F. DEHAIRS

Annexe 1

INCO-DC : International Cooperation with Developing Countries (1994-1998)

Contract number : ERBIC18CT960065

FINAL REPORT

Start date : 01 November, 1996 **Duration : 33 months**

Title : Anthropogenically induced changes in groundwater outflow and quality, and the functioning of Eastern African nearshore ecosystems (GROFLO)

Keywords : groundwater; coastal lagoons; East Africa; ecosystem functions, anthropogenic inputs

GROFLO Final Report Annexes

I. Meeting Reports
II. Copies of Publications
III. Questionnaires

Shared-Cost Rtd **Contract number : ERBIC18CT960065**

TITLE : Anthropogenically induced changes in groundwater outflow and quality, and the functioning of Eastern African nearshore ecosystems (GROFLO)

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Annex I. Meeting Reports

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Report of the first workshop, Mombasa 4-6 1997: List of participants

EU - INCO WORKSHOP

Antropogenically Induced changes in groundwater outflow and quality, and the functioning of Eastern African nearshore Ecosystems

4th - 6th March, 1997, Reef Hotel, Mombasa, Kenya

List of Participants

Kenya

Dr. Okemwa, E.
Dr. Kazungu, J.M.
Mr. Mwaluma, J.
Mr. Mwashote, B.
Mr. Wawiye, P.
Mr. Kitheka, J.

Netherlands

Dr. Hemminga, M.
Dr. Mateo, M.
Dr. Kamermays, P.
Dr. Bordalba, N.M.

Mozambique

Dr. Domingos Gove
Dr. Marcia, A.
Ms. Filomena Barba

Portugal

Prof. Saldanha, L.

Dr. Paula, J.

Zanzibar

Mr. Mmochi, A.J.

Mr. Mwaipopo, O.U.

Dr. Mtolera, M.

Dr. Shunula

Sweden

Dr. Ron Johnstone

Belgium

Dr. Jurgen Tack

List of Observers

Kenya

Dr. Ruwa, R.K.

Ms. Uku, J.

Mr. Kairu, K.

Mr. Ohowa, B.

Italy

Prof. Vannini, M.

Dr. Cannici, S.

Dr. Contini, C

Report of the first workshop, Mombasa 4-6 1997: Programme

ANTHROPOGENICALLY INDUCED CHANGES IN GROUNDWATER OUTFLOW AND QUALITY, AND THE FUNCTIONING OF EASTERN AFRICAN NEARSHORE ECOSYSTEMS

EU - INCO 1st WORKSHOP - PROGRAMME
4-6 MARCH 1997: Reef Hotel, Mombasa

Tuesday 4th, March

13.30	Registration (Reef conference room)
14.00	Welcome(J.M. Kazungu, KMFRI)
14.15	Introduction, general remarks (M. A. Hemminga NIOO-CEMO)
14.45	Formal inauguration of the workshop (E. Okemwa - KMFRI /DIRECTOR)
15.15	Break - soft drinks

1st session	**session chairman - Dr. Okemwa, E.**
15.30	Hydrography of Kenyan lagoons: what can we measure? (J. Kitheka, KMFRI)
16.00	Nitrogen transformational processes in the Kenyan nearshore zone (J. Kazungu, KMFRI)
16.30	Nutrients and plankton distribution and productivity in Kenyan lagoons (J. Mwaluma, KMFRI)
17.00	Tracing groundwater effects on macrobenthic community structures in the Inhaca Island nearshore zone (L. Saldanha, GML)

Wednesday 5th, March

2nd session	**Session chairman - Prof. Saldanha, L.**
9.00	Tracing groundwater effects on lagoonal seagrasses (P. Kemermans, NIOO-CEMO)
9.30	Productivity of holothurians (D. Gove, UEM)
10.00	Population dynamics of penaeid shrimps (A. Macia/J. Paula, UEM, GML)
10.15	Monitoring pollution of groundwater on Zanzibar (IMS/SU)
10.45	**Tea / Coffee**

3rd session Session chairman - Dr. Kazungu, J.M.

11.15 Anthropogenic inputs in the nearshore zone and community metabolism (R. Johnstone, SU)

11.45 Anthropogenic inputs in the nearshore zone and macrophyte community structure (IMS)

12.15 Anthropogenic inputs in the nearshore zone and meiofauna community structure (IMS)

12.45 Elemental changes in biogenic carbonates as records of groundwater flow (VUB); poster)

12.45 - 14.00 Lunch

4th session Session chairman - Dr. Hemminga, M.

14.00 Construction of groundwater models: general remarks (J. Tack, VUB)

14.30 Groundwater outflow along the coast of Kenya, Zanzibar and Inhaca Island (J. Tack, VUB):

(1) pinpointing appropriate research sites for 1997 on basis of the coarse groundwater model;

(2) refining the coarse groundwater models

15.00 Tuning action plans of individual partners to each other (small group discussions on concerted research in Kenya, Zanzibar and Inhace Island

19.30 Workshop cocktail reception

Thursday 6th, March

9.00 Reports of group discussions, addressing:

(1) cooperation

(2) specific sites of research in relation to groundwater outflow and anthropogenic inputs

(3) nature of research activities

10.30 Tea / Coffee

10.45 Discussion of possible relations with the parallel INCO project on macrobenthos in Eastern African mangroves

11.15 Final remarks and conclusion of plenary part of workshop (J. Kazungu, M. A. Hemminga)

11.45 Meeting of project leaders on administrative matters and any other business.

Report of the first workshop, Mombasa 4-6 1997: Summary of group and plenary discussions

Report of group discussion on research activities in Kenya

Pauline Kamermans

After extensive discussions it was decided to focus the research activities in Kenya on the following three sites:

1. Mida Creek
This site is presently under study by the Kenian Marine Fisheries Research Institute in the framework of a biodiversity programme funded by the Kenya Wildlife Service. It is a mangrove area where the freshwater input is exclusively groundwater outflow. Eleven different species of seagrass have been encountered here.

2. Nyali Beach
This is a reef lagoon with groundwater outflow as identified by the groundwater flow model of Jurgen Tack. Extensive seagrass meadows are present.

3. Diani Beach
This is a reef lagoon with seawater intrusion as identified by the groundwater flow model of Jurgen Tack. Seagrass meadows are present.

The sampling frequency will depend on the type of data that will be collected. However, all three sites will be sampled at least once per season. In Kenya representative months for the dry season are January and February while May is a representative month for the wet season.

Below it is listed which data will be collect by which investigator at the three study sites:

J. Kitheka	salinity, temperature, conductivity, current speed, tidal elevation changes, bathymetry of water body, water exchange rate, water residence time, flushing rate, depth of seawater intrusion into aquifer, length of seepage zone, groundwater flux rate, climatological data
B. Mwashote	nitrogen, phosphorus and silicon concentration in water column, pore water and surrounding wells, nutrient flux rates from sediment cores that will be incubated in the lab
J. Kazungu & S. Mwangi	nitrogen transformation processes, seasonal variation in total organic matter, seasonal variation in ammonification, denitrification and nitrification
J. Mwaluma & P. Wawiye	species composition, abundance and distribution of zooplankton, phytoplankton and benthic diatoms, primary production of microalgae
P. Kamermans	seagrass species composition, coverage and biomass, of the dominant species nitrogen, phosphorus and silicon content of seagrass leaves, leaf production rate and age distribution, sediment grain size
F. Dehairs	elemental composition of mollusc shells

If time and money allows two additional studies will be included:

J. Uku	species composition of macroalgae
G. Mwatha	abundance and biomass of macrobenthos in cooperation with L. Saldanha

Report of group discussion on research activities in Zanzibar and Inhaca Island

R. Johnstone

Discussion was entered into to identify, and ultimately plan, areas of direct cooperation and collaboration between the research groups in Sweden, Tanzania, Portugal and Mozambique. Considerable time was spent discussing the possibilities for collaboration of all four countries in the areas of benthic sampling, and eventual groundwater sampling and analysis. In particular, it was realised that it was essential that all parties involved used the same techniques in these fields so that data sets would be directly comparable at the end of the larger study.

With regard to benthic sampling, it was pointed out that a thorough survey of the benthos would require considerable manpower and that the techniques were very time consuming. Consequently, it was suggested that the respective groups might try to assist each other in carrying out the baseline studies for the respective sites in Tanzania and Mozambique. Further, it was agreed that, at a time to be later defined, Tanzanian researchers would travel to Mozambique and participate in the benthic sampling to be conducted by the Mozambique and Portuguese counterparts. This would allow them to learn the techniques to be used, and it would also give them a direct knowledge of the Mozambique study sites. As a follow-up of this exercise, it was also proposed that the Mozambique-Portuguese researchers visit the Tanzanian study sites at a later date and take part in a similar survey.

Discussion of the groundwater nutrient work lead to a similar set of proposals. It was decided that members of the Tanzanian-Swedish group would travel to Mozambique early in 1998 to assist in establishing and conducting a baseline survey of the groundwater characteristics relevant to the Mozambique study site. Again, this would facilitate inter-calibration of methods and would also help to alleviate the pressure on the manpower available for nutrient work in Mozambique.

Report of plenary discussion on interaction with the EU-INCO "MEAM" project

M.A. Hemminga

A plenary discussion was devoted to the question to what extent interaction and cooperation would be possible with the "MEAM" project (Macrobenthos of Eastern African mangroves: life cycles and reproductive biology of exploited species). This EU-INCO project comprises virtually the same institutional partners as the GROFLO project on groundwater. Professor M. Vannini, general coordinator of the MEAM project, was present during the plenary discussion to contribute his views on interaction and cooperation. A practical difficulty hampering cooperation is the fact that the actual field sites only partially overlap; the MEAM projects focusses on mangroves, whereas these ecosystems are less prominent as research sites in the GROFLO project. In addition, sampling schemes are not easily combined. There was a generally shared view, however, that cooperation would be to the benefit of both projects, both in financial and in scientific terms, and should be pursued as much as possible. After extended discussion the following conclusions were reached:

(1) Both financial and scientific benefits can be gained by combining the workshops of both projects. It was decided that the next workshop (for both projects) would take place in Mozambique, in April 1998.

(2) In the framework of the MEAM project a house will be rented near Mida creek (a main site of research for the MEAM project). This house will also be available for the GROFLO project. Mida creek is an important research site for the GROFLO project as well.

(3) Each institute participating in both projects (i.e. the majority of the partners) will carefully schedule the field expeditions of both projects in such a way that, by combination of expeditions, a maximum financial economy is achieved.

(4) A final, and challenging suggestion was to jointly organize an international symposium on the ecology of East African coastal wetlands directly after the end of both projects. It was realized that the institutes involved in both project had accumulated large amounts of information on wetland ecology over the years, and that a symposium would be an appropriate outlet for this information. In addition, bringing the researchers working in this field together would provide the opportunity to discuss a research agenda for the next decade on basis of regionally perceived environmental threats and management needs.

Report of second workshop, Yerseke, The Netherlands, 30 March - 1 April 1998

Programme & list of participants

SECOND WORKSHOP OF THE EU-INCO PROJECT

"ANTHROPOGENICALLY INDUCED CHANGES IN GROUNDWATER OUTFLOW AND QUALITY, AND THE FUNCTIONING OF EASTERN AFRICAN NEARSHORE ECOSYSTEMS"

Yerseke, March 30th- April 1th, 1998

Monday, 30 March

9.00 - 9.30.	Arrival of participants, coffee
9.30 - 9.45.	Welcome, introductory remarks (M. Hemminga)
9.45 - 10.15.	Groundwater utilisation and its implications in the coastal zone of Unguja Island, Zanzibar. (R. Johnstone & E. Hansson)
10.15 - 10.45.	Types, trends and amounts of pesticides used in Zanzibar in the last ten years: their influence in the groundwater and their possible environmental effects in the nearshore marine ecosystems. (A. Mmochi)
10.45 - 11.00.	Coffee break.
11.00 - 11.30.	Groundwater outflow in a coral reef lagoon and its potential role as a nutrient source. (R. Johnstone & J. Hast)
11.30- 12.00.	Groundwater outflow and quality, and the functioning of the Diani and Nyali nearshore coastal ecosystems: (I) physical and chemical aspects. (J. Kazungu, B. Mwashote & J. Kitheka)
12.00 - 13.00.	Lunch
13.00 - 13.30.	Human influence on quality and outflow of groundwater at Inhaca Island. (H. Chavale)
13.30 - 14.00.	Developing a groundwater model for Eastern Africa: methodology. (A. Verheyden & J.F.Tack)
14.00- 15.00.	General discussion: -how do our own field observations on salinity and groundwater outflow fit the model? -what is needed for further validation of the model? -.....
15.00 - 15.15.	Coffee/tea break
15.15 - 16.15.	Visit to NIOO-CEMO facilities
16.15 - 17.30.	Meeting of project leaders

Tuesday, 31 March

9.00 - 9.30.	Activities of GML within the GROFLO programme: work developed and future actions. (J. Paula)
9.30 - 10.00.	Reproduction of *Holothuria scabra* in relation to environmental parameters. (R. Abdula)
10.00 - 10.30.	Macrobenthic assemblages in freshwater and salt water influenced areas: the Zanzibar case. (J. Shunula)
10.30 - 10.45.	Coffee break
10.45 - 11.15.	Ecological aspects of meiobenthos in the intertidal areas influenced by groundwater in Zanzibar. (S. Ndaro)
11.15 - 11.45.	Groundwater outflow and quality, and the functioning of the Diani and Nyali nearshore coastal ecosystems: (II) biological aspects. (S. Mwangi, P. Wawiye, J. Mwaluma & J. Uku)
11.45 - 12.15.	Tracing groundwater effects on abundance and diversity of lagoonal seagrasses. (P.Kamermans, M. Hemminga & M. Mtolera)
12.15 - 13.15	Lunch
13.15 - 13.45.	Groundwater outflow and the distribution and ecology of seagrasses at Inhaca Island. (D. Gove)
13.45 - 14.15.	The influence of groundwater on the productivity of seagrasses and the associated macroalgae: productivity of *Eucheuma denticulatum* and *Kappaphycus alvarezii* commercially grown in the intertidal pools in Zanzibar. (M. Mtolera)
14.15 - 14.45.	Ecological differences in *Avicennia marina* (Forrsk.) Vierh. and *Rhizophora mucronata* Lam. in relation to groundwater flow along the Kenyan coast. (J.F. Tack & A. Verheyden)
14.45 - 15.00.	Coffee/tea break
15.00 -	Group discussions -the picture emerging from the biotic studies -priorities in future biotic studies -.....

Wednesday, 1 April

9.00 - 10.00.	Presentation conclusions of group discussions, general discussion
10.00- 10.15.	Coffee break
10.15 - 11.00.	Summary, final remarks
11.00 - 12.00.	Finalisation of administrative matters
12.00 - 12.45.	Lunch

12.45 - 18.00.	Excursion to storm surge barrier and exposition at Neeltje Jans
18.00 -	Workshop dinner

List of participants

KMFRI

J. M. Kazungu
S. Mwangi

IMS

M.S.P. Mtolera
A. Mmochi
S. Ndaro
J. Shunula

UEM

D. Z. Gove
R. Abdula
H. Chavale

NIOO-CEMO

M.A. Hemminga
P. Kamermans

VUB

J.F. Tack
A. Verheyden

SU

R. Johnstone
E. Hansson
J. Hast

GML

J. Paula
P. Fidalgo

Summary of group and plenary discussions

Report of plenary discussion on groundwater outflow model

Pauline Kamermans

A special session was devoted to the refinement and validation of the groundwater outflow model. The following topics were discussed.

refinement
The refinement of the model to cells of 100 by 100 m will be based primarily on topographical data. Additional rainfall data would be useful for the improvement of the model. However, for reasons of scale, such a refinement is only possible for Kenya.

salinity
The field data on porewater salinity obtained by NIOO-CEMO in Kenya and on Zanzibar do not fit the model very well. A substantial decrease in salinity was observed only within a few meters of a groundwater well on Zanzibar. The samples collected were probably taken too shallow in the sediment (10 cm). It was concluded that porewater samples should be taken at a depth of 20 cm in the sediment. All groups agreed to increase salinity measurements in order to include more data on differences over a tidal cycle and between wet and dry seasons. In addition, more salinity data from village wells are needed. It was suggested to use a standard salinity meter for comparison purposes.

scale
The different groundwater studies are carried out on different scales, e.g. the samples collected in the Kenyan lagoons always span areas of several hundreds of meters, while the collections on Zanzibar are generally very locallized covering areas of less than 100 m. The scale of the latter studies is too small to link the results directly to the model. However, by sampling close too and away from the intertidal groundwater wells very useful information on the effect of groundwater outflow can be obtained.

Report of group discussion on botanical research activities

Pauline Kamermans

Based upon the results presented at the workshop, the botany group observed that certain groups or species could be identified as indicators of groundwater outflow. The possibilities to expand the research efforts on these groups were discussed.

Ulva / Enteromorpha
In the Kenyan lagoons a relation seems to exist between macroalgal abundance and groundwater outflow. Separation of the data on green algae obtained by KMFRI into major taxa could show if especially *Ulva* and *Enteromorpha* react to the lowered salinity or increased nutrient levels at groundwater outflow sites. On Zanzibar Island, *Ulva* and *Enteromorpha* are present around the intertidal groundwater wells. The biomass of the algae will be determined by IMS and SU and normalised for amount of available substrate. Salinity and nutrient concentrations of the wells and C/N ratios of algal tissue will be measured. On Inhaca Island *Ulva* and *Enteromorpha* are not present at the study sites.

Convoluta macnae
Although this organism is a worm, it does have symbiotic algae. This may explain its presumed dominance at groundwater outflow sites. On Zanzibar and Inhaca islands the possible relation of *C. macnae* with groundwater outflow will be studied by GML, IMS and UEM. The abundance of this species will be determined separately during the macrozoobenthic samplings. As no macrobenthic sampling is scheduled for Kenya, this part of the study will not be carried out in Kenya.

Thalassodendron ciliatum
It is unclear from the data obtained so far whether the dominance of the seagrass *T. ciliatum* is caused by lowered salinity or increased nutrient levels at groundwater outflow sites. Comparison of *T. ciliatum* abundance data and salinity data (collected by NIOO-CEMO) with nutrient data from Kenya (collected by KMFRI) and Zanzibar (collected by SU) may give some more insight in this matter. In addition, an extensive *T. ciliatum* population at the west coast of Inhaca seems to exist without groundwater outflow, but near oyster banks. This suggests that dominance of *T. ciliatum* is mainly a nutrient effect. This population will be included in the samplings carried out by UEM.

epiphytes on *Thalassodendron ciliatum*
The study carried out by KMFRI suggests a higher epiphytic load on *T. ciliatum* stems at groundwater outflow sites in Kenya than at sites without groundwater outflow. To expand the data set on this issue similar collections will be carried out on Zanzibar Island (IMS) and Inhaca Island (UEM). A standard protocol will be used to optimize comparison of the data.

Rhizophora mucronata
The study of the VUB in Kenya showed a negative relation between groundwater outflow and the number of propagules present on the mangrove tree *R. mucronata*. This study will be repeated on Zanzibar (IMS & VUB). In this way it can be shown if the observed pattern is general for the East African coast.

phytoplankton
Results obtained by KMFRI suggest an effect of groundwater outflow on phytoplankton abundance. The results need to be compared to oceanographic data for the different lagoons to be able to separate the effect of residence time of the water and groundwater outflow rate. The studies on Zanzibar Island (IMS) and Inhaca Island (UEM) will be expanded with chlorophyll measurements.

The following researchers were asked to be coordinator of the different sub-projects:

Johnstone & Kamermans	*Ulva / Enteromorpha*
Fidalgo & Gove	*Convoluta macnae*
Kamermans & Johnstone	*Thalassodendron*
Uku & Mtolera	epiphytes on *Thalassodendron*
Shunula & Verheyden	*Rhizophora*
Gove & Kyewalwanga	phytoplankton

Report of group discussion on zoological research activities

Marten Hemminga

From the work presented at the workshop the general conclusion was made that the analyses of the zoological research in general lagged behind that of the botanical research. Part of the explanation for this backlog was the unfortunate death of Prof. Saldanha, responsible for the coordination and fine-tuning of the zoobenthic work. Because of the comparative scarcity of fully analysed data, it was difficult to decide which specific lines of research should be emphasized in the second part of the investigations. The need to get solid, publishable results was stressed.

Research at Inhaca Island
José Paula, the successor of Prof. Saldanha for the GML team, presented a thorough evaluation of the various research options. He indicated that there are no clear differences in the benthic fauna between the mangrove bay sites, making it imperative to change course and decide on new research directions. After lenghty discussion, it was decided that it was best to continue the investigations by focussing on the seagrass sites studied by UEM and to include a new *Thalassodendron ciliatum* site as well. It was also noticed that for the finalisation of the groundwater model of Inhaca Island there is an urgent need of accurate maps. Domingos Gove will look into this matter.

Research at Zanzibar
The macrobenthos sampling follows identical procedures as applied at Inhaca. There are problems of scale and underground rivers at Zanzibar that were extensively discussed. Evaluation of the sampling sites studied until now, led to the conclusion that the sampling sites should be left unchanged. For meiobenthos sampling it was agreed that deeper sampling was necessary for detection of groundwater effects.

Research in Kenya
Budget reductions have precluded planning of zoobenthos work in Kenya.

