficial to the Government of Botswana.