Report of third workshop, Inhaca Island, Mozambique, 12 - 15 April 1999

Programme & list of participants

FINAL WORKSHOP OF THE EU-INCO PROJECT

"ANTHROPOGENICALLY INDUCED CHANGES IN GROUNDWATER OUTFLOW AND QUALITY, AND THE FUNCTIONING OF EASTERN AFRICAN NEARSHORE ECOSYSTEMS"

Inhaca Island, April 12th- April 15th, 1999

Monday, 12 April

09.00 - 09.30. Arrival of participants, coffee

09.30 - 09.45. Welcome, introductory remarks

09.45 - 10.30. Large-scale groundwater modellisation along the East-African coast: results. (A. Verheyden & J. Tack)

10.30 - 11.15. Surface water, groundwater and coastal water qualities at selected sites of Unguja Island. (A. Mmochi)

11.15 - 11.30. Coffee break

11.30 - 12.15. Groundwater influence on meiobenthos in the nearshore regions of Zanzibar. (S. Ndaro)

12.15 - 13.30. Lunch

13.30 - 14.15. Macrobenthic assemblages in freshwater- and saltwater-influenced sites in Zanzibar. (J. Shunula)

14.15 - 15.00. The influence of groundwater on the productivity of marine macrophytes found on selected sites in Zanzibar. (M. Mtolera)

15.00 - 15.30. Coffee/tea break

15.30 - 16.15. Anthropogenically induced water outflow and quality and the functioning of nearshore ecosystems of Inhaca Island. (D. Gove)

16.15 - 17.00. Mangrove macrobenthos and groundwater outflow. (P. Fidalgo, J. Paula & R. Costa)

Tuesday, 13 April

09.00 - 09. 45. Standing crop of seagrasses and associated infaunal communities. (J. Paula, P. Fidalgo, A. Martins & D. Gove)

09.45 - 10.30. Tracing groundwater effects on abundance and diversity of lagoonal seagrasses. (P. Kamermans, M. Hemminga & M. Mtolera)

10.30 - 11.00. Coffee break

11.00 - 11.45. Groundwater outflow dynamics and circulation at Diani and Nyali mesotidal beaches in Kenya. (J. Kitheka)

11.45 - 12.30. Groundwater-associated anthropogenic influences on coastal lagoons: Diani and Nyali Beach, Kenya. (J. Mwangi, B. Mwashote & J. Kazungu)

12.30 - 13.45. Lunch

13.45 - 14.30 Impact of groundwater discharge on community structure in Kenyan coastal lagoons: Diani and Nyali Beach. (J. Mwaluma, P. Wawiye & J. Uku)

14.30 - 15.00. Break

15.00 - 17.00. Plenary discussion. What are the general conclusions that can be drawn regarding the impact of groundwater on nearshore ecosystems?

Wednesday, 14 April

Field excursion

Thursday, 15 April

09.00 - 10.00. Administrative matters (Final Report, Cost Statements etc.)

10.00 - 10.30. The future: part 1; the Fifth EU Framework Programme. (M.Hemminga)

10.30 - 11.00. Coffee break

11.00 - 12.00. The future: part 2; ideas for cooperation (group discussions).

12.00 - 13.15. Lunch

13.15 - ...... The Future: part 3; plenary discussion on future projects.

Closure of workshop
(M. Hemminga / D. Gove)

List of participants

KMFRI
J.M. Kazungu
J.M. Mwaluma
B.M. Mwashote

NIOO-CEMO
M.A. Hemminga
P. Kamermans

VUB
A. Verheyden

IMS
A.J. Mmochi

GML
J. Paula
P. Fidalgo

UEM
D.Z. Gove
R. Abdula

Summary of plenary discussions

Report of plenary discussion on general conclusions

Pauline Kamermans

The general conclusion of the GROFLO project is that the East African nearshore coastal ecosystem is affected by anthropogenically induced changes in groundwater outflow and quality. Data collected in Kenya and on Zanzibar Island (Tanzania) showed a strong impact of groundwater outflow on a number of components of the back-reef lagoon ecosystem. Sites with a relative high groundwater outflow displayed a lower seagrass species diversity than sites with a relative low groundwater outflow. Differences in optimum salinity for growth between species and competition for nitrogen may explain the observed pattern in seagrass diversity and abundance. The epiphytic load on seagrass stems was slightly higher at groundwater outflow sites. Seagrasses are "structuring species". This means that they constitute an important component of the system. Changes in seagrass vegetation can affect the whole ecosystem. Results also indicate that elevated nutrient inputs caused enhanced phytoplankton cell abundance and reduced species diversity. Furthermore, certain groups or species in the lagoon ecosystem could be identified as indicators of groundwater outflow. The presence of mysids at particular spots and throughout the year, was indicative of groundwater discharge. And, at the beach sites where freshwater influence is highest, a proliferation of green macroalgae was observed. At present, information on the function of many of these species in the ecosystem of back-reef lagoons is absent, which impedes predictions of possible consequences of changes in groundwater outflow. At Inhaca Island (Mozambique), there was no strong evidence of large-scale effects of groundwater outflow on the ecosystem, due to the fact that the catchment area of the island is too small to produce large aquifers. Studies on a more detailed level may provide some evidence of groundwater effects.

The groundwater model was an indispensable tool for the field studies. To improve its performance in future excercises, further validation of the model is still needed. In addition, data on aquifer depth and the pattern of outflow in the lagoons should be collected. On Zanzibar Island, measurements of the underground rivers would be very helpful in understanding the groundwater flow on the island.

The socio-economic studies provided valuable baseline data on water usage patterns. An interesting comparison was made between the more touristic Zanzibar Island and the more rural Inhaca Island. It was noted that data from the Kenyan coast would have been a welcome addition to the data set. Analysis of the water quality of the wells yielded results on levels of contamination with micro-oganisms, nutrients and pesticides that call for caution. Nutrient concentrations in the boreholes/wells indicated highly elevated levels in Kenya and on Zanzibar Island. In addition, in the majority of the wells, contamination with faecal coliforms exceeded the maximum acceptable value in Kenya and on Inhaca Island. Microrganisms were not measured on Zanzibar Island. Pesticide levels in bays, rivers and streams were determined on Zanzibar Island. Lindane was present at all sampling sites. DDT was more closely associated with townships rather than agriculture areas and may be a result of fumigation. The results on micro-oganisms, nutrients and pesticides will be coveyed to the local administrators.

Report of plenary discussion on future projects

Pauline Kamermans

The results of the GROFLO project were considered very promising and possible research subjects in the framework the 5th Framework Programme (INCO-Dev A4 domain c, Ecosystem Management for Sustainability) were discussed. It is important to investigate how changes in seagrass abundance and diversity influence the rest of the ecosystem. Effects of groundwater on commercial species needs further attention. For example, it is unknown whether the impacts on seagrasses, macroalgae, zooplankton and phytoplankton, that were observed during the GROFLO project, have effects on fish and shrimp abundance and diversity. In addition, shellfish culturing in Kenya and seaweed farming on Zanzibar Island are activities that may be affected by changes in groundwater outflow and quality. In view of the date of the call for proposals (15 March 2000), it was concluded that was is too early to formulate a new INCO research proposal.

Annex II. Copies of Publications

Contents

Causes and Consequences of Groundwater Use
on a Tropical Island: Zanzibar, Tanzania

by

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Stockholm/ Lund
March 1999

Abstract
Groundwater is a very essential resource: its occurrence and quality are a precondition of human welfare and of the persistence of ecosystems. On carbonate tropical islands, groundwater is often entirely recharged by rainfall, and stored in less efficient aquifers that can easily be overused. The possible consequences of overexploitation include the lowering of the groundwater table, land subsidence, deteriorating groundwater quality, and saltwater intrusion (1, 2). For the east cost of Zanzibar, Tanzania, there is some evidence that present water use is less sustainable and might lead to socio-economic problems in the future. In the light of this, the causes and consequences of groundwater abstraction were investigated.

Background and introduction

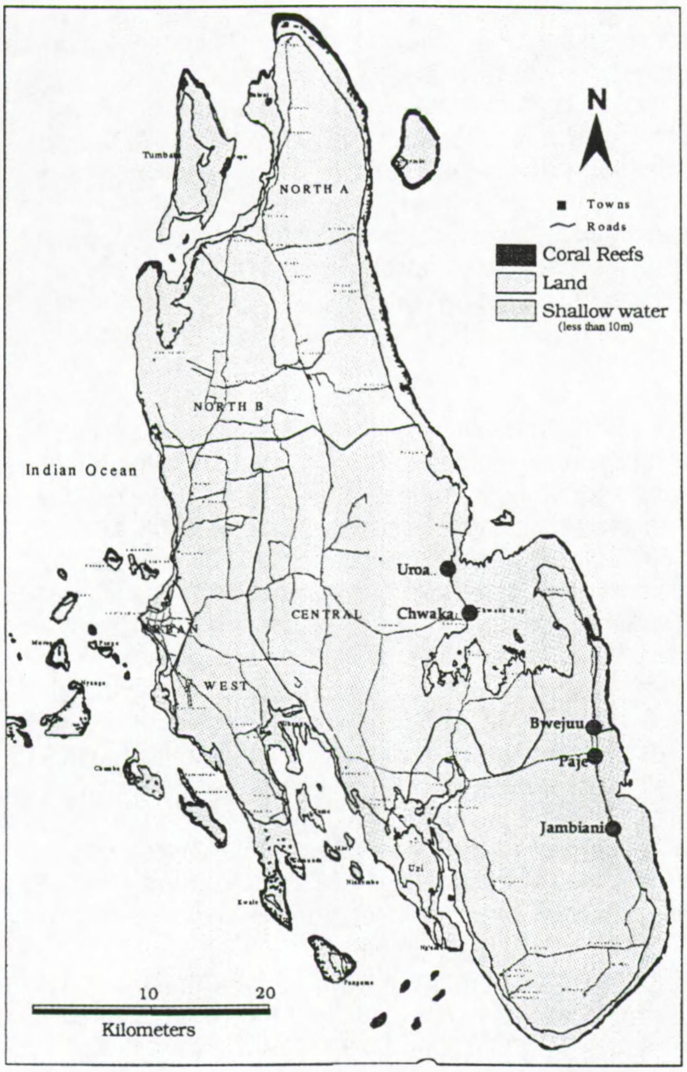
Unguja Island (Zanzibar), with a size of 995 square miles, is located off the coast of mainland Tanzania between 5°40' and 6°30' S. The island has two wet seasons, the southern Masika Rains from March to May, and the Vuli Rains from the northeast during November and December. The majority of rain is falling during Masika (49%), followed by Vuli rains (27%). Average annual rainfall on the island varies from 1000-2000 mm, with a mean of about 1600 mm, and a minimum (with 10% probability) of 1100 mm (3,4).

The topographical watershed devides Unguja Island into a western and an eastern half (5). The west receives most of the precipitation, while the coral rag areas in the east and south have the lowest rainfall with 1000-1500 mm per year. In consequence, water becomes scarce foremost in these areas (3, 4). Moreover, strata in the east consists of cavernous and fissured limestone with high transmissivity. Drainage is almost entirely sub-surface, and watertables are not much above sealevel, indicating shallow fresh water lenses and less productive aquifers. These are mostly recharged by rainfall, with overflow discharging into the sea (6). This way saltwater intrusion is prevented, which can occur when freshwater flow has been reduced to less than 1 m2 d-1 (7).

The coral rag areas on the east cost are mainly covered with canopies and bushes, and coconut palm trees growing in the stretch of beach adjacent to the ocean. Historically, villages have existed in the areas close to the coastline, where freshwater is abundant and can be abstracted either from natural caves or wells, and where palm tree-cover is extensive, providing both food and building materials. Since agriculture is less efficient on weathered limestone (8), the local residents are very dependent on marine resources for subsistence. In recent years, however, population growth and unsustainable exploitation of natural resources have led to declining fish catches and the degradation or even destruction of the ecosystems (9, 10, 11). Groundwater is abstracted to supply an increasing number of humans, and a rapidly spreading tourist industry. Since saltwater intrusion has already occured in some places, the implementation of a precautionary water management strategy has become an urgent issue.

Approach and method

In the light of the current state of knowledge, it was the aim of the survey to provide a data base on the use of groundwater applicable for the development of management strategies. The survey focused on the east coast of Zanzibar, including 22 villages between Nungwi in the north and Jambiani in the south (Map 1). In total, approximately 35,000 people live in the study area, representing about 7% of the total population of the island.



Source map: URT 1985
Department of Land and Survey
Zanzibar (Z1,Z2,Z3,Z4, & Z5)

Map 1: Overview of the study area on Zanzibar

The survey was conducted during March-April 1998. Three different questionnaires were administered to i) the chief (sheha) of each village, ii) local inhabitants, and iii) hotel managers. The sheha was asked for general information, namely the number of inhabitants, water supply schemes, and aspects of water quality. Local inhabitants were interviewed on their age, number and age of children, personal water use (totals and percentages for different uses), water use of children under 15 years, and aspects of waste water treatment. Tourist facilities were asked to provide information on water supply systems, water use (totals and percentages of different uses), hotel size (number of beds), occupancy rates, and sewage systems.

Results

In general, villages can be devided up in such with a pipe system, abstracting water from springs and caves, and such using local wells. Piped water is available in Nungwi, Kigomani, Tundangaa, Matemwe, Mbupurini, Klima Juu, Pwani Mchangani Ndogo, Pwani Mchangani, Kiwengwa, Marumbi, Chwaka, and Jambiani. Uroa, Uroa Dikoni, Michamvi and Pingwe also receive piped water, but in contrast to the other villages, it is pumped from boreholes or wells close to the

villages. Pongwe, Ndudu Mkubwa, Charawe, Ukongoroni, Bwejuu and Paje are dependent on well water.
Problems attributed to water are mainly the continuity of supply and its quality (salinity). Piped water has a good quality, but due to breakdowns or repairs, even villages connected to the pipe system have to use local wells for up to one, or, in the case of Nungwi, even several months per year.
The situation of the wells is different in each village, even though the number of fresh ones has decreased in almost all of them. Cholera cases, possibly on account of well pollution, have occured in Pingwe, Ndudu Mkubwa, and Pwani Mchangani. Well-water shortages occur mainly at low tide, and in dry season (December, January, February). This has led to an increasing dependency on piped water in some villages.

Sewage is treated differently in the villages. Pit latrines within the house, for instance, serving as toilets and deposits for waste water from taking showers, are not equally common in the villages. Basically, villages with sandy grounds have a higher number of pit latrines, since rocky grounds make any digging a major investment, with costs ranging between TSh 30,000-60,000 (US$ 50-100). There is no village with more than 80% of houses having pit latrines, and on average the number might be in the order of 30%. Pit latrines are generally not concreted on the bottom. Where pit latrines are less common, the beaches are used for toilet purposes, while showers are taken inside a fenced area that belongs to the house. Clothes are sometimes also washed within the fenced area, sometimes at the next well or tap in order to avoid carrying water. Water from washing dishes is not put into the latrines for religious believes, but thrown on the ground outside the house. Overall, part of the sewage is evaporating, part is leaching into the ground. The latter can be directly from washing dishes or cloths, or indirectly through non-concreted pit latrines.

Within the villages, a sample of 107 local residents was interviewed on aspects of water use. Samples were drawn randomly; data was collected from locals aged 15 and above with the help of a translater. Parents were asked about the water use of their children. This way, additional data for children (n = 34) was gained.
Difficulties arose from estimating the accurate amount of water used. Therefore, buckets and a plastic bottle with volumes of 1.5, 10, and 20 litres were shown to provide a basis for estimates. To interview women about patterns of water use for taking showers and toilet purposes turned out to be a sensitive issue. For this reason, a female translater was brought into action whenever possible.
Freshwater is mainly used for eight different purposes: taking showers, toilet purposes, cooking, washing dishes, drinking, washing cloths, cleaning, and feeding animals. Some water use patterns are individual (taking showers, toilet purposes, drinking), while others are family uses (cooking, washing dishes and clothes, cleaning the house and feeding the animals).
It did not seem feasible to divide family uses into weighted per capita averages. Thus, for family water uses, per capita averages were calculated by dividing the total amount of water used by the number of family members. Afterwards, these were added on the individual water demand. To define 'adults' and 'children', the data on individual water use was plotted against age in a scatter-diagramm, showing a rather strong increase in water use for those being aged 15 and above. Accordingly, 'children' were defined aged 0-14, 'adults' 15 and above. The water use patterns of children and adults are shown in Fig. 1 and 2.

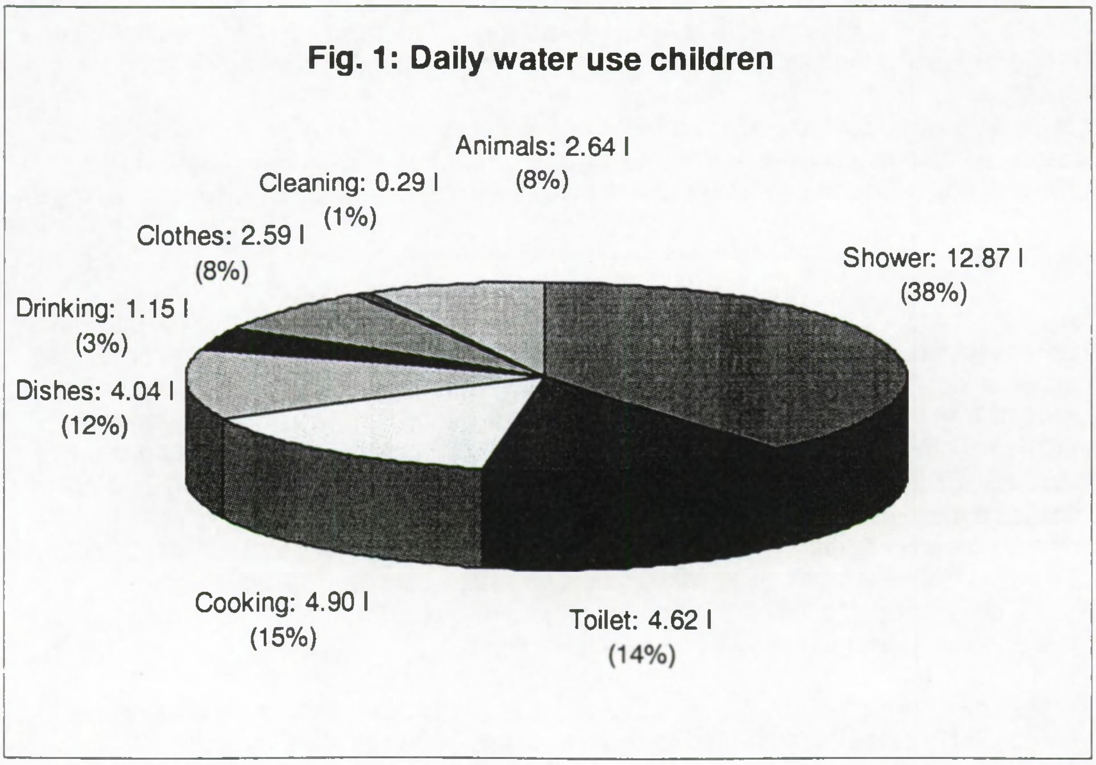


Fig. 1: Daily water use children

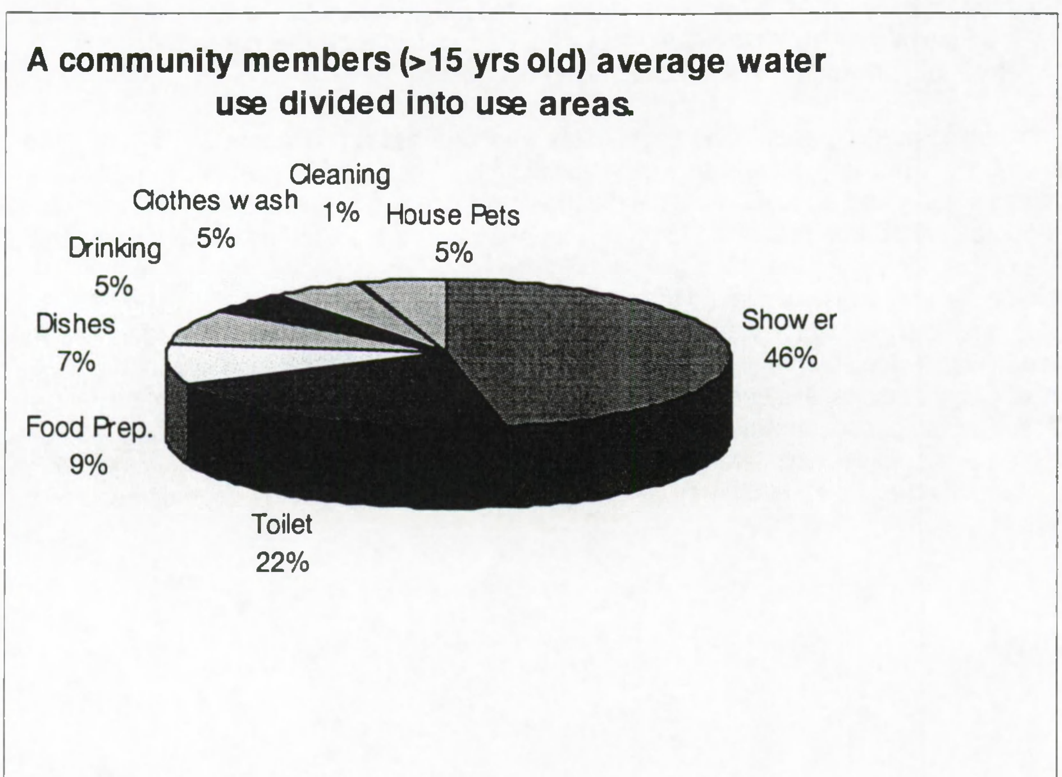


Fig. 2: Daily water use adults

For children, daily water use consists of 12.87 l (38%) for taking showers, 4.9 l (15%) for cooking, 4.62 l (14%) for toilet purposes, 4.04 l (12%) for washing dishes, 2.59 l (8%) for washing clothes, 2.64 l (8%) for feeding the animals, 1.15 l (3%) for drinking, and 0.29 l (1%) for cleaning the house.
For adults, daily water use amounts to 25.21 l for taking showers (46%), 11.92 l (22%) for toilet purposes, 4.9 l (9%) for cooking, 4.04 l (7%) for washing dishes, 2.64 l (5%) for feeding the animals, 2.59 l (5%) for drinking, 2.59 l (5%) for washing clothes, and 0.29 l (1%) for cleaning the house.
In total, the daily water demand amounts to 33.46 l for children and 54.54 l for adults.

To interpolate the total amount of water used on the east coast, results were multiplied by the number of residents. As stated above, about 35,000 people live in the study area. According to the Department of Statistics (1998, pers. comm.), 44.5% of the island's population belong to the age group of 0-14 years. Applying this percentage to the east coast leads to a daily water consumption of about 1,059,440 l for adults and 521,140 l for children, or a summed up total of 1,580,580 l d-1. The average daily per capita demand is therefore in the order of 45.2 l. Note that this includes the use of both well and piped water.
However, public water demand (mosques, schools, etc.) was not included into calculations. Based on observations in the villages, this might account for a 10% surplus. The overall water demand on the east coast of Unguja Island is therefore in the order of 1,738,638 l d-1, increasing the per capita demand to an average of 49.7 l d-1 (see also Fig. 5).

Within the tourist industry, 32 of 58 hotels and guesthouses located in the study area were interviewed. Out of these, 28 answered the questionnaires correctly.
Tourist infrastructure consists of guesthouses and hotels. Guesthouses are rather small units, mainly owned by Zanzibarians. They are foremost found within the villages, where water is abstracted from local or private wells. Hotels, in contrast, are located outside the villages in uninhabited areas, have resort character, and belong to foreign investors. To meet water demands, local caves or wells have been developed. Both hotels and guesthouses abstract groundwater without any form of overall planning or control.

In total, hotels and guesthouses on the east coast combine a capacity of about 2,570 beds (own observations, 12). Their occupancy rates vary significantly. While guesthouses are bound to the touristic season (July and August, with a second peak in December), hotels often have contracts with tour operators in Europe, allowing for high annual occupancy rates of up to 80%. Based on the results of this survey, the weighted average high seasonal occupancy rate for all guesthouses and hotels on the east coast was found to be 72.1%.
To calculate the daily per capita water demand in a hotel or guesthouse, the total amount of water used per day was divided by the number of tourists staying at the hotel or guesthouse that very day. For simplicity reasons, this does not take into consideration the water demand of owners or employees. Overall, per capita water demand varies extremely, ranging between 100-2,000 l d-1. The weighted average was calculated at 685.0 l d-1, foremost on account of the very high per capita demand of one hotel (2,000 l d-1). 685.0 l d-1 is about 15 times the average demand of a local resident (Fig. 3).

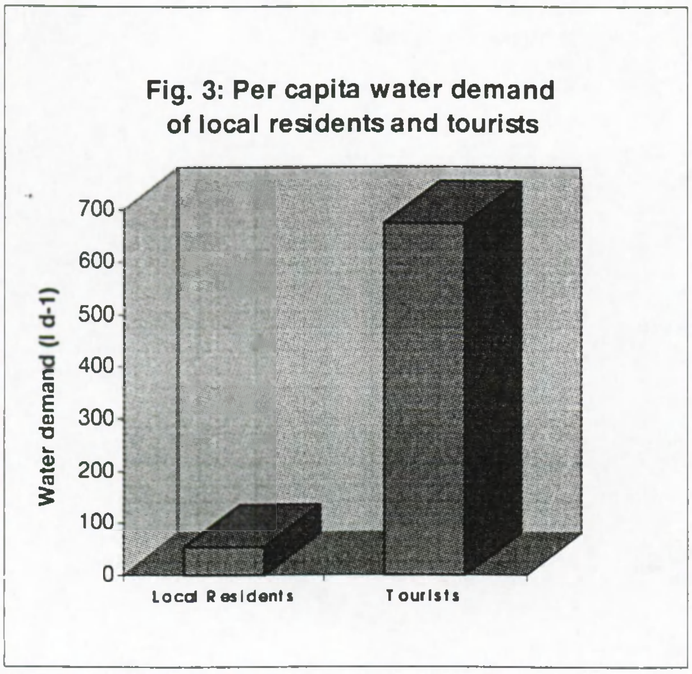


Fig. 3: Water demand local residents and tourists

The total number of beds of the 28 hotels and guesthouses investigated was 1,757. Out of these, on average 1,267 are occupied in high season (72.1% weighted occupancy rate). Calculated for all existing tourist facilities (about 2,570 beds), the total number of beds occupied on the east coast in high season may therefore be in the order of 1,853, entailing a water demand of approximately 1,269,305 l d-1 (at 685.0 l d-1 per tourist). Out of this sum, about 112,000 l are ocean water desalinated by two of the hotels.

In general, the average daily per capita water demand is far higher in hotels. In those tourist facilities defined as hotels in this survey, daily water use per tourist amounted to 930.9 l (weighted average). In guesthouses, the equivalent was 247.5 l d-1.

Within the tourist industry, water is not only used directly by the tourists, but for irrigation, swimming-pools, cleaning, washing, and restaurants. Hotels with expansive gardens use most water for continuous irrigation (on average 50%), because soils have a poor storage capacity, evaporation is high, and the species planted are not adapted to arid conditions. Swimming-pools consume large amounts of water, both due to high evaporation and water renewal. Moreover, additional showers are taken frequently at pools, and extra towels handed out to guests. Water used by tourists for taking showers, flushing toilets and other sanitary purposes constitutes a rather small proportion of the overall demand of hotels (20%). In contrast, 55% of the water in small guesthouses is used directly by tourists.

Sewage from hotels and guesthouses is piped into septic tanks. These are not necessarily concreted, as the survey revealed: out of 24 hotels and guesthouses, only 12 had fully concreted tanks, while the rest had open ones leaking into fissures and caves. One guesthouse piped its sewage into a cave, and one hotel into a former well. Treatment of any kind was generally not provided.

Future Development

Given the fact that a range of natural resources including groundwater face overexploitation, the question arises which future trends in population and tourist arrival growth have to be expected. According to data of the Department of Statistics (1998, pers. comm.), population on Unguja Island has grown from 190,117 (1967) to about 510,000 in 1997. For the future, the 'medium growth rate decline' scenario indicates an increase in population numbers to 806,000 by 2015 (8). In fig.4, both population and tourist arrival growth have been projected.

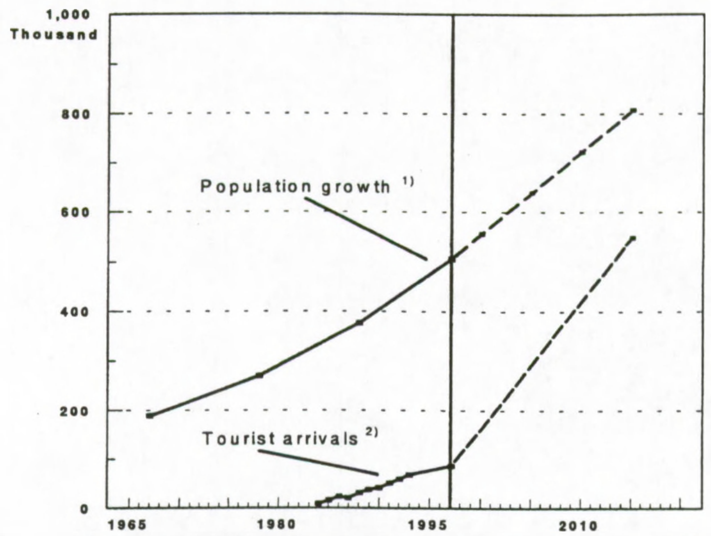
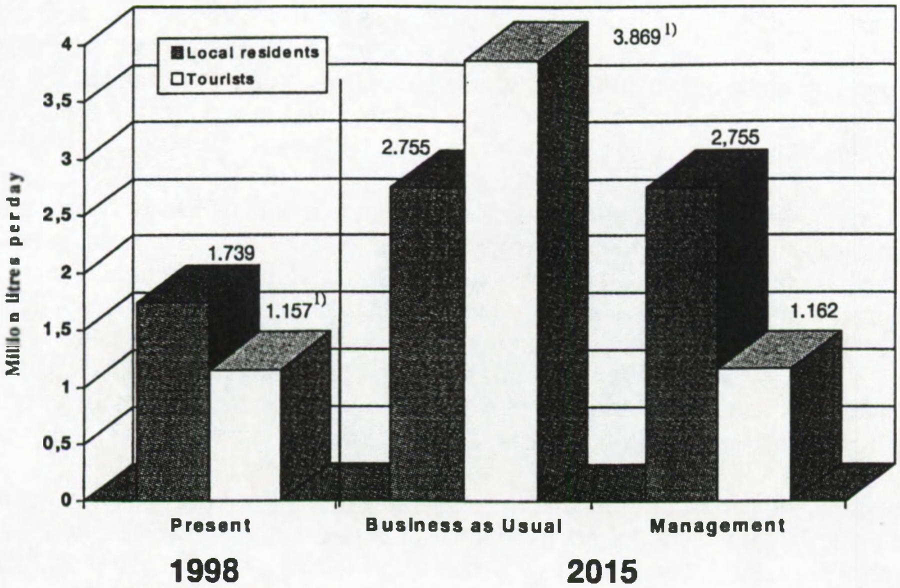


Fig. 4: Population and tourist arrival growth 1967-1997, and scenario 2015

Source: MWCELE 1995a, Commission for Tourism 1998
1) Medium growth rate decline scenario (MWCELE 1995a).
2) Interpolated between 1983-97 because of statistical insufficiencies

Assuming a rather low average population growth rate of 2.5% for the east coast, population in the study area would rise from presently 35,000 to about 53,000 in 2015.
In the past, shortages of arable land have led to migration from the coral rag to the deep soil areas (13), but tourism might reverse this trend due to its job generating effects. The eight biggest hotels alone have more than 1,500 Zanzibarian employees, with less than 20% coming from the adjacent villages.
Another development on the east coast is the construction of a considerable number of huge private houses, indicating a change in landownership and -use patterns, now permitting villagers to sell areas to private investors that have formerly been under common ownership. This contributes as well to the increase in population numbers and thereby water demand.
To calculate the future water demand on the east coast, it was assumed that the population would grow to 53,000, per capita water demand and age structure being constant. On top of this, a surplus of 15% was added for public uses (schools, mosques, etc.), migration due to tourism, and construction of private houses.
Under these assumptions, the amount of water being used on the east coast by 2015 was estimated to be in the order of 2,754,940 l d-1 (scenario Business as Usual, Fig. 5).

Fig. 5: Present and future water demand on the East Coast, high season



1) Desalinated sea water subtracted

The expected growth in tourist arrivals may become even more important. Since 1985, tourist arrivals on Unguja Island have grown consistently at around 20% per year, increasing from 8,967 (1984) to 86,495 in 1997 (12, 14, 15, Fig. 4). This trend is expected to continue, leading to 550,000 tourist arrivals by 2015 (8). Accordingly, the number of beds on the east coast is planned to increase from presently 2,570 to 8,060 (14).

Given the high seasonal occupancy rate found in this survey (72.1%), on average about 5,811 tourists would then stay on the east coast. This would entail a total water demand of 3,980,535 l per day, assuming no change in per capita demand (685.0 l d-1).

However, this scenario (Business as Usual, fig. 5) has to be considered as rather conservative, as it is based on the present mixture of hotels and guesthouses, while new buildings along the coast will almost entirely be hotels, which have been shown to have a higher per capita water demand and possibly higher occupancy rates.

Moreover, existing guesthouses will have to improve their standards: presently, 65% do not fullfil the prerequisites of the Commission for Tourism. Requirements include for example private bathrooms attached to each room (Mlingoti 1998, pers. comm.). Per capita water demand might therefore increase in guesthouses as well.

Discussion

It has been shown that groundwater abstraction on the east coast of Zanzibar is substantial. Therefore, the question arises of up to which amount of water can be withdrawn without negative consequences.

Basically, water resources on the island as a whole are said to be sufficient to meet the anticipated demands of the population and the tourist industry until 2015, but current abstractions are concentrated on single spots in areas on the east coast where recharge is low and where the karstic nature of the limestone makes it difficult to predict the safe yield (3). Consequences of overuse can be proceeding saltwater intrusion, land subsidence, and deteriorating groundwater

quality (1,2). Moreover, global warming and resulting sea-level rise could force saltwater intrusion in the future, enhancing the local effects of over-use (16). Ecologically, it is not known yet how groundwater use will influence ecosystem functionability, for instance by lowering the groundwater table below the rooting zone. Falling water tables might also impart effects on Zanzibar's National Park, the wetland Jozani Forest (3).
While over-exploitation has not yet been proven scientifically, there is evidence that present abstractions on the east coast are unsustainable. In some areas, hotels or guesthouses reported that water had become slightly salty. In Nungwi, all local wells have become saline, making the village dependent on piped water. Here, piped water is available only half the year, which is partly due to the demand of guesthouses abstracting water from the same pipe that supplies the village. In consequence, local residents have to fetch freshwater from a well that is located more than 1 km outside the village. A similar situation has been reported for Uroa (17).

Groundwater has been recognized as an important source for nutrient influx to coastal marine ecosystems, especially if it is subject to human activities like the construction of buildings with poor treatment facilities (e.g. 18, 19). On the east coast of Zanzibar, poor treatment of waste waters (deposition in former wells or caves, non-concreted pit latrines and septic tanks, etc.) has possibly increased the nutrient content of the groundwater. A study conducted by Johnstone (1998, pers. comm.) has shown there to be greatly elevated nutrient levels in coastal aquifers adjacent to a number of villages and hotel complexes. This could indicate contamination of the groundwater by human activities and thus be a potential for low level chronic anthropogenic inputs to coastal water bodies.
Depending on ocean conditions, currents, and according to their concentrations, these nutrients impart an effect on ecosystems, often in combination with, for example, the impacts of sedimentation, physical modifications like mining, destructive fishing practices or the alteration of fish communities. While it is very difficult to separate an individual factor as the sole force of degradation, it is clear that nutrients play a vital role, because coastal waters in the tropics are typically oligotrophic, and nutrient concentrations in groundwater can be considerably high compared to those of the receiving seawater (11, 20).

For the future, a worsening of the situation can be expected. By 2015, population on the East Coast will have grown to 53,000, not including migration. Newly built private houses will contribute to water withdrawl. Tourism will have become the major factor in water abstraction, foremost because of the increase in tourist arrivals. Additional pressure on water resources may result from the fact that the government intends to increase the standard of the guesthouses. Development is in favour of big hotel projects, which have an exponentially increasing water demand with size. Moreover, the water demand of the tourist industry is highest in the dry tourist season, when recharge is lowest. An additional risk factor is the El Niño phenomenon, which can severely influence rainfall, as has been shown in 1998, when March and April were extremely dry. In the light of this, and with increasing demand due to an expected doubling of the coastal population in 22-25 years time (8), a precautionary water management approach should be taken. Such a strategy would have to internalize the environmental costs of water abstraction and sewage release (21, 22).

As has been stated above, most villages receive piped water. For these, control and repair of the pipes might be a primary measure, because losses due to leakages are substantial. This has been proved by personal observations, and commentaries of local residents. Halcrow (3) estimates that leakages might account for losses in the order of 25% of the total amount being pumped.
The simplest and less cost intensive management strategy seems to be the reduction of water use. For the local population, present consumption patterns are considered to be close to minimum standards, and could possibly be reduced by no more than 10-20%. However, a strategy building on such minimum standards would imply that pressure on aquifers has proved to

be severe, and other options being exhausted. It is therefore not discussed here as a suitable option (Fig. 5, scenario Management).

Tourism has the most outstanding potential to safe water. Halcrow (3) estimated that hotels should manage to keep the average daily consumption down to an equivalent of 200 l per bed. This estimate, though, was based on the assumption that average water use would be in the order of 300 l d-1 per tourist, a figure presently only reached by some of the guesthouses. Given the projected development in tourism, even the less realistic reduction to an equivalent of 200 l d-1 per tourist (including desalinated water) would lead to withdrawl in the order of almost 1,162,200 l d-1 in high season by 2015 (Fig. 5, scenario Management).
As irrigation is the major factor for water use, composition and structure of the gardens should be re-considered, turning to less extensive areas in need of irrigation and to more drought-resistant plants. Wastewater reuse under a controlled environment might be a viable option to supplement necessary irrigation, even though caution must be exercised to ensure its use without causing environmental and health hazards (2, 23). Another possibility might be to collect and store rainwater. Within the hotel or guesthouses, flow limiters on taps and showers could be installed and lavatory cisterns be fitted with reduced flush option. Educational programmes for the staff and informative signs on water scarcity addressing tourists could contribute as well to water reduction.

In the past, groundwater has been an open-access resource in Zanzibar. Even though hotels and most guesthouses are charged a monthly tax for water today, this does not take into consideration the quantities being abstracted. It is therefore necessary to introduce an incentive based strategy, leading to the taxation of the abstracted quantities. Such an approach would significantly increase the interest to save water. Therefore, meters should be installed on all major pipes to control water use. Water saving measures would also help to solve the problem of sewage. For unavoidable sewage, treatment with closed cycles of organic matter flow should become the standard (24). To minimize the danger of upconing, the pressure on single withdrawl spots should be reduced by increasing the number of wells, and distributing these in a larger area.

Technical options include abstraction of water further inland, which would entail major costs for new pipline-systems and is at present not considered by either the government or the tourist industry. Desalination increases the dependency on imports (fuel) and entails environmental costs due to the emission of ecologically relevant trace gases contributing to, for instance, global warming and atmospheric nitrogen deposition (25). The discharge of brine could lead to locally raised levels of salinity with negative effects for corals (26). Therefore, it is not considered to be a feasible solution.

Conclusions

The study has shown that water use on the east coast is an important issue. A comparison of the scenarios shows that future water demand will be closely related to the measures being taken. At present, a total of about 2.9 million litres of water are used per day by both local residents and the tourist industry. There is evidence that withdrawl in this order is not sustainable. However, even under the less realistic scenario Management, which demands heavy cut-backs for implementation, water demand will rise to 3.9 million l d-1 by 2015. Without any management steps being taken (Business as Usual), water demand will even increase to 6.6 million l d-1. Such a development might have severe negative consequences, both for local residents and the tourist industry. As tourism is responsible for most of the additional demand, it is therefore recommended to re-consider the plans for future tourist development.

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Sustainable Management of Groundwater Resources on a Tropical Island: Issues and Dillemmas.

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(Submitted to Coastal Management)

Abstract

Many developing countries have focused on tourism to generate additional income sources and to diversify the economy. The development of the necessary infrastructure in combination with the presence of a large number of tourists can have detrimental effects for the resource base on which local communities depend.

In this article, the situation is described for the East Coast of Zanzibar, Tanzania. Causes and consequences of groundwater withdrawl are investigated, analyzed and put into context of the overall tourist development. Results show that present levels of groundwater extraction are less sustainable, and problems might increase substantially with further growth in tourist arrivals. Therefore, a precautionary water management approach is suggested. Future plans to force tourist development are considered as less favourable.

Keywords: *Tropical Islands, Local Communities, Tourism, Natural Resources, Groundwater*

1. Introduction

In recent years, many developing countries in the tropics have focused on tourism to generate additional jobs and income, raise foreign exchange earnings, and to diversify the economy. Coastal zones have been on the forefront of tourist infrastructure development, as they provide the scenery for the sun, sand and sea image that represents the major travel magnet, and are seen to be of less value for other uses (e.g. Miller and Auyong, 1991; Salm, 1985; Sida/World Bank, 1997; Vorlaufer, 1996).

Historically, coastlines and their ecosystems have supported the world's densest populations with food, and contributed in many ways to local income (e.g. Andersson and Ngazi, 1995; Khatib, 1996; Lindén and Lundin, 1996; Petterson-Löfquist, 1995). Today, increasing and unsustainable use of natural resources, both for reasons of population growth and commerce including tourism, has forced the degradation or even destruction of coastal ecosystems in many regions of the world (e.g. Dulvy et al., 1995; Gomez, 1988; Ngoile and Horrill, 1993; Sheppard, 1998; Wilkinson, 1992).

This article describes how tourism is contributing to the over-use of groundwater and other coastal resources on a tropical island, and how local communities are interacting with and responding to the ecological and socio-economic changes tourism has brought about.

2. Background

Unguja Island and Pemba are the two major islands that make up Zanzibar. Unguja Island, in this text also referred to as Zanzibar, has been chosen as study site. The island has a surface area of 995 square miles, and is located between 5°40' and 6°30' S off mainland Tanzania. The West of Zanzibar is dominated by cultivated land, while the East consists mostly of coral rock, covered with bushy vegetation. Here, shorelines are fringed by palm trees and natural beaches.

Within the last 20 years, the island has seen a substantial population growth, going along with a rapid increase in tourist arrivals. Simultaneously, a great number of hotels and guesthouses have been built, with construction being concentrated on the East Coast. This development has both directly and indirectly increased the demand of natural resources.

Groundwater is a very central resource in coastal areas. Its occurrence and quality are a precondition of the persistence of ecosystems, and of major importance for the welfare of local residents. For the East Coast of Zanzibar, there is evidence that over-use has locally resulted in saltwater intrusion, while water quality has been degraded on account of effluents.

Tourism development

In the 1960's and 1970's, Zanzibar was one of the world's major exporters of cloves, which brought in 85% of the countries' foreign exchange earnings. During the 1980's, world market prices fell substantially, and the Government of Zanzibar, realizing its dependency on the cash-crop, initiated a liberalization policy for the trade and tourism sector in 1984, followed by a tourism investment act in 1986 (Johnstone et al., 1998; Khatib, 1998). Since then, tourism has become ever more important: today, Zanzibar is a popular tourist destination, profiting from its cultural and historical heritage, its white beaches and coral reef gardens (Ali, 1998; Khatib, 1998; Scholz, 1995).

In 1997, international tourist arrivals had risen to 86,495 compared to 8,967 in 1984 (fig.1) (MWCELE, 1993; Commission for Tourism, 1996, 1998). For 2015, more than half a million arrivals are projected. A development like this would stand for a more than 6-fold increase from 1997-2015, while the number of tourist nights would grow even more rapidly to 3.8 million as a result of an extended average length of stay of 7 days compared to 4 in 1994 (MWCELE, 1993; Commission for Tourism, 1995).

Recent tourist development has been concentrated on the East Coast of Unguja Island, where large areas along the coastline have remained uninhabited, and where white sandy beaches provide the precondition for infrastructure development. A great number of hotels have already been built along the coastline, and many are still under construction.

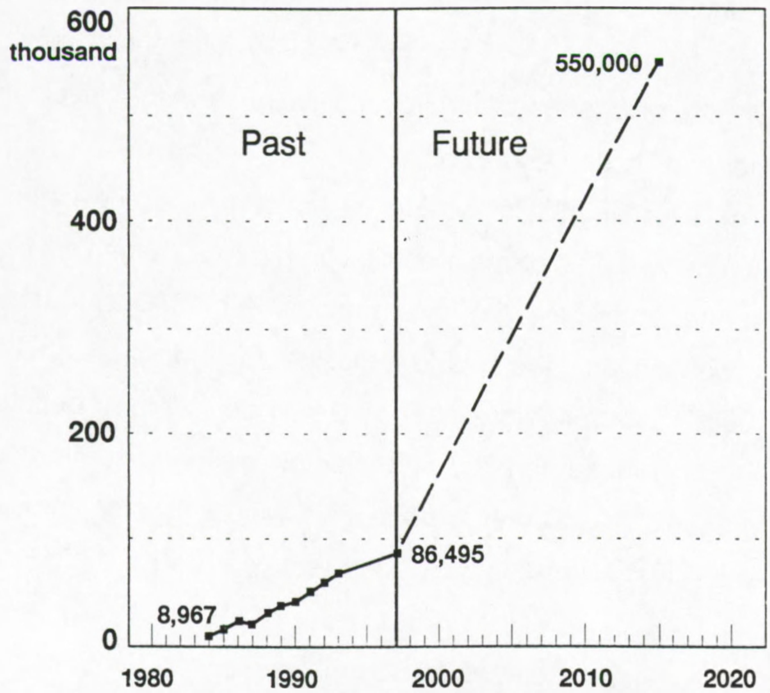


Fig.1: Tourist arrival growth[1] 1965-1997, and scenario 2015

Source: MWCELE 1993; Commission for Tourism 1996, 1998

1) interpolated between 1993-97 due to statistical insufficiencies

Fig. 1: Tourist arrival growth 1965-1997, and scenario 2015

Groundwater

Carbonate tropical islands contain fresh groundwater of meteoric derivation, salty groundwater of marine derivation, and mixtures of the two. Density differences make the fresh groundwater float on salty groundwater, resulting in stratification, and the development of freshwater lenses (e.g. Vacher and Quinn, 1997).

The topographical watershed devides Unguja Island into an eastern and a western half (FAO/ UNDP, 1982). The West receives most of the precipitation (up to 2000 mm yr^{-1}), while the coral rag areas in the East and South have the lowest rainfall with 1000-1500 mm yr^{-1}. Rainfall is concentrated on two wet seasons, the southern Masika Rains from March to May (49%), and the northeastern Vuli Rains from November to December (27%). Aquifers are recharged by rainwater mostly during these periods, with overflow discharging into the sea (Halcrow, 1994; Zanzibar Hydrogeological Survey, 1987). This way, saltwater intrusion is prevented, which can occur when freshwater flow has been reduced to less than 1 m^2 d^{-1} (Stanger, 1985).

As mentioned above, recent tourism development has been focused on the East Coast, where rainfall is low and evapotranspiration high. Strata in this area consists of cavernous and fissured limestone with high transmissivity and hydraulic connection to the sea. In consequence, drainage is fast and almost entirely sub-surface, and watertables are not much above sealevel, indicating shallow freshwater lenses, and less productive aquifers (Halcrow, 1994; UNEP/FAO, 1982). In fact, pressure on aquifers is highest in dry season, when most tourists visit the island. Figure 2 shows the relation of tourist arrivals and precipitation: the number of tourists visiting the island is highest in July and August, when rainfall drops to a minimum. Consequently, this is the period when most water is needed by the tourist industry and recharge of the aquifers is lowest.

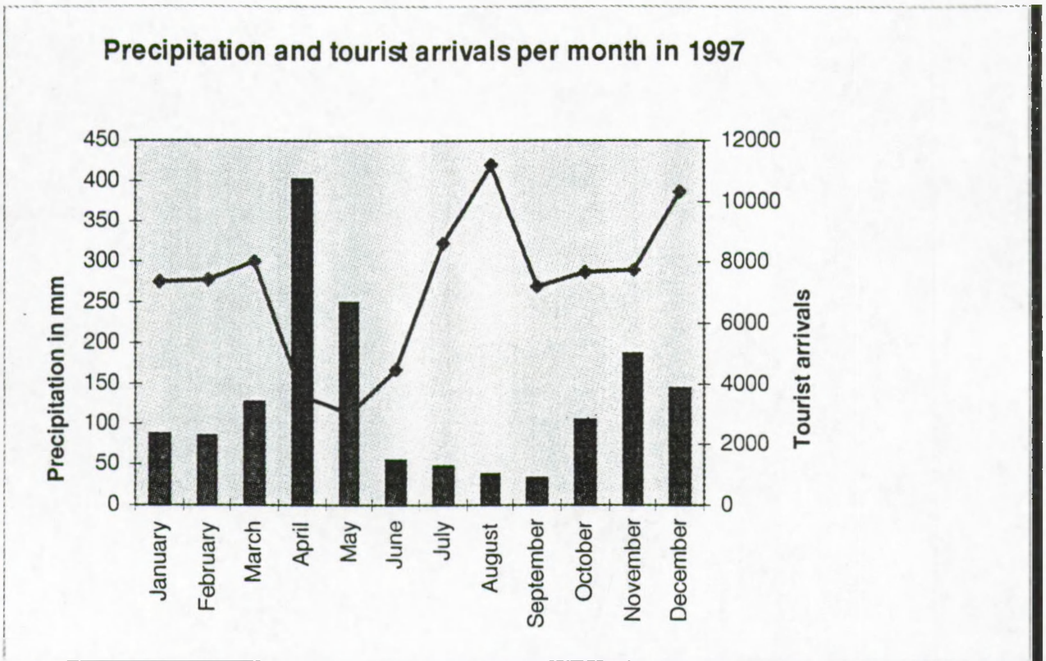
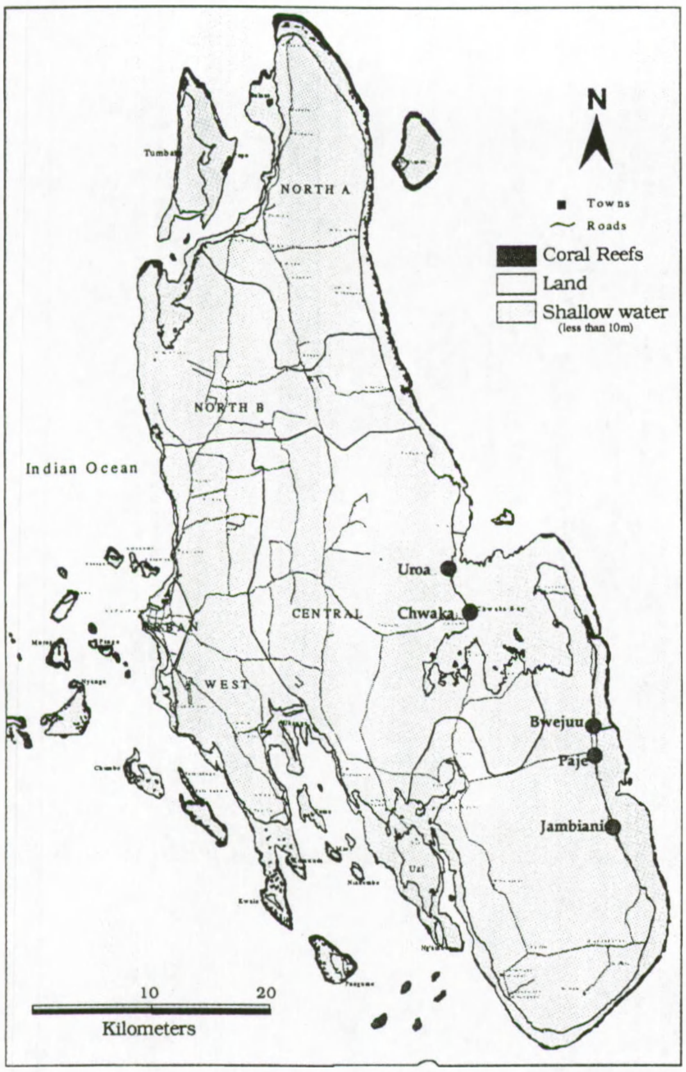


Fig. 2: Precipitation and tourist arrivals

2. Method and analysis

The survey was conducted on the East Coast of Zanzibar between the villages of Nungwi and Jambiani, a 100-km stretch of coastline (Map 1).



Source map: URT 1985
Department of Land and Survey
Zanzibar. (Z1,Z2,Z3,Z4, & Z5)

Map of Zanzibar showing the study area

The area was chosen, because tourist development has been intense in the past five years, and is planned to be continued. Saltwater intrusion has been reported at several places, and withdrawl is expected to increase due to population and tourism growth. In total, 24 villages and 58 hotels/ guesthouses are located in the study area.

During March/ April 1998, a questionnaire was administered to 32 tourist facilities. These represent a cross-section of the tourist infrastructure on the East Coast. The questionnaire included questions on water supply schemes and uses (totals and percentages of different uses), hotel size (number of beds), occupancy rates, prices, number of employees (foreign and Zanzibarian), and sewage systems. In total, 28 questionnaires were answered completely.

Tourist infrastructure on the East Coast can be divided in hotels and guesthouses. In this survey, guesthouses were defined as rather small units, mainly owned by Zanzibarians. These are foremost found within villages, where water is abstracted from local or private wells. Hotels, in contrast, are located outside the villages in uninhabited areas, have resort character, and belong to foreign investors. To meet water demands, local caves or wells have been developed. Both hotels and guesthouses abstract groundwater without any form of overall planning or control.

The hotels and guesthouses on the East Coast combine a capacity of about 2,570 beds (own observations; Commission for Tourism, 1998a). Their occupancy rates vary significantly. While guesthouses are bound to the touristic season, hotels often have contracts with tour operators in Europe, allowing for high annual occupancy rates of up to 80%. In general, though, occupancy rates appear to be far lower. Based on the results of this survey, the weighted average high seasonal occupancy rate for all guesthouses and hotels on the East Coast was found to be 72.1%. Note, however, that some guesthouses and hotels reported occupancy rates of 100%, which is less realistic. Table 1 summarizes data collected for hotels and guesthouses.

Tab.1: High seasonal water demand of hotels and guesthouses on the East Coast of Zanzibar

No.	Village	Hotel	Beds, total	Beds, occ.	Occup. rate (%)	Prices (US$)[1]	Water Use ($l\ d^{-1}$)		Sewage System
							(total)	(tourist)	
1.	Nungwi	Annex of Amaani	24	20	83	35	7,000	350	non-concreted tank
2.	Nungwi	Salehes Beach Bung.	12	12	100	20	2,000	167	concreted tank
3.	Nungwi	Kendwa Rocks	44	40	91	24	8,000	200	concreted tank
4.	Nungwi	Baraka Bungalows	27	22	81	40	6,000	273	piped into cave
5.	Nungwi	Ras Nungwi Hotel	60	36	60	130	14,000	389	concreted tank
6.	Nungwi	Safani Bungalows	22	20	91	30	4,000	200	non-concreted tank
7.	Nungwi	Paradise Beach	16	14	88	26	7,000	500	concreted tank
8.	Nungwi	Amaan Beach Bungalows	44	35	80	25	10,000	286	non-concreted tank
9.	Nungwi	Kigoma Beach Hotel	28	9	32	16	4,000	444	concreted tank
10.	Nungwi	Mnarani Beach Cottages	24	22	92	70	8,000	364	non-concreted tank
11.	Kigomane	Kigomane Beach Hotel	20	11	55	50	2,000	182	concreted tank
12.	Matemwe	Matemwe Bungalows	24	16	67	130	3,800	238	concreted tanks
13.	Klima Juu	Holiday Guest House	40	30	75	n.a.	7,000	233	n.a.
14.	Pwani Mchangani [2]	Mapenzi Hotel	128	83	65	180	45,000	542	non-concreted tank
15.	Pwani Mchangani [2]	Coral Reef Village	54	24	44	160	3,750	156	concreted tank
16.	North of Kiwengwa	Venta Club	276	200	72	160	400,000	2,000	concreted tank
17.	Kiwengwa	Francorosso	200	140	70	n.a.	80,000	571	concreted tank
18.	North of Pongwe	Pongwe Beach Hotel	20	15	75	80	2,000	133	n.a.
19.	Michamvi	Karafu Beach Resort[3]	200	200	100	130	90,000	450	piped in former well
20.	Pingwe	Blue Marine Club	144	54	38	n.a.	29,000	537	concreted tank
21.	Pingwe	Breezes[3]	140	98	70	n.a.	97,000	990	concreted tank
22.	Bwejuu	Twisted Palm Guesth.	12	10	83	20	2,000	200	non-concreted tank
23.	Bwejuu	Twisted Palm Bungalows	18	16	89	16	2,800	175	non-concreted tank
24.	Bwejuu	Palm Beach Inn	30	28	93	30	4,000	143	n.a.
25.	Bwejuu	Ndere Hotel	52	35	67	20	14,000	400	n.a.
26.	Paje	Ndame Village	46	40	87	26	4,000	100	non-concreted tank
27.	Paje	Paradise Beach Bung.	13	12	92	35	2,500	208	non-concreted tank
28.	Paje	Paje by Night	39	25	64	26	9,000	360	non-concreted tank
Total:		-	1,757	1,267	-	-	867,850 (755,850)[4]	685.0[5]	-

n.a.: data not available; occ.: occupied

1) Per double room and day; 2) Location South of Pwani Mchangani; 3) The Karafu Beach Resort uses 15,000 l of desalinated sea water per day, the Breezes uses only desalinated sea water; 4) Desalinated sea water subtracted; 5) Weighted average.

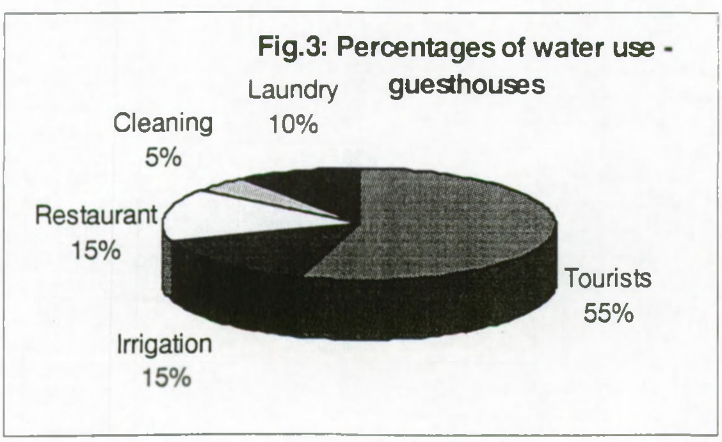
To calculate the daily per capita water demand in a hotel or guesthouse, the total amount of water used per day was divided by the number of tourists staying at the hotel or guesthouse that very day. For simplicity reasons, this method does not take into consideration the water demand of owners or employees.

Overall, per capita water demand varies extremely, ranging between 100-2,000 l d^{-1}. The weighted average was calculated at 685.0 l d^{-1}, foremost on account of the very high per capita demand of the Venta Club (2,000 l d^{-1}). 685.0 l d^{-1} is about 15 times the average daily demand of a local resident (Johnstone and Gössling, 1998).

The total number of beds of the 28 hotels and guesthouses investigated was 1,757. Out of these, on average 1,267 are occupied in high season (72.1% weighted occupancy rate). Calculated for all existing tourist facilities (about 2,570 beds), the total number of beds occupied on the East Coast in high season may presently be in the order of 1,853, entailing a water demand of approximately 1,269,305 l d^{-1} (at 685.0 l d^{-1} per tourist). Out of this sum, about 112,000 l are ocean water desalinated by the Breezes and the Karafu Beach Hotel.

In general, the average daily per capita water demand is far higher in hotels. In those tourist facilities defined as hotels in this survey (Ras Nungwi Hotel, Mapenzi Hotel, Venta Club, Francorosso, Karafu Beach Resort, Blue Marine Club, Breezes), daily water use per tourist amounted to 930.9 l (weighted average). In guesthouses, the equivalent was 247.5 l d^{-1}.

Within the tourist industry, water demand can be related to direct uses (taking showers, flushing toilets, etc.), and indirect uses (irrigation, swimming-pools, cleaning, washing, restaurant purposes). In figure 3, percentages of water use are given for hotels and guesthouses (in 5%-units).



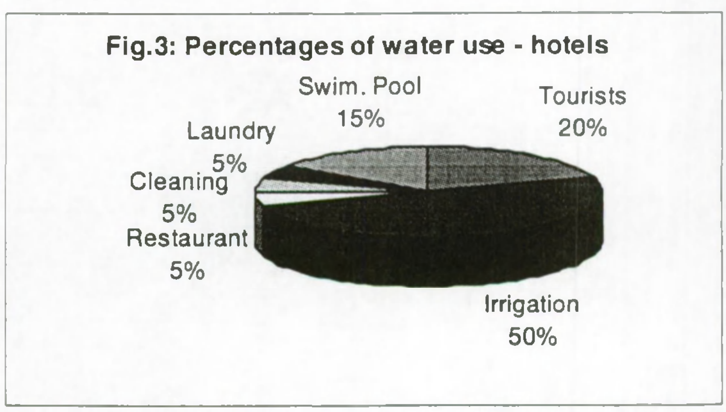


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Fig. 3: Percentages of water use - guesthouses and hotels

Hotels with extensive gardens use most water for continuous irrigation (50%), because the soils have a poor storage capacity, evaporation is high, and species planted are not adapted to arid conditions. In guesthouses, irrigation has only a proportion of 15%. In terms of total water use, hotels spend almost 465 l d^{-1} (weighted average) per tourist (t^{-1}) on irrigation, while in guesthouses the equivalent is about 37 l d^{-1} t^{-1}. The major proportion of water in guesthouses is spent for direct uses including taking showers, flushing the toilet, and the use of tap water (55%, 136 l d^{-1} t^{-1}), while this proportion is comparatively low in hotels, even though higher in absolute terms (20%, 186 l d^{-1} t^{-1}). The higher demand of tourists in resort hotels is due to, for example, additional showers taken at pools, more luxurious or better functioning bathroom facilities, etc. Swimming pools represent another important factor of water use, accounting for about 15% of the water demand of hotels (about 140 l d^{-1} t^{-1}). This is due to water renewal and high evaporation rates. Indirectly, swimming pools add to laundry, because additional towels are handed out to the guests. Guesthouses visited during the survey did not have swimming pools. Laundry in guesthouses accounts for about 10% (25 l d^{-1} t^{-1}) of the water used in guesthouses, and 5% in hotels (47 l d^{-1} t^{-1}), respectively. The higher water demand in hotels is a result of larger laundry quantities (staff uniforms, restaurant tissues, tourist cloths, etc.). Cleaning adds with 5% on the water demand in both guesthouses (12 l d^{-1} t^{-1}) and hotels (47 l d^{-1} t^{-1}). Again, the total amount is higher in hotels, because public areas and tourist rooms are cleaned frequently with water, while in guesthouses rooms are basically only swept with brooms. Restaurants in guesthouses use rather high quantities of water (15%, or 37 l d^{-1} t^{-1}), if compared to hotels (5%, 47 l d^{-1} t^{-1}).

To show the relation of hotel/ guesthouse size and the total daily water use, the number of beds (as an indicator for size) was plotted against water demand (fig.4).

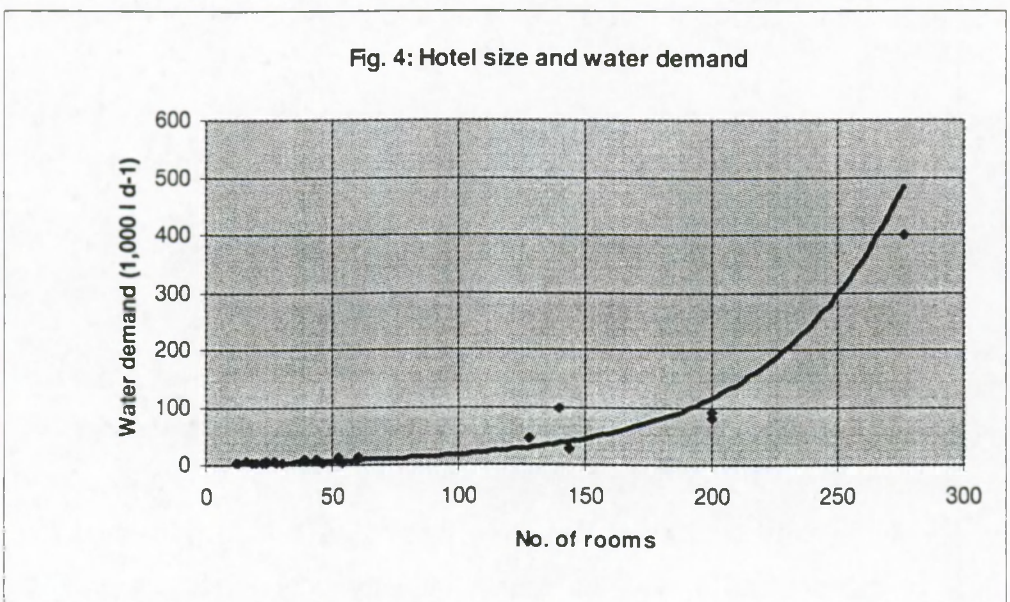

Fig. 4: Hotel size and water demand

The two variables have a good correlation (r=0.82). The graph shows that water use is growing exponentially with increasing hotel size. A possible explanation for this is that bigger hotels use more water for larger pools, and have more extensive irrigated gardens – the two major water consuming factors.

Sewage

Sewage from hotels and guesthouses is piped into septic tanks. These are not necessarily concreted as the survey revealed: out of 24 hotels and guesthouses, only 12 had fully concreted tanks, while the rest had open ones leaking into fissures and caves. One guesthouse piped its sewage into a cave, and one hotel into a former well. Treatment of any kind was generally not provided.

Future tourist development

Even though the number of tourist arrivals has grown rapidly in the past, future growth rates are expected to outpace those of the past. Accordingly, the construction of additional hotels is favoured.

As has been stated above, there are approximately 2,570 beds existing on the East Coast at present, but their number is planned to be increased to 8,060 by 2015 (MWCELE, 1993). Given the weighted average high seasonal occupancy rate found in this survey (72.1%), 5,811 tourists would then stay on the East Coast. This would entail a daily water demand of 3,980,535 l assuming no change in per capita demand (685.0 l d^{-1}). However, such a scenario has to be considered as rather conservative, as it is based on a the present mixture of hotels and guesthouses, while new buildings along the coast will be resort hotels, which have been shown to have higher per capita water demand, and possibly higher occupancy rates.

Halcrow (1994) reports that transportation of water to guesthouses and hotels causes losses in the order of 25% of the total amount (leakages, etc.). Such losses have to be included into considerations on water demand.

3. Discussion

It has been shown that tourism-related groundwater abstraction on the East Coast is substantial. Therefore, the question arises of up to which amount water can be withdrawn without negative consequences.

Basically, water resources on the island as a whole are said to be sufficient to meet the anticipated demands of the population and the tourist industry until 2015, but current abstractions are concentrated on single spots in areas on the East Coast, where recharge is low and where the karstic nature of the limestone makes it difficult to predict the safe yield (Halcrow, 1994). Consequences of over-use can be proceeding saltwater intrusion, land subsidence, and deteriorating groundwater quality (Dirks et al., 1989; Ukayli and Husain, 1988). Moreover, global warming and resulting sea-level rise could force saltwater intrusion in the future, enhancing the local effects of over-use (Haq, 1997). Ecologically, it is not known yet how groundwater use will influence ecosystem functionability, for instance by lowering the groundwater table below the rooting zone. Falling water tables might also impart effects on Zanzibar's National Park, the wetland Jozani Forest (Halcrow, 1994).

While over-exploitation has not yet been proven scientifically, there is evidence that present abstractions on the East Coast are unsustainable. In some areas, hotels or guesthouses reported that water had become slightly salty. In Nungwi, all local wells have become saline, making the village dependent on piped water. Here, piped water is available only half the year, which is partly due to the demand of guesthouses abstracting water from the same pipe that supplies the village. In consequence, local residents have to fetch freshwater from a well that is located more than 1 km outside the village. A similar situation has been reported for Uroa (Dahlin and Stridh, 1996).

Groundwater has been recognized as an important source for nutrient influx to coastal marine ecosystems, especially if it is subject to human activities like the construction of buildings with poor treatment facilities (e.g. Capone and Bautista, 1985; Johannes, 1980; Lapointe et al., 1990; Sewell, 1982; Valiela et al., 1992). On the East Coast of Zanzibar, poor treatment of waste-waters (deposition in former wells or caves, non-concreted septic tanks, etc.) has possibly increased the nutrient content of the groundwater. A study conducted by Johnstone (1998, pers. comm.) indicated greatly elevated nutrient levels in coastal aquifers adjacent to a number of villages and hotel complexes. This could indicate contamination of the groundwater by human activities and thus be a potential for low level chronic anthropogenic inputs to coastal water bodies.

In this survey, the amount of nutrient-containing sewage leaching into the groundwater was not estimated. For Mediterranean countries, however, it was assumed that 60% of tourist water consumption resulted in sewage in need of disposal (GFANC, 1997).

Tourism-related nutrient loads reaching nearshore waters are a combination of different organic and inorganic particles, often including chlorinated swimming pool water, and chemicals used to dissolve fats and oils, etc. (Ceballos-Lascurain, 1996; Johnstone and Suliman, 1998; Kuss et al., 1990). Depending on ocean conditions, currents, and according to their concentrations, these nutrients impart an effect on ecosystems, often in combination with, for example, the impacts of sedimentation, physical modifications like mining, destructive fishing practices or the alteration of fish communities. While it is very difficult to separate an individual factor as the sole force of degradation, it is clear that nutrients play a vital role, because coastal waters in the tropics are typically oligotrophic, and nutrient concentrations in groundwater can be considerably high compared to those of the receiving seawater (D'Elia and Wiebe, 1990; Johnstone and Suleiman, 1998; Valiela et al., 1990). Positive changes in nutrient content trigger increased primary production and growth of opportunistic macroalgae; they have a range of detrimental consequences for the structure and function of shallow coastal ecosystems (e.g. Bell, 1990; Hunte and Wittenberg, 1992; Sheppard, 1998; Tomascik and Sander, 1986; Valiela et al., 1990, 1992; Wilkinson, 1987).

By 2015, tourism will become the major factor of water abstraction on the East Coast, foremost because of the increase in tourist arrivals (Johnstone and Gössling, 1998). Additional pressure on water resources may result from the fact that the government intends to increase the standard of the guesthouses. Requirements include for example private bathrooms, possibly leading to higher per capita water consumption. Presently, 65% of tourist facilities do not fullfil the prerequisites of the Commission for Tourism (Mlingoti, 1998, pers. comm.). Future development is in favour of big hotel projects, which have an exponentially increasing water demand with size.

Water demand is highest in dry season, when recharge is very low, and may thus be an important factor in unsustainable groundwater abstraction. An additional risk factor is the El Niño phenomenon, which can severely influence rainfall, as has been shown in 1998, when March and April were unusually dry. In the light of this, and with increasing demand due to an expected doubling of the coastal population in 22-25 years time (MWCELE, 1995b), a precautionary water management approach should be taken. Such a strategy would have to internalize the environmental costs of water abstraction and sewage release (Sida/World Bank, 1997; for discussion see Garrod and Whitmarsh, 1995).

4. Management options

Current water abstraction schemes on the East Coast are likely to be less sustainable. Thus, and to reduce sewage in need of disposal, reduction of water use is a primary measure. Halcrow (1994) estimated that hotels should manage to keep the average daily consumption down to an equivalent of 200 l per bed. This estimate, though, was based on the assumption that average water use would be in the order of 300 l d^{-1} per tourist, a figure presently only reached by some of the guesthouses. For the Venta Club, for instance, this would mean a reduction by an order of magnitude.

However, there is no doubt that all tourist facilities could safe substantial amounts of water. As irrigation is the major factor for water use, composition and structure of the gardens should be re-considered, turning to less extensive areas in need of irrigation and to more drought-resistant plants. Wastewater reuse under a controlled environment might be a viable option to supplement necessary irrigation, even though caution must be exercised to ensure its use without causing environmental and health hazards (Ukayli and Husain, 1988; UNEP, 1988). Another possibility might be to collect and store rainwater. Within the hotel or guesthouses, flow limiters on taps and showers could be installed, and lavatory cisterns be fitted with reduced flush option. Educational programmes for the staff, and informative signs on water scarcity addressing tourists could contribute as well to water reduction. Other measures should include the regular control of pipes to avoid losses due to leakages.

In the past, groundwater has been an open-access resource on Unguja Island. Even though hotels and most guesthouses are charged a monthly tax for water today, this does not take into consideration the quantities being abstracted. It is therefore necessary to introduce an incentive based strategy, leading to the taxation of the quantities of water being abstracted, which would increase the interest in saving water by far. Therefore, meters should be installed on all major pipes to control the withdrawl of water. Water saving measures would also help to solve the problem of sewage. For unavoidable sewage, treatment with closed cycles of organic matter flow should become the standard (Appasamy, 1993). To minimize the danger of upconing, the pressure on single withdrawl spots should be reduced by increasing the number of wells, and distributing these in a larger area.

Technical options include abstraction of water further inland, which would entail major costs for new pipline-systems. This is at present not considered by either the government or the tourist industry. Desalination, as practised by the Breezes, is expensive, increases the dependency on imports (fuel), and entails environmental costs due to the emission of ecologically relevant trace gases contributing to, for instance, global warming and atmospheric nitrogen deposition (Nixon et al., 1986; quoted in Valiela et al., 1990). The discharge of brine could lead to locally raised levels of salinity with negative effects for corals (Kühlmann, 1988). Therefore, it is not considered to be a feasible solution.

Given the projected development in tourism, even the less realistic reduction to an equivalent of 200 $l\ d^{-1}$ per tourist would lead to water abstraction in the order of almost 1,162,200 $l\ d^{-1}$ in high season by 2015. Subtracting desalinated water, this is about as much as used today, which already proved to be less sustainable. Therefore, it is recommended to re-consider the plans for future tourist development.

5. Putting results into context

The major economic sectors on the East Coast, tourism and fishing, depend directly on coastal environmental resources: coral reefs, beaches, mangroves. Indirectly, they also rely on the ecosystem services that the coastal environment provides, sinks for wastes and residues, storage of sediments and organic carbon, physical protection against storms, breeding grounds, and the provision of food and building materials (e.g. Peterson and Lubchenco, 1997; Spurgeon, 1992).

To fully understand the role of tourism, all impacts of this industry on the ecosystems have to be taken into consideration, because coastal ecosystems are interconnected, and the condition of one of these cannot be seen in isolation from that of others (Sheppard, 1998).

It has been shown that tourist development has increased the pressure on water resources with negative consequences for both local residents and ecosystems. Other changes are on account of coastal sand and limestone quarrying, and the conversion of large areas for infrastructure development, leading to loss of habitat, decreased species abundance and diversity (see e.g. Dulvy et al., 1995; Kaufman and Dayton, 1997; Ngoile and Horrill, 1993).

Zanzibarian coral reefs show signs of overfishing and degradation, which might restrict their functioning (Muhando, 1998; Msuya, 1998). Tourism has been contributing to this development both directly and indirectly. Apart from trampling, breakage, picking, anchor damage, and buying of corals and shells (e.g. Liddle and Kay, 1987), tourism is as well responsible for an increasing demand of seafood (Scholz, 1995). On account of this, the local economy has been disrupted, and prices for fish have grown significantly in the villages, excluding part of the population from the market (Andersson, 1998). Moreover, despite of declining fish catches hunting intensity has increased, because a more time-intensive hunt will be compensated for by higher prices paid by the hotels. In some cases, fishermen have even turned to destructive fishing activities to increase catches (dynamite fishing, poisoning, spearing, and the use of fishing nets with small mesh sizes; Msuya, 1998). Seafood sold to hotels represents a loss in protein for the local population, even though it was already reported in 1995 (MWCELE, 1995b) that 60% of all children in Zanzibar suffer from malnutrition. Meat and eggs are other sources of protein increasingly lost to the tourist industry (MWCELE, 1995a). Further tourism growth will deepen this use conflict.

Mangroves are another central ecosystem being destroyed for burning of lime, fuel wood, and poles for construction (Khatibu, 1998). Deforestation of mangroves increases the rate of erosion that deposits sediments on coral reefs, contributing to the degradation of this ecosystem. Removal and clearing of vegetation on the beach-front has forced beach erosion

(Dahlin and Stridh, 1996). Again, the tourist industry is a major factor behind this development.

Tourism is as well responsible for a number of social and economic changes that have resulted in shifts in the economic base of the area and changes in land ownership patterns. Culturally, changes in values, shifts in lifestyles, and increase in crime rates have been observed. The traditional village life is changing rapidly (Andersson, 1998; Dahlin and Stridh, 1996; Khatib, 1996).

On a more global scale, tourism contributes substantially to resource depletion. On the East Coast, fossil fuel is used for cars, trucks, boats, and generators. The energy demand for generators of the Venta Club alone, for instance, amounts to 1,500 l of fuel per day, or 7.5 l d^{-1} per tourist. The use of fossil fuels for air-transport and imports has to be added up on top of this.

6. Concluding remarks

Tourism has become an important economic sector of Unguja Island. Benefits include hotel and restaurant earnings, support to other economic and leisure sectors, foreign exchange earnings, and employment (Dahlin and Stridh, 1996; Johnstone et al., 1998). At the same time, tourist development has influenced both local communities and ecosystem functioning, often with negative consequences.

The groundwater-survey on the East Coast revealed that water is abstracted in substantial quantities, and possibly beyond sustainable levels, leading locally to saltwater intrusion and upconing. Sewage discharge leads to nutrient enrichment in nearshore waters, and might contribute to changes in ecosystem composition and functioning.

Other impacts of tourism include the conversion of natural areas for infrastructure development, and the high demand for building materials like sand, lime, poles, etc. Sand quarrying and deforestation of mangroves enforce coastal erosion. Tourists contribute to reef degradation and destruction both directly (trampling, breaking, buying, and collecting reef species), and indirectly (nutrient release, demand of construction material, food, fossil fuels). These threats add on external stresses like climate change (e.g. Smith and Buddemeier, 1992; Wilkinson, 1987), which are partly result of tourist activities themselves (Gössling, in prep.).

One of the major changes forced by tourism is the shift in local resource-use patterns. Historically, local communities have been depending on material and food provided by the

local environment. This dependency on adjacent ecosystems ensured rather sustainable resource-use practices, supported by profound knowledge of the behaviour of complex ecological systems accumulated over historical time (see e.g. Gadgil et al., 1993).
On the East Coast of Unguja Island, knowledge of unsustainable practices and reasons for degradation of ecosystems is widely spread (Msuya, 1998), and mechanisms of self-regulation and control have existed in many areas (Jiddawi, 1998). Today, tourism forces the turning away from sustainable use practices and traditional regulation systems, because income generation for those employed in this industry is no longer directly dependent on the state of the ecosystems. Tourism has also spread the idea that resources can be substituted by imports, and has turned marine resources into commodities that were traditionally only exploited for subsistence. This way, societal change has been initiated, resulting in vanishing communal property rights and control systems, and turning ecosystems into open access regimes. Local residents on the East Coast are increasingly torn between the requirements of their traditional systems and modernity, emphasizing cash economy and individual benefit.

A number of studies have shown that tourism can generate income through non-consumptive resource-uses like diving and snorkelling, or outweigh the opportunity costs of conservation or less exploitative uses (Agardy, 1993; Cesar, 1997; Dixon, 1993; Dixon et al., 1993; White and Dobias, 1991). However, such a tourism requires the acceptance of limits to development in terms of physical, social, economical, and perceptional carrying capacities (O'Reilly, 1986; see also Davis and Tisdell, 1995; Tisdell, 1991).
On the East Coast, there is rising concern that destruction of coral reefs has forced coastal erosion, and might make the island less attractive for tourists (Msuya, 1998). With awareness of the importance of ecological issues about to emerge in the tourist industry, and the legal basis to force changes being contained in the National Land Use Plan and the Tourism Zoning Plan (Dahlin and Stridh, 1996), there is a clear chance to restructure tourism in a more sustainable way. For this, tourist numbers should be stabilized on present levels or even reduced to establish a small-scale, high value tourism that is supported by the islands' image as a unique destination. This would guarantee stable income in the long run, and reverse the trend of competition-related price-dumping between hotels that has already occured. Clearly, a continuation of present development might lead to the destruction of the environmental base on which the tourist industry is founded (Scholz, 1995; see also Sida/ World Bank, 1997; Vorlaufer, 1996).
In the medium-term future, government and tourist industry need to involve local residents in decision-making and benefit sharing, both to convince local people that the coastal resources are valuable for tourism (and thereby the community) when intact, and to provide a sound information basis on the consequences of tourism and the need of mitigation

strategies (Agardy, 1993; McManus et al., 1988; Stewart, 1993; Vorlaufer, 1997; Wilkinson, 1992). Traditional knowledge of ecosystem functioning should be reinforced; in fact, a successful implementation of more sustainable resource-use practices seems to be based on the continuation and re-establishment of traditional, local use systems and societal structures (Gadgil et al., 1993; Johannes, 1978, 1981; Veitayaki, 1998).

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Leaf production, shoot demography, and flowering frequency of the seagrass *Thalassodendron ciliatum* (Cymodoceaceae) along the East African coast

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Abstract

Several characteristics of *Thalassondendron ciliatum* populations were evaluated by a large scale sampling effort along the Kenyan coast and Zanzibar Island, with the aim to study spatial variability. A reconstruction technique, which makes use of scars left by abscised leaves and flowers, was employed to determine leaf production, shoot demography and flowering frequency of a number of *T. ciliatum* populations. Eight subtidal back-reef lagoons were sampled. Furthermore, samples were collected in an exposed subtidal site, intertidal rock pools, and a subtidal mangrove bay. Leaf production rates ranged from 33 to 57 leaves shoot^{-1} year^{-1}. Differences could not be related to habitat type. Median ages of the populations varied almost six fold from 0.34 year to 1.93 years. The population of the intertidal rock pools showed the lowest shoot age and a small shoot size. The rock pools may experience high temperatures and light intensities. Thus, they presumably provide a more stressful environment for *T. ciliatum* than the lagoons or the bay. The mangrove-bay population showed internodal lengths of almost 7 cm, stem lengths of almost 90 cm and leaf life spans of ca. 45 days. The stem values were two to four fold longer, and leaf life spans were 10 to 50 % shorter than those at the other sites. This investment in vertical rhizome growth at the expense of leaf maintenance is probably caused by inferior light conditions in the mangrove bay compared to the other locations. Shoot recruitment and mortality rates differed significantly among sites. Both rates showed a decline with increasing median age, suggesting a relation with time after colonisation. All meadows in the present study were either expanding or in steady state. This suggests that, even though some sites were located near accumulations of beach hotels, all populations appeared to be healthy. Flowering frequencies were generally low. In addition, seedlings were not found in our study. These results indicate that sexual reproduction is of minor importance for the permanently submerged *T. ciliatum* populations, which reduces the ability to adapt to changes.

Keywords: Seagrass; Demography; East Africa; Flowering; Population dynamics; *Thalassondendron ciliatum*

1. Introduction

In the tropics, shallow coastal areas are characterised by extensive seagrass meadows. The seagrass beds are found in lagoons behind coral reefs that fringe the coast, in mangrove bays or in estuaries. The seagrass habitats provide food and shelter for a variety of other organisms, including commercially important fish species, and thus constitute an important component of the nearshore ecosystem (Nienhuis *et al.*, 1989; Marguilier *et al.*, 1997). Increased growth of the human population in tropical coastal zones puts pressure on seagrass functioning (Johnson and Johnstone, 1995). At the same time, the local economy often depends on the presence of seagrass biotopes (Pointer *et al.*, 1989). Conservation of these habitats is therefore recommended.

In many tropical seagrass species, knowledge on spatial variability in population dynamics is scarce. *Thalassodendron ciliatum* (Forsk.) den Hartog is a very common seagrass species in the Red Sea, the western Indian Ocean and the tropical part of the Indo-Pacific region (den Hartog, 1970). Its wide distribution makes it a suitable species to study spatial variability in population dynamics. *T. ciliatum* has horizontal as well as vertical rhizomes. The horizontal rhizomes show a distinct pattern in branching; every fourth node a new vertical rhizome or shoot is produced. A cluster of leaves is present at the top of each living stem. New leaves are constantly being produced and old leaves are shed. Leaf scars from shed leaves remain visible on the stems. Thus, the total number of leaves produced by a shoot can be counted. Studies on other seagrass species showed that internodal lengths between two successive leaf scars are longer during fast growth and smaller during periods of slow growth (e.g. Duarte and Sand-Jensen, 1990). Variability in internodal length reflects seasonal variability in plant growth (Duarte *et al.*, 1994). Duarte *et al.* (1996) used the seasonal signal on *T. ciliatum* stems to determine the leaf production rate, and consequently the age of the shoots. Assessment of seagrass dynamics, using this so called reconstruction technique (Duarte *et al.*, 1994), can reveal whether a population is expanding, declining or in steady state. The advantage of the reconstruction technique is that one can forecast meadow development from a single visit to the study site. However, the method must be used with caution, because determination of recruitment is based on the proportion of shoots older than 1 year. Therefore, meadow development can only be determined for the next year.

This paper presents several characteristics, such as leaf-production rates, shoot demography, and flowering frequency for a number of *T. ciliatum* populations along the East African coast. The data were collected with the reconstruction technique and provide an indication of the status of different *T. ciliatum* meadows in relation to their location.

2. Material and methods

In March 1997, six back-reef lagoons along the southern part of the Kenyan coast were sampled and in February 1998 sampling was carried out at five sites on Zanzibar Island: three back-reef lagoons, one site that was not sheltered by a reef and one mangrove bay (Fig. 1). *Thalassodendron ciliatum* is a common species in this part of East Africa. The tidal range is 4 m at spring tide and 1 m at neap tide. All sampling sites were subtidal and located at the same depth (1.5 m below 0 Chart Datum, or 1.5 m below the lowest water level during an extreme spring tide), except for one of the lagoons on the Kenyan coast (Vipingo), where the site was intertidal (1.2 m above 0 Chart Datum) and the samples were collected in permanently submerged pools in the reef flat. At each site, samples of *T. ciliatum* shoots were collected at two to three different locations that were 30 to 120 m apart. Clumps of vertical shoots together with attached horizontal rhizomes were randomly removed from the sediment with a knife. When *T. ciliatum* occurred in patches, collection of shoots was restricted to the middle of the patches.

The leaf-production rate, age structure, recruitment and mortality rate of the different *T. ciliatum* populations were determined following Duarte *et al.* (1994). On minimally 100 living shoots per sample, the number of leaf scars from shed leaves were counted starting from the insertion point of the vertical rhizome in the horizontal rhizome, or in the vertical rhizome in case of a side branch. In addition, the number of attached leaves was counted. Leaves of which the length was smaller than 1 cm (sheath excluded) were not included in the countings. The shoots were also examined for the presence of standing flowers or distinct scars left by the flowers on the stems to determine the flowering frequency and the age at which the shoot flowered (Duarte *et al.*, 1994). At Nyali, Kenyatta and Watamu, only the shoots collected for determination of the leaf production rate were inspected for flower scars. At the other sites all shoots were examined for flower events.

For each population, annual leaf-production rates were determined using the reconstruction technique. Per sampling site, 10 to 15 vertical shoots with largest number of leaf scars (the oldest shoots) were selected. The number of standing leaves was recorded and the sequence of distance between two successive leaf scars (internodal length) was measured using a dissecting microscope at a magnification of 16x fitted with a calibrated scale (Kenyan samples) or with a 50-mm macro lens connected to a calibrated LEICA Image Analysis System (samples from Zanzibar Island). The sequence of vertical internodal lengths were smoothed (five-internode running average) to exclude short-term variability. The internodal lengths of similar age on the shoots were averaged to obtain the mean variability in the internode length of the sample. The average sequence of internodal lengths was examined for the presence of annual signals, i.e. minimum and maximum internodal lengths. The number of leaf scars in a year cycle was considered to represent the number of leaves produced per year. The shoot leaf production was calculated as the product of the number of leaves produced annually per shoot and the mean weight of fully developed leaves. Earlier work showed that the 4th leaf can be considered representative of a mature leaf, while at the same time epiphytic overgrowth is still fairly low (Hemminga *et al.*, 1995). Of each sample, ten 4th *T. ciliatum* leaves were cut at the break point with the sheath, and cleaned with paper to remove any epiphytes. Prior to weighing, the leaves were dried at 60 $^{\circ}$C for two days. The plastochrone interval (P.I.), or the average number of days between the formation of two sucessive leaves, was calculated from the leaf-production rate. To determine the average life span of the leaves, the plastochrone interval of the oldest shoots was multiplied by the number of standing leaves on those shoots. Maximal stem lengths of *T. ciliatum* were determined from the sum of internodal lengths on the longest shoots.

The age of the *T. cilatum* shoots expressed as total number of leaves produced (leaf scars plus attached leaves) was converted to years by dividing this value by the number of leaves produced per year. Per sample, the median shoot age was calculated. All *T. ciliatum* shoots were separated into age classes of 0.5 years to obtain the age distribution per sample. Exponential shoot mortality rates (*M*, In units yr^{-1}) were estimated as the slope of a linear regression fitted to the natural log-transformed age distribution using the equation:

$$N_t = N_0 e^{-Mt}$$

where N_0 and N_t are the number of shoots present at times 0 and t. The calculation of mortality rates is preferably based on the age distibution of dead shoots. However, in our study, this method was hampered by the fact that old shoots tended to be broken. In the absence of evidence that shoot mortality is age dependent, the use of age distributions of living shoots instead of the distribution of age-at-death is recommended as an alternative method to calculate mortality rates (Duarte *et al.*, 1994; Durako and Duarte, 1997). Annual shoot recruitment rates (R, In units yr^{-1}) were calculated from the proportion of living shoots older than one year using the equation:

$$R = \ln\sum_{t=0}^{\infty} N_t - \ln\sum_{t=1}^{\infty} N_t$$

in which $\sum_{t=0}^{\infty} N_t$ is the total number of shoots and $\sum_{t=1}^{\infty} N_t$ the number of shoots older than 1 year in the age-distribution samples.

A one-way analysis of variance (ANOVA) was used to test the effect of sampling site on *T. ciliatum* variables (Sokal and Rohlf, 1995). The significance of relationships between different *T. ciliatum* variables was determined with linear regression analyses (Sokal and Rohlf, 1995). Prior to each analysis, the data were tested for heteroscedacity with a Bartlett's test for homogeneity of variances (Sokal and Rohlf, 1995). Data that scored as significant were log-transformed, which yielded non-significant results in Bartlett's test. A Tukey-Kramer procedure was used as a post-hoc test for significance of differences between populations (Sokal and Rohlf, 1995). A significance level of 0.05 was set in all tests. The statistical analyses were conducted using the STATISTICA programme (StatSoft Inc., Tulsa, Oklahoma).

3. Results and discussion

Thalassodendron ciliatum occurred both in monospecific and in mixed meadows. Extensive monospecific meadows of at least more than 500 m long were found in the back-reef lagoons at Nyali and Watamu. In the lagoon at Roka, *T. ciliatum* was also the only seagrass species, but here it occurred in small patches of 30 m wide in between rocky areas. All other sites had mixed populations where *T. ciliatum* patch size ranged from less than 1 m^2 to about 120 m in diameter. Co-occuring species were: *Thalassia hemprichii* (Ehrenb.) Aschers., *Syringodium isoetifolium* (Aschers.) Dandy, *Cymodocea serrulata* (R. Br.) Aschers. and Magnus., *Cymodocea rotundata* Ehrenb. and Hempr. ex Aschers., *Halodule uninervis* (Forsk.) Aschers., *Halodule wrightii* Aschers., *Halophila stipulacea* (Forsk.) Aschers., *Halophila ovalis* (R. Br.) Hook. F. and *Enhalus acroides* (L. f.) Royle. The highest number of species occurring together with *T. ciliatum* was observed in the lagoon at Kenyatta, where seven other species were counted. On Thursday Island in Papua New Guinea, a seagrass community with similar diversity as the present study was encountered. There, a total of eight other species co-existed with *T. ciliatum* (Johnstone, 1984). According to Den Hartog (1970) *T. ciliatum* is generally found in extensive and monotonous meadows. However, in the present study, *T. ciliatum* occurred mostly in mixed seagrass meadows.

Leaf production

An example of a clear pattern in the sequence of internodal lengths along a vertical stem of *T. ciliatum* is shown in Fig. 2. Internodes were very large near the insertion point with the horizontal rhizome. These are the first internodes that were produced. The large lengths of internodes produced at the initial stage of shoot development has been related to reduction of shading through rapid raising of the leaves on these young *T. ciliatum* shoots to the canopy level (Duarte *et al.*, 1996). Apart from the decline in internodal lengths as the shoot grows, the stem also showed rhythmic cycles in internodal lengths (Fig. 2). Two minima could be distinguished in a year. This pattern was demonstrated earlier for several other tropical seagrass species and is probably related to the variability in light conditions as a result of alternations between rainy and dry seasons (Duarte *et al.*, 1996; Vermaat *et al.*, 1995).

The average year pattern in internodal length of 10 to 15 stems per site was used to determine the number of leaves produced in a year. Most *T. ciliatum* populations showed two repetitive cycles. Thus, two estimates of leaf production were possible (arrows in Fig. 2). The vertical stems of Roka and Vipingo allowed only one estimate. Production rates ranged from 33 to 57 leaves shoot^{-1} yr^{-1} and showed fairly large variations within populations (Table 1). Thus, significant differences among sites were not found. The observed range of leaf-production rates encompasses other rates reported for *T. ciliatum* (Brouns, 1985; Hemminga *et al.*, 1995; Duarte *et al.*, 1996). Leaf production rates were lowest for the subtidal *T. ciliatum* population of the exposed site. Supposed increased physical disturbance of the exposed habitat may cause this difference. However, differences in exposure between lagoons and other coastal sites is probably not extreme. Seagrasses in the lagoons also experience strong water movements. This is due to the large tidal range of the East African region.

The leaf production rate of *T. ciliatum* was expressed in g DW $shoot^{-1}$ yr^{-1} by multiplication of the number of leaves produced with the weight of a mature leaf determined at each site. Leaf production rate was similar at most sites (2.0 to 3.1 g DW $shoot^{-1}$ yr^{-1}). Only one site in a back-reef lagoon showed a lower rate of 1.7 g DW $shoot^{-1}$ yr^{-1} which differed significantly from the two highest leaf-production rates found at two other lagoons (Table 1). Thus, the observed difference was not related to habitat or meadow type.

The vertical shoots of *T. ciliatum* showed large variability in distance between two successive leaf scars, which resulted in significant differences in average internodal length between sampling sites (Table 1). The longest internodal length (6.9 mm) was observed on shoots collected at Chwaka, the mangrove bay. Other differences were much smaller (range of 2.3 to 3.6 mm) and not affected by habitat or meadow type. E.g. larger internodal lengths were found on shoots from the rock-pool site (Vipingo), two lagoonal sites with monospecific *T. ciliatum* meadows (Nyali and Watamu), and the exposed coastal site with a mixed meadow (Nungwi). Maximal stem length of *T. ciliatum* varied widely from 20 cm in a back-reef lagoon on Zanzibar Island to almost 90 cm in the mangrove bay (Table 1). The latter stem length is much higher than the maximal stem length of 65 cm recorded for *T. ciliatum* by Den Hartog (1970). The large internodal lenghts and long shoots observed in the mangrove bay suggest a strong investment in vertical shoot elongation.

The number of standing leaves increased rapidly during the first year of life of a *T. ciliatum* shoot, and levelled off afterwards (Fig. 3). Apparently, young shoots do not allocate much energy to maintenance of their leaves. They invest more in vertical rhizome growth to reach the level of improved light conditions. Duarte and Sand-Jensen (1990) observed a similar increase in number of standing leaves and shoot lenght with increasing age for *Cymodocea nodosa* (Ucria) Aschers.. Habitat or meadow type did not influence the number of standing leaves on *T. ciliatum* shoots (Table 1).

The life span of the leaves was determined by multiplication of the leaf P.I. (the number of days between the formation of two successive leaves) of the oldest shoots, and the number of standing leaves on that shoot. Significant differences in leaf life span were observed between sites (Table 1). Life span was shortest at Chwaka, the mangrove site (46 days), and almost twice as long (90 days) at Watamu, a site in a back-reef lagoon in Kenya (Table 1). The short leaf life span found in the mangrove bay indicates that investment in stem growth occurs at the expense of leaf maintenance. In general, the leaf life span in Kenya and on Zanzibar Island was between 60 and 70 days. This is much higher than the leaf life span of 30 to 45 days observed for intertidal *T. ciliatum* populations (Bandeira, 1997; Johnstone, 1984). At intertidal sites, increased stess by desiccation may reduce the life span of the leaves.

When leaf life span is long, one would expect more standing leaves on the shoots. However, the present study showed no relation between leaf life span and number of standing leaves (linear regression $R^2 = 0.004$, $n = 11$, $p > 0.05$). This discrepancy may be caused by the fact that the number of standing leaves was calculated from a large sample of shoots, while the leaf life span was calculated from the P.I. for the oldest shoots only. As many shoots are less than one year old, determination of the P.I. for each individual shoot is not possible.

The most striking differences were observed for the mangrove bay population. There, we observed internodal lengths and stem lengths that were two to four fold longer, and leaf life spans that were 10 to 50 % shorter. Light availability in mangrove bays is usually less than in coastal lagoons. This is caused by the high concentration of humic acids in these waters (REFERENTIE?). For some additional samples, the weight distribution among stems and leaves was determined for the mangrove site Chwaka and two lagoonal sites, Tumbatu and Dongwe (Fig. 4). Results showed the highest relative stem weights at Chwaka. This is in accordance with the long internodes found at this site. Thus, the population in the mangrove area strongly invests in vertical shoot elongation, which is compensated by lower leaf growth and maintenace. This will rapidly raise the leaves to better light conditions.

Shoot demography

The age distribution of living *T. ciliatum* shoots showed different patterns at the different sites (Fig. 5). At five populations from different habitats, the highest fraction of shoots was less than 0.5 year old. In four other populations, most shoots were between 0.5 and 1.0 year old. The population in the back-reef lagoon at Tumbatu had the highest frequency for shoots that were aged 1.5 year. The population at Watamu had two peaks in the age distribution, one at 1.0 year old and one at 2.5 year old. Median ages of the populations varied almost six fold from 0.34 year to 1.93 years (Table 2). Maximum age showed a smaller variability from 1.75 years at Vipingo to 5.40 years at Watamu (Table 2). The low age of the population of the rock pools (Vipingo) may be caused by reduced development as a result of stress from higher water temperatures and light intensities. The maximal shoot age at Watamu was significantly different from all other sites except Tumbatu. These two populations can be considered the oldest.

Shoot recruitment and mortality rates differed significantly among sites (Table 2). Shoot recruitment and mortality rates were closely linked, i.e. when mortality rates were low, recruitment was low as well (linear regression $R^2 = 0.67$, $p < 0.001$). In addition, the rates were lower when the median age of the shoots was higher (linear regression between median shoot age and mortality $R^2 = 0.43$, $p < 0.01$, and between median shoot age and recruitment $R^2 = 0.40$, $p < 0.001$). Duarte and Sand-Jensen (1990) observed the same relations between median age, and recruitment and mortality rates for *Cymodocea nodosa*. They collected their samples along transects from the centre to the edge of a number of patches and could thus include patch development time in their analysis. Recruitment and mortality rates declined with increasing time after patch development (Duarte and Sand-Jensen, 1990). The development of a seagrass patch causes a reduction in current speed and an increase in organic mater content of the sediment (Fonseca *et al.*, 1982; Fonseca and Bell, 1998). Such habitat alterations can improve the growth conditions for the shoots and reduce mortality rates. In addition, as the bed ages, shoot recruitment rates may decline as a result of space limitation for rhizome extension (Duarte and Sand-Jensen, 1990). The same may be true for the *T. ciliatum* populations of the present study. The oldest populations were found at Tumbatu and Watamu and they had the lowest recruitment and mortality rates (Table 2). The low rates may indicate that these two populations were the earliest that were established in the area.

Recruitment rates were generally slightly larger than mortality rates (Table 2). The ratio between recruitment and mortality (R:M) can give an indication of the colonisation state of a population for the next year. The following assumptions are made: when R:M < 1 the meadow is in decline, when R:M > 1 the population is expanding, and when R:M = 1 the seagrass bed is in steady state. All populations in the present study were either expanding or in steady state (Table 2). At Nyali, Kenyatta and Diani the sampling sites were located close to densly populated areas with large numbers of beach hotels. Waste water discharge into the lagoon may threathen the health of the seagrasses. However, our results suggest that the *T. ciliatum* meadows were not declining at these sites.

Flowering frequency

T. ciliatum meadows can expand via horizontal rhizome growth and branching of vertical shoots, but the plants can also produce flowers. It was calculated that an average of 11 % of all inspected shoots had flowered (Table 3). In this case, the three sites at which only old shoots were examined were excluded. These old shoots will give an overestimation of the proportion of shoots flowering in the population. Differences between populations were large, ranging from 0.2 % to 21.9 % of the shoots, but significant differences between populations were not found (Table 3). This was caused by the fact that the variation in abundance of flowering shoots within the populations was also large, as indicated by high values for the standard errors (Table 3).

The flowering frequency is the number of flowering events per total number of leaves produced by all examined shoots. This frequency can be converted to years by dividing the total number of leaves produced with the number of leaves produced in a year (Table 3). Flowering frequency also showed large variations, both within and among popuations. The lowest frequency was observed at Dongwe, and was 0.01 flowers shoot^{-1} year^{-1} (Table 3), which means that, theoretically, a shoot will flower only once in every 100 years. As the maximal shoot age at Dongwe was 2.9 years (Table 2), most shoots at this site will never flower. Other sites at which the flowering frequency was lower than the maximal age of the shoots were Kiwengwa, Vipingo and Nungwi, with flowering events every 5.5, 2.9 and 3.1 years respectively. The higest frequency of 1.26 flowers shoot^{-1} year^{-1} was found at Chwaka, indicating that shoots flowered on average every 0.8 year. These results suggest that sexual reproduction is of minor importance for the studied *T. ciliatum* populations. Examination of the age at which a shoot flowered revealed the occurrence of well defined peaks at certain ages (Fig. 6). In most populations, the first peak was observed when the shoots were between 0.5 and 1 year old. This indicates that a maturation period is necessary to be able to flower. Similar maturation periods were observed for *Cymodocea nodosa* (9 months; Marbà and Duarte, 1995), *Cymodocea rotundata* and *Thalassia hemprichii* (0.5 to 1 year; Duarte *et al.*, 1997) and *Thalassia testudinum* Banks ex König (1 year; Gallegos *et al.*, 1992).

Most of the stems that flowered, did so more than once. The maximum number of flower scars on a single *T. ciliatum* stem was 21. This was observed on a stem that had produced 157 leaves. Flower scars tended to be clustered on the stems. In several cases, two or more of such clusters were found on a stem and the time elapsed between two flowering events could be determined (Table 3). The number of leaf scars between the means of these flower clusters was less than the number of leaves produced in a year (compare Tables 3 and 1). This indicates that the cycle in flower production was shorter than a year. In addition, the time elapsed between two flowering events was not proportional to the number of leaves produced (linear regression $R^2 = 0.10$, $p > 0.05$), suggesting that, within a year, the timing of flowering is not determined by the number of leaves produced, but by an external factor.

In Kenya, Cox (1991) observed that flowering of a *T. ciliatum* population in the low intertidal occurred at extremely low spring tides. Tides with differences of 3.7 m or more take place for three to four consecutive days each month in January, February, March, April and May and again in September, October, November and December (KBP tide table). In the present study, sampling was carried out in February and March. At several sites, flowers were visible on the stems just below the leaf clusters indicating that the latest flower formation took place 4 to 13 P.I. ago, or approximately 1.5 to 3 months earlier, i.e. in November or December. These results suggest that the subtidal populations also show cycles in flower production which are attuned to the occurrence of low spring tides. Indeed, going back in time along the stems, most flower scars were observed at specific times, indicated by peaks in the frequency distribution (Fig. 7). At Watamu, the peak at 2.5 years ago was higher than the peak at 1 year ago (Fig. 7). The age distribution of this site, however, showed that more shoots of 1 year old were present in the sample, than 2.5 year old shoots (Fig. 5). Thus, the results indicate a lower sexual effort during the last floweing event.

Cox (1991) explaines the timing of flowering by suggesting that, at extreme low tides, floating pollen can collide on the water surface with female stigmas emerging at the surface. The only population of the present study that was sampled at the intertidal level was located in rock pools that remained covered at low tide. The other populations were all located at 1.5 m below chart datum, i.e. 1.5 m below the water level at extreme low water spring. Thus, none of the studied populations will become exposed. Seedlings were not found in our study. Kuo and Kirkman (1990) studied seedlings collected from subtidal populations of *T. pachyrhizum* den Hartog growing at 4 to 27 m depth in Australia. Apparently, this closely related species is able to produce seedlings without emerging at the water surface. Why the East African subtidal *T. ciliatum* populations invest in flower production without succesful reproduction remains to be explained.

Summarizing, this paper presents the first large scale sampling effort on the East African coast to evaluate the status of *T. ciliatum* meadows. All populations in the present study appeared to be either expanding or in steady state. This suggests that the environmental quality is still suitable for seagrass development, which is indicative of a healthy ecosystem. The lack of sexual reproduction may imply the presence of few genotypes, which reduces the ability to adapt to changes.

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Table 1. Average (± SE), leaf production rates, internodal lengths, maximal stem lengths, number of standing leaves, and leaf life spans for the *Thalassodendron ciliatum* populations studied (msl = Kenyan mainland subtidal back-reef lagoon, isl = Zanzibar Island subtidal back-reef lagoon, ise = Zanzibar Island exposed subtidal site, mil = Kenyan mainland intertidal rock pools in lagoon, ism = Zanzibar Island subtidal mangrove bay, * = monospecific meadow). Probability values from one-way analysis of variance to test for significant differences among populations are reported (ns is not significant). Populations that share the same letter in superscript do not differ significantly from each other (Tukey-Kramer comparison test). When SE values are lacking the variable only has one value and is not included in the statistical analysis.

Population	No. of leaves produced (shoot^{-1} yr^{-1})	Leaf P.I. (d)	Leaf production (g DW shoot^{-1} yr^{-1})	Internodal length (mm)	Maximal stem length (cm)	Number of standing leaves on 1 yr old stem	Leaf life span (d)
Nyali (msl*)	43.0 ± 3.0	8.5 ± 0.6	2.2 ± 0.1 ^{ac}	3.6 ± 0.2 ^{a}	40.2 ± 1.9^{beg}	6.9	63.4 ± 3.6 ^{abcdefgh}
Watamu (msl*)	38.0 ± 6.0	9.8 ± 1.6	2.4 ± 0.2 ^{ac}	2.9 ± 0.1 ^{ad}	54.0 ± 2.1^{a}	7.8	90.4 ± 9.7^{c}
Kenyatta (msl)	41.5 ± 2.5	8.8 ± 0.5	2.3 ± 0.1^{ac}	2.4 ± 0.1^{d}	27.7 ± 0.8^{defhi}	6.3	69.5 ± 3.1 ^{abcdefg}
Roka (msl*)	42.0	8.7	2.6 ± 0.1^{ac}	2.3 ± 0.1^{d}	23.7 ± 0.8^{dfhi}	6.9	67.3± 9.9 ^{abcdefgh}
Diani (msl)	47.0 ± 3.0	7.8 ± 0.5	2.9 ± 0.2^{a}	2.7 ± 0.2^{bd}	35.2 ± 0.9^{eghi}	7.4	63.1 ± 3.0^{d}
Kiwengwa (isl)	34.0 ± 4.0	10.9 ± 1.3	1.7 ± 0.1^{bc}	2.5 ± 0.1^{d}	20.5 ± 1.5^{h}	6.8	67.0 ± 4.2 ^{e}
Tumbatu (isl)	43.0 ± 5.0	8.6 ± 1.0	2.6 ± 0.2^{ac}	2.4 ± 0.1^{d}	37.1 ± 1.6^{gh}	7.2	59.8 ± 2.4 ^{abdefgh}
Dongwe (isl)	51.5 ± 1.5	7.1 ± 0.2	3.1 ± 0.2^{a}	2.6 ± 0.1^{d}	30.9 ± 2.0^{ghi}	7.2	51.0 ± 3.9 ^{abdefh}
Nungwi (ise)	33.0 ± 3.0	11.1 ± 1.0	2.0 ± 0.3 ^{ac}	3.0 ± 0.2^{ad}	32.4 ± 1.5^{bdeghi}	7.3	71.8 ± 6.2^{g}
Vipingo (mil)	57.0	6.4	2.5	3.6 ± 0.3^{ab}	26.8 ± 0.8^{hi}	8.0	60.8 ± 6.4 ^{abdefgh}
Chwaka (ism)	51.5 ± 8.5	7.3 ± 1.2	2.6 ± 0.4^{ac}	6.9 ± 0.4^{c}	87.4 ± 3.0^{c}	7.3	46.5 ± 2.2 ^{h}
p of ANOVA	ns	ns	< 0.01	< 0.01	< 0.01		< 0.0001

Table 2. Average (± SE) median and maximum shoot age, shoot recruitment and mortality rate and the ratio between recruitment and mortality of the *Thalassodendron ciliatum* populations studied (msl = Kenyan mainland subtidal back-reef lagoon, isl = Zanzibar Island subtidal back-reef lagoon, ise = Zanzibar Island subtidal exposed site, mil = Kenyan mainland intertidal rock pools in lagoon, ism = Zanzibar Island subtidal mangrove bay, * = monospecific meadow). Probability values from one-way analysis of variance to test for significant differences among populations are reported (ns is not significant). Populations that share the same letter in superscript do not differ significantly from each other (Tukey-Kramer comparison test).

Population	Median shoot age (yr)	Maximum shoot age (yr)	Shoot recruitment rate R (ln units yr^{-1})	Shoot mortality rate M (ln units yr^{-1})	R:M
Nyali (msl*)	0.53 ± 0.02^{acde}	2.59 ± 0.08^{a}	1.35 ± 0.11^{abdefh}	0.75 ± 0.02^{ab}	1.82 ± 0.19
Watamu (msl*)	1.93 ± 0.24^{b}	5.40 ± 0.04^{b}	0.39 ± 0.03^{c}	0.26 ± 0.01^{b}	1.52 ± 0.10
Kenyatta (msl)	0.71 ± 0.11^{acde}	2.72 ± 0.37^{a}	1.02 ± 0.14^{bdefhg}	0.51 ± 0.09^{ab}	2.10 ± 0.31
Roka (msl*)	0.73 ± 0.08^{acde}	2.50 ± 0.08^{a}	1.31 ± 0.22^{abdefh}	0.70 ± 0.22^{ab}	2.22 ± 0.55
Diani (msl)	0.47 ± 0.08^{ade}	2.87 ± 0.71^{a}	1.88 ± 0.26^{abehi}	0.94 ± 0.28^{ab}	2.23 ± 0.38
Kiwengwa (isl)	0.95 ± 0.03^{ace}	2.64 ± 0.51^{a}	0.82 ± 0.05^{d}	0.86 ± 0.13^{ab}	0.97 ± 0.10
Tumbatu (isl)	1.10 ± 0.02^{c}	3.96 ± 0.17^{ab}	0.53 ± 0.02^{cg}	0.48 ± 0.09^{ab}	1.17 ± 0.19
Dongwe (isl)	0.71 ± 0.10^{acde}	2.91 ± 0.63^{a}	1.22 ± 0.25^{h}	0.73 ± 0.06^{ab}	1.68 ± 0.31
Nungwi (ise)	0.88 ± 0.06^{acde}	2.71 ± 0.62^{a}	1.00 ± 0.19^{abdefgh}	1.02 ± 0.37^{ab}	1.13 ± 0.22
Vipingo (mil)	0.34 ± 0.04^{d}	1.75 ± 0.61^{a}	3.67 ± 1.27^{i}	1.83 ± 0.54^{a}	1.97 ± 0.11
Chwaka (ism)	0.57 ± 0.07^{e}	3.05 ± 0.24^{a}	1.17 ± 0.10^{abdefh}	0.67 ± 0.10^{ab}	1.76 ± 0.12
p of ANOVA	< 0.0001	< 0.01	< 0.0001	< 0.05	ns

Table 3. Average (± SE) abundance of flowering shoots, flowering frequency and flowering timing of the *Thalassodendron ciliatum* populations studied (msl = Kenyan mainland subtidal back-reef lagoon, isl = Zanzibar Island subtidal back-reef lagoon, ise = Zanzibar Island subtidal exposed site, mil = Kenyan mainland intertidal rock pools in lagoon, ism = Zanzibar Island subtidal mangrove bay, * = monospecific meadow). Probability values from one-way analysis of variance to test for significant differences among populations are reported (ns is not significant). When SE values are lacking the variable only has one value and is not included in the statistical analysis. ** At Nyali, Kenyatta and Watamu, only the oldest shoots, that were collected for determination of the leaf production rate, were inspected for flower scars. The old age of these shoots results in an overestimation of the proportion of flowering shoots and flowering frequency. Nd = no data.

Population	Abundance of flowering shoots (% of total # shoots)	Flowering frequency (# flowers $shoot^{-1}$ yr^{-1})	Distance between flower clusters (# leaf scars)
Nyali (msl*)	26.1**	0.46**	Nd
Watamu (msl*)	95.4**	0.25**	Nd
Kenyatta (msl)	39.4**	0.40**	Nd
Roka (msl*)	14.6 ± 8.4	0.68 ± 0.14	31.0
Diani (msl)	5.6 ± 4.9	0.44 ± 0.41	28.7 ± 3.3
Kiwengwa (isl)	4.9 ± 4.9	0.18 ± 0.18	22.6
Tumbatu (isl)	21.0 ± 4.9	0.50 ± 0.12	26.8 ± 0.8
Dongwe (isl)	0.2 ± 0.2	0.01 ± 0.01	23.5
Nungwi (ise)	15.5 ± 8.3	0.32 ± 0.29	20.7 ± 1.3
Vipingo (mil)	2.6 ± 2.6	0.35 ± 0.35	24.1
Chwaka (ism)	21.9 ± 5.0	1.26 ± 0.15	28.3 ± 1.7
p of ANOVA	ns	ns	ns

Figure legends

Fig. 1. Map of study sites along the Kenyan coast and on Zanzibar Island.

Fig. 2. Sequence of internodal lengths recorded for the three oldest *Thalassodendron ciliatum* shoots sampled at Diani, Kenya.

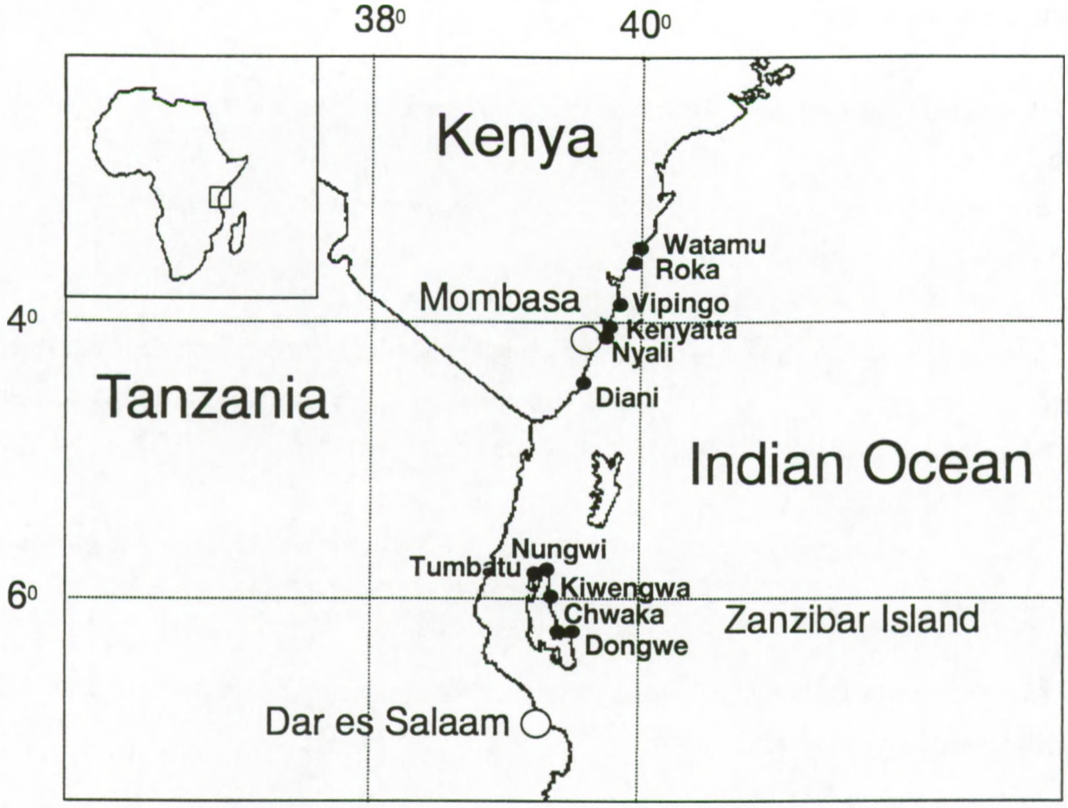
Fig. 3. Relation between shoot age (expressed as total number of leaf scars and attached leaves) and number of standing leaves for *Thalassodendron ciliatum* shoots sampled at Nungwi, Zanzibar Island. Regression equation: $y = 1.5 \ln(x) + 1.9$, $R^2 = 0.66$.

Fig. 4. *Thalassodendron ciliatum* stem weight divided by leaf-cluster weight for shoots of different ages (indicated by the number of internodes on each stem) for Chwaka, Tumbatu and Dongwe.

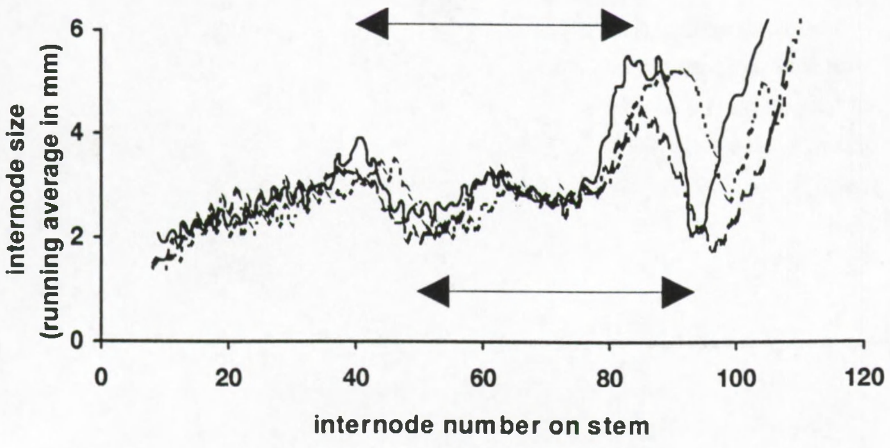
Fig. 5. Shoot age structure of living shoots of different *Thalassodendron ciliatum* populations along the Kenyan coast and on Zanzibar Island.

Fig. 6. Shoot age at time of flowering for different *Thalassodendron ciliatum* populations along the Kenyan coast and on Zanzibar Island.

Fig. 7. Time elapsed since flower was produced for different *Thalassodendron ciliatum* populations along the Kenyan coast and on Zanzibar Island.



Kamermans *et al.* Fig. 1



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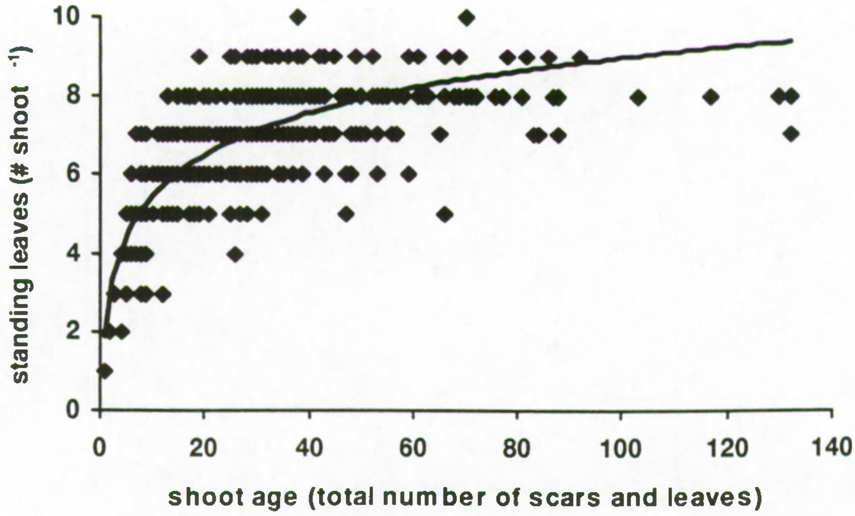
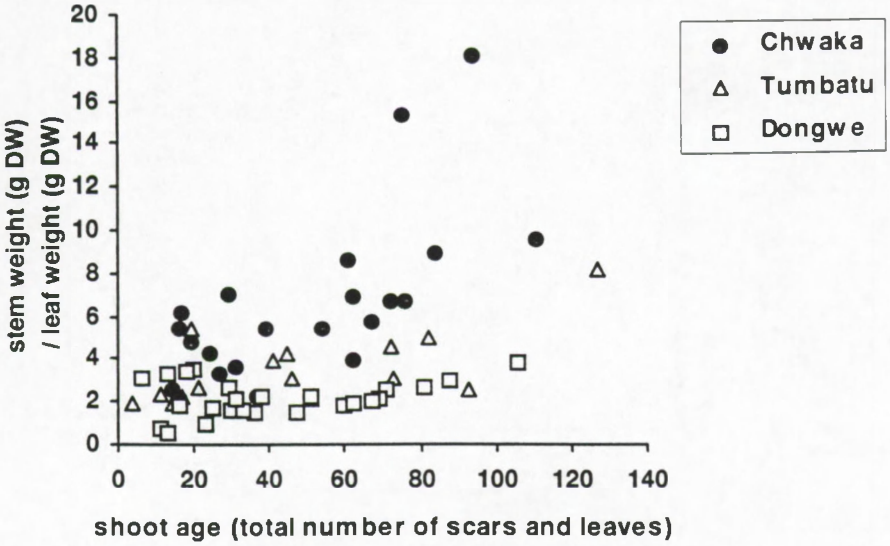
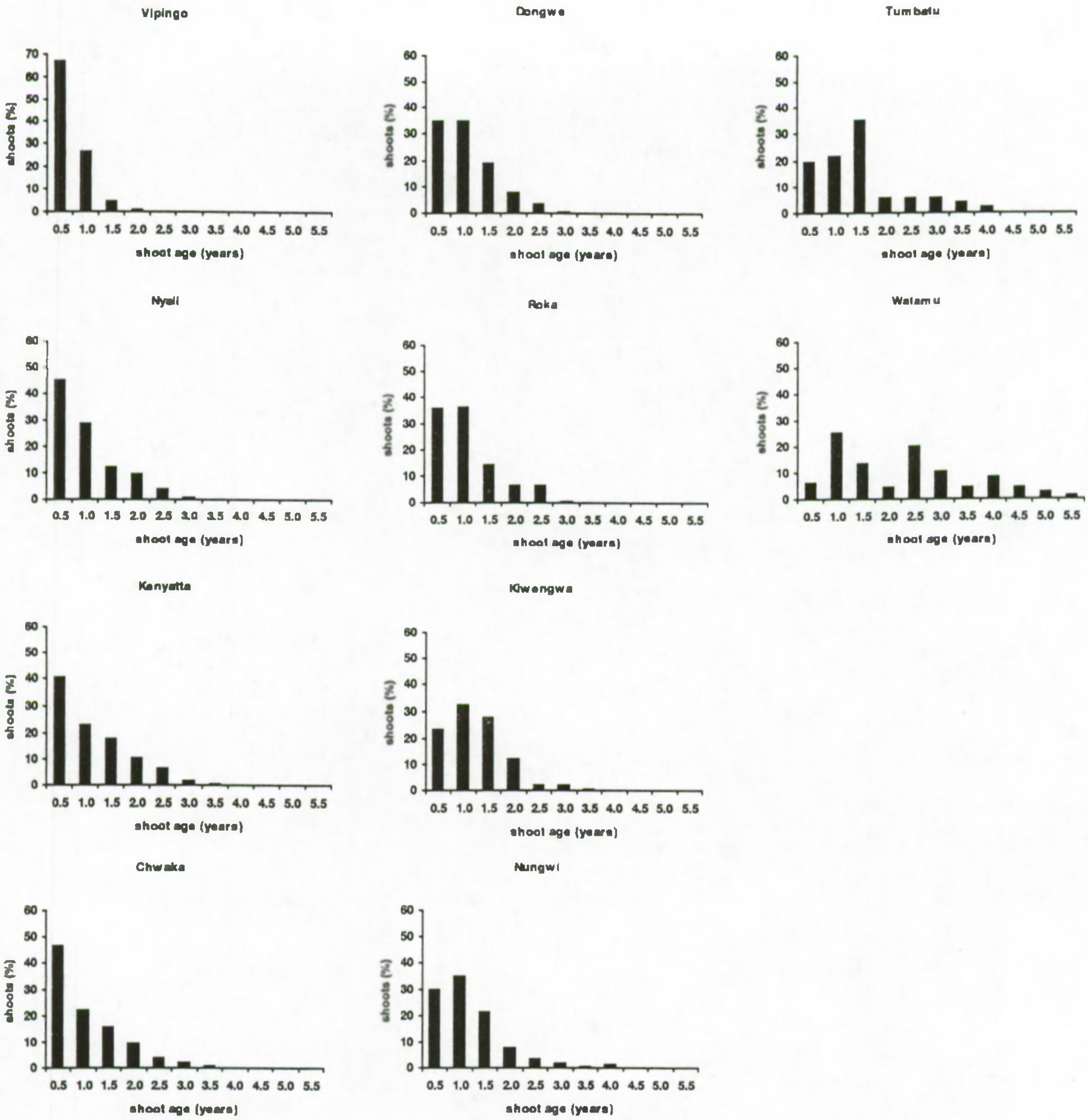
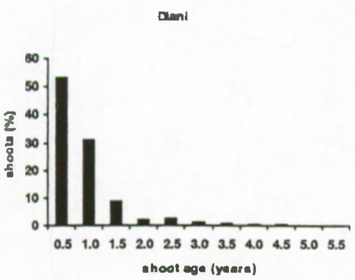


Kamermans *et al.* Fig. 3

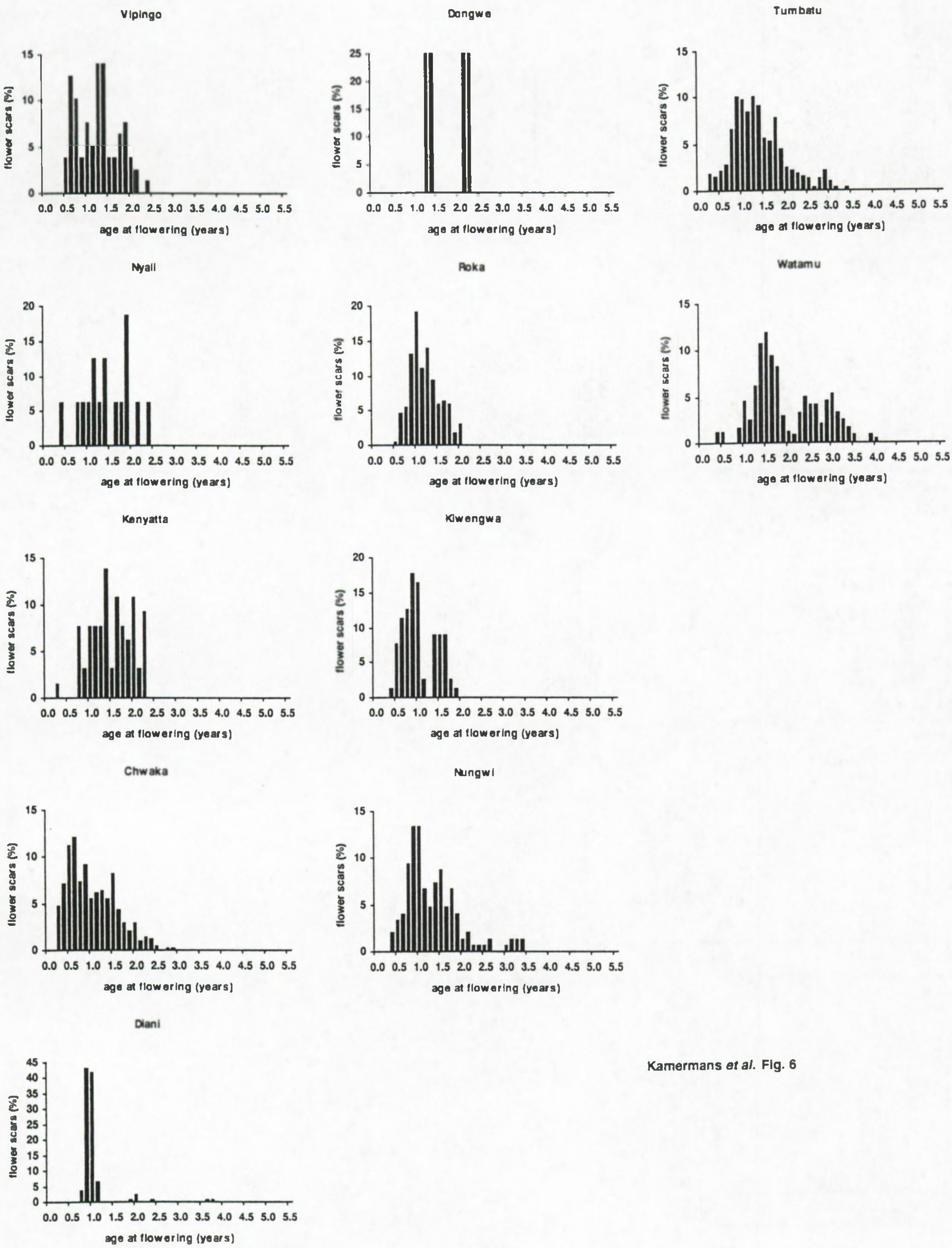


Kamermans *et al.* Fig. 4

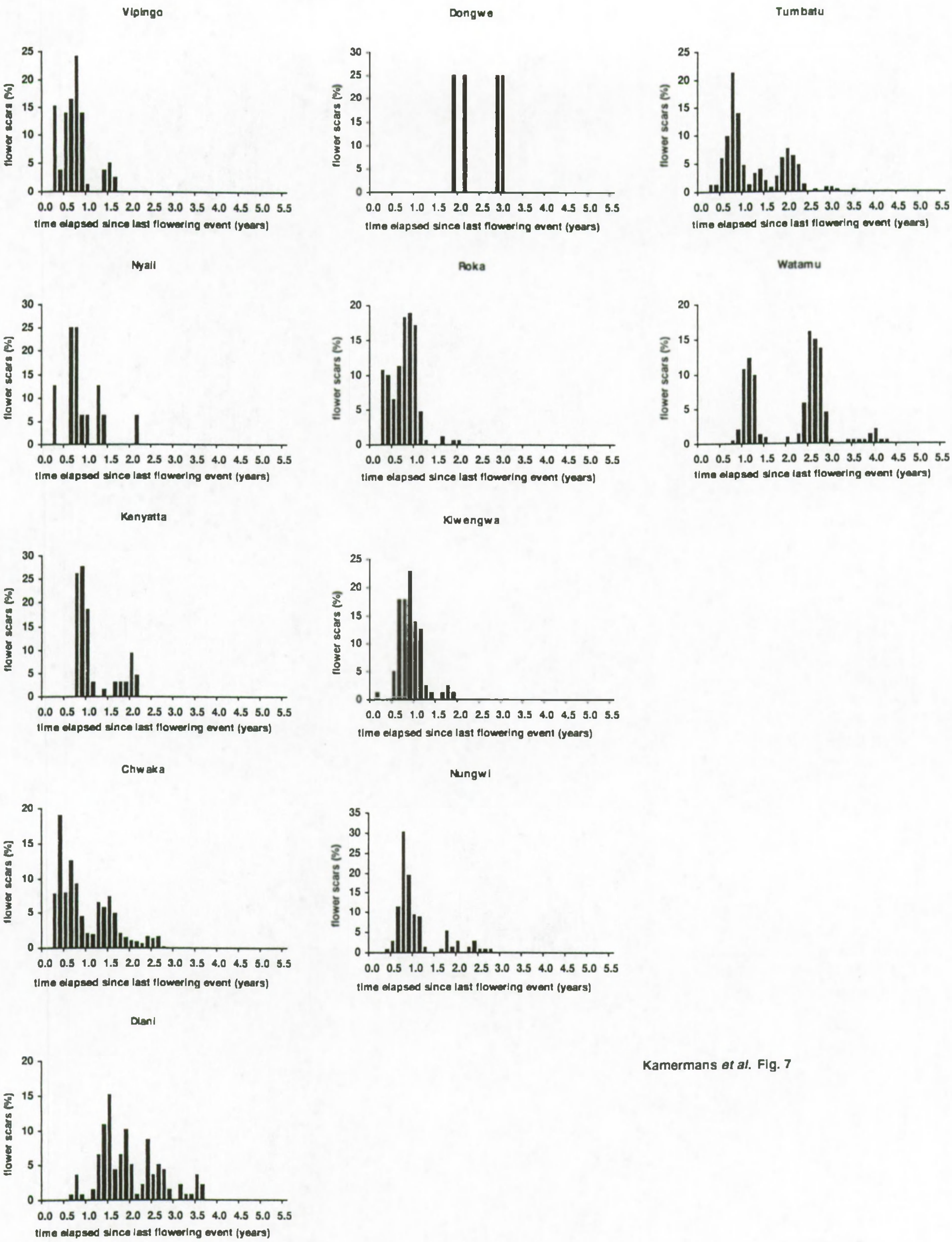




Kamermans *et al.* Fig. 5



Kamermans *et al.* Fig. 6



Kamermans *et al.* Fig. 7

Groundwater flow in the coastal zone influences mangrove distribution

Abstract

Mangroves are the only protection in the tropics against coastal erosion, are nursery grounds for a variety of marine animals and increase sedimentation of particles brought to the coast by rivers. Mangrove distribution in the tropics and subtropics is often linked with the presence of estuaries and creeks. There is a consensus that the brackish water micro environment is caused by river discharges into the oceans. However all over the world mangrove areas are found where no rivers or estuaries are in the immediate neighbourhood. An explanation is reported here for a number of those exceptions. Using a mathematical groundwater flow model it is shown how human activities as far as several hundreds of kilometres inland can destroy vast areas of mangroves by changing the groundwater flow. The model predicts and/or confirms the destruction of large mangrove areas in Kenya and in Florida (USA).

Introduction

Walsh (1974) suggested the existence of extensive mangal depended upon five basic factors. Chapman (1975, 1977, 1984) believed there are seven: (1) air temperature, (2) ocean currents, (3) protection from wave action, (4) shallow shores, (5) salt water, (6) tidal range, and (7) substrate.
Mangrove distribution in the tropics and subtropics is often linked with the presence of estuaries and creeks (Macnae, 1968; Barth, 1982; Blasco, 1991). There is a consensus that the brackish water micro environment, which is the key factor for the development of mangroves, is caused by river discharges into the oceans (Macnae, 1968; Barth, 1982; Snedaker, 1982).

However all over the world mangrove areas are found where no rivers or estuaries are in the immediate neighbourhood. In this study an explanation is presented for a number of those exceptions making use of a mathematical groundwater flow model. Figure 1 shows the distribution of mangroves along the Kenyan coast. Most of the mangrove areas are in the proximity of one or more rivers. However, the rivers north of Mombasa are perennial while the rivers south of Mombasa are drying up after the rainy season. On the other hand there are a number of mangrove areas with no rivers in the immediate neighbourhood. The mangrove forest of Mida Creek (between Kilifi and Malindi, Kenya) is a clear example of a mangrove forest growing in an area without a visible freshwater source.

For regions whose groundwater flow pattern is not known, the use of mathematical models can be a powerful tool in predicting unknown variables, e.g. the impact of a changing groundwater flow pattern on the mangrove ecosystem. The model used is able to explain mangrove distribution in two different areas (Kenyan coast and the Everglades National Park in Florida (USA)). Also the usefulness of the model in predicting mangrove destruction in the above mentioned mangrove areas is shown.

This study describes the groundwater flow of two different regions by a mathematical groundwater model (Ituli, 1984; Dapaah-Siakwan, 1986). Such a model consists of a set of mathematical differential equations with their boundary and initial conditions, and a numerical solution procedure.

Groundwater flow takes place according the gradient of piezometric heads. This means that by solving the model equation for piezometric heads and by knowing their distribution in the study areas the groundwater flow pattern can be established.

Material and methods

Groundwater model

The mathematical model used in this study was developed by the Laboratory of Hydrology of Brussels Free University (De Smedt and Bronders, 1985). The model used is designed to simulate the response of a phreatic, semi-confined or confined aquifer to an imposed stress. The model allows homogeneous or heterogeneous aquifers with irregular boundaries. The model also

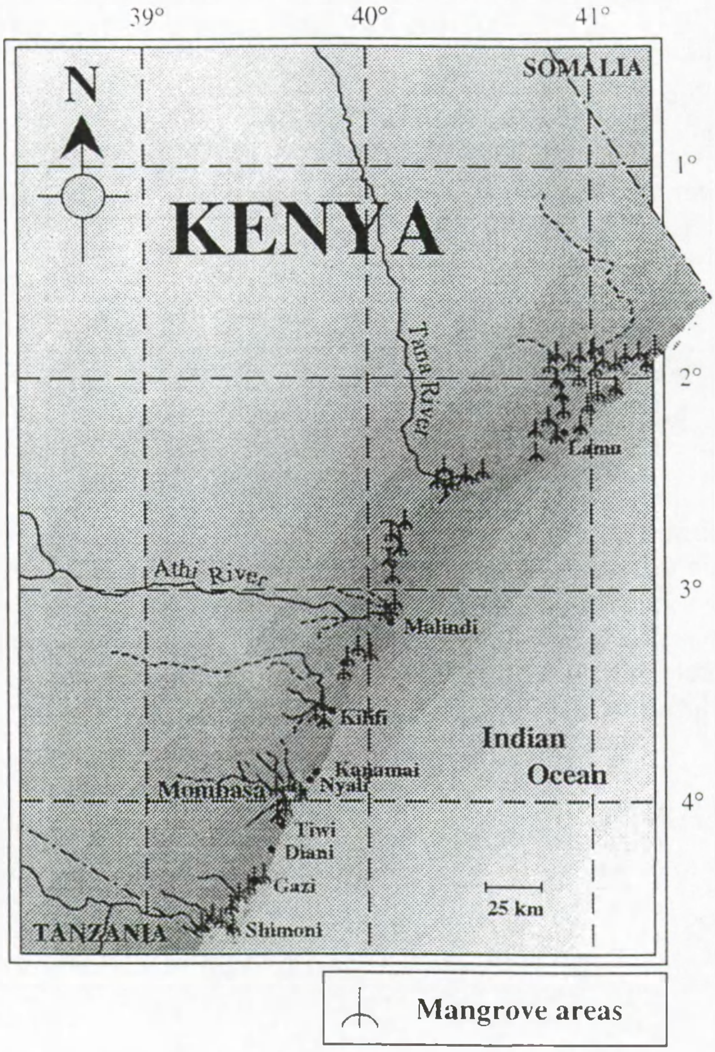


Figure 1. Distribution of mangrove forests along the Kenyan coast.

allows constant/variable recharge, constant/variable and surface inflow or outflow. The groundwater flow is considered horizontal in the model. Because of the large surface of the study areas the aquifers vary in geological composition from place to place. This implicates that the transmissivity also varies with the geologic composition of the aquifer.
To describe the groundwater flow through porous media, the model is based on Darcy's Law and the Law of Conservation of Mass. The model considers steady-state two-dimensional, horizontal flow through a non-homogeneous isotropic aquifer of variable thickness, including source and sink terms, as groundwater recharge and withdrawal.
To formulate the governing equation for groundwater flow, the Continuity equation is applied to an elemental volume within the aquifer (Fig. 2):

$$\frac{\partial q_x}{\partial x}\Delta x(d\Delta y)+\frac{\partial q_y}{\partial y}\Delta y(d\Delta x)=R(x,y)\Delta x\Delta y-Q(x,y)\Delta x\Delta y$$

(equation 1)

where
x and y are the horizontal Cartesian co-ordinates;
q_x is the flux in the x-direction;
q_y is the flux in the y-direction;
d is the thickness of the aquifer;
R(x,y) is the recharge; and
Q(x,y) is the surface outflow.

The components of the groundwater flux are obtained by Darcy's law:

$$q_x=-K\frac{\partial h}{\partial x}$$ (equation 2)

$$q_y=-K\frac{\partial h}{\partial y}$$ (equation 3)

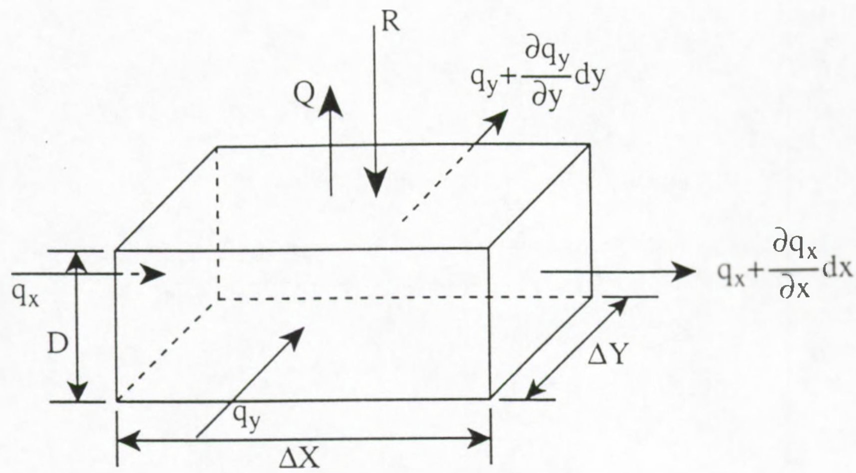


Figure 2. An elemental volume within the aquifer.

where
K is the hydraulic conductivity; and
h is the piezometric head or groundwater elevation.
Equation 1, after substitution of equitions 2 and 3 and after dividing by ΔxΔy, becomes:

$$\frac{\partial}{\partial x}(-Kd\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(-Kd\frac{\partial h}{\partial y})=R(x,y)-Q(x,y)$$
(equation 4)

The transmissivity is defined as T=Kd in case of a homogeneous aquifer, or as

$$T=\int_0^d Kdz$$
(equation 5)

in case of a layered medium, such that equation 4 can be written as:

$$\frac{\partial}{\partial x}(T\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(T\frac{\partial h}{\partial y})+R(x,y)-Q(x,y)=0$$

(equation 6)

In the model recharge and discharge zones are considered:

A. a recharge zone: if the piezometric head h is less than the topographic level h_t, the surface outflow Q(x,y) is taken to be equal to zero:
$Q(x,y)= 0$ for $h<h_t$
Equation 6 becomes:

$$\frac{\partial}{\partial x}(T\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(T\frac{\partial h}{\partial y})+R(x,y)=0$$

(equation 7)

B. a discharge zone: if the piezometric head h is equal to or tends to be greater than the topographic level h_t, the surface outflow Q(x,y) is taken to be greater than zero, so that the piezometric head becomes equal to the topographic level:
$Q(x,y)>0$ for $h=h_t$
Equation 6 becomes:

$$\frac{\partial}{\partial x}(T\frac{\partial h_t}{\partial x})+\frac{\partial}{\partial y}(T\frac{\partial h_t}{\partial y})+R(x,y)=Q(x,y)$$

(equation 8)

If surface outflow occurs, the model considers the water to flow downwards to the adjoining areas with lower topographic levels. This water is than added to the normal recharge input in these areas.
The flow equation now becomes:

$$\frac{\partial}{\partial x}(T\frac{\partial h_t}{\partial x})+\frac{\partial}{\partial y}(T\frac{\partial h_t}{\partial y})+R(x,y)-Q(x,y)+Q_s(x,y)=0$$

(equation 9)

where Q_S is the surface inflow from the neighbouring areas.

Excessive withdrawals from wells can have adverse effects on the groundwater storage in the aquifer. This effect can be studied when a well, located at a point (x,y), is pumped at a rate of $Q_W(x,y)$ and this withdrawal is incorporated in the flow equation as follows:

$$\frac{\partial}{\partial x}(T\frac{\partial h_t}{\partial x})+\frac{\partial}{\partial y}(T\frac{\partial h_t}{\partial y})+R(x,y)-Q_w(x,y)-Q(x,y)+Q_s(x,y)=0$$

(equation 10)

where Q_W is the withdrawal from the well.

In order to solve the groundwater flow equation, we need to specify the boundary and the initial conditions. A groundwater flow domain can be defined by several types of boundary conditions. In the regions studied, use is made of two boundary conditions:

Potential boundary conditions
In this type of boundary conditions the piezometric heads are known: $h=h^*(x,y)$ where h^* is a known piezometric head for all points along the boundary. In the model this type of boundary represents that part of the aquifer where the piezometric head would not change in time. In natural conditions, such boundary conditions occur as recharge boundaries or areas beyond the influence of hydraulic stresses and are defined by known equipotential lines.

No flow boundary conditions
These boundaries are defined by a line across which no flow is occurring, thus

$$\frac{\partial h}{\partial x}=0$$

(equation 11) or

$$\frac{\partial h}{\partial y} = 0 \qquad \text{(equation 12)}$$

This means that perpendicular to the boundary no flow is occurring. This kind of boundary can be defined in nature by two situations: the existence of an outcropping of impervious rock, or a groundwater divide.

Initial conditions

The groundwater flow equation describes a steady state situation so no initial condition is required. However, the topographic levels are required to calculate the piezometric heads in the study area, and to identify the discharge and recharge zones.

The central finite difference approximation method is used to solve the partial differential equation describing the groundwater flow. The model equations describing the regional groundwater flow are solved by a computer programme originally written in FORTRAN IV (Ituli, 1984; Dapaah-Siakwan, 1986). For this application it has been rewritten in C^{++}, and also a number of graphic outputs were added.

Input

The basin characteristics that serve as inputs for the computer to solve the model equations are the transmissivity values T, the areal net precipitation R, the topographic levels $h_{t,}$ the aquifer thickness d and the porosity of the aquifer material n.

The transmissivity values are obtained by the product of hydraulic conductivity and the thickness of the aquifer: T=KD, where K is the hydraulic conductivity and d is the thickness of the aquifer. The flow domains are divided into several zones having different transmissivity values. Those zones correspond to the geological units distinguished in the flow domains. Transmissivity data of Kenya were obtained from Ituli (1984) and are shown in Figure 3. Transmissivity data of Florida were obtained from the Water Resources Research Center (Florida). In this study the transmissivity data for Florida were kept constant at a mean value of 0.242 10^4 m^2/day for the whole study area.

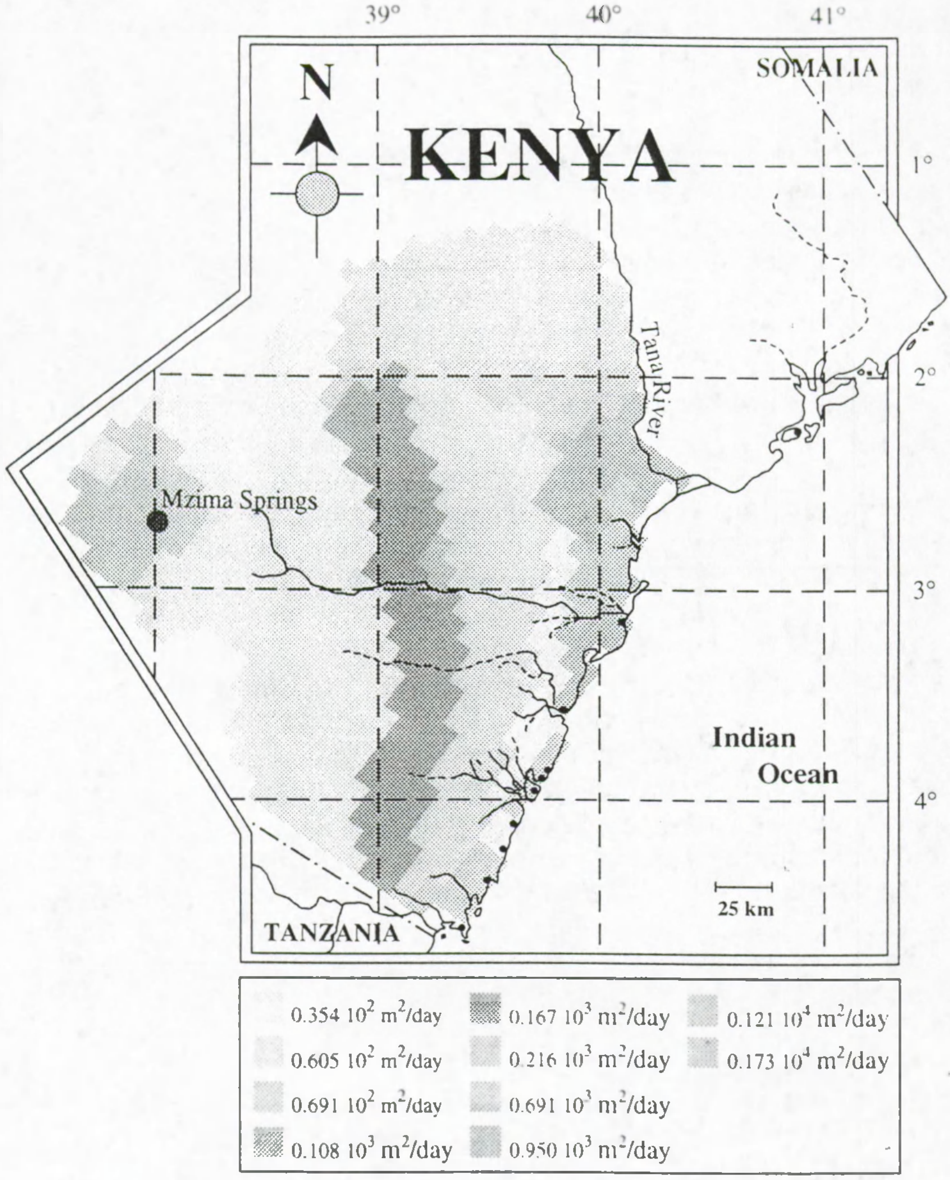


Figure 3. Zones with equal mean transmissivity (m^2/day) in the study area (Kenya).

Similarly to the transmissivity the flow domains are divided into zones of equal net precipitation.
The areal net precipitation has been estimated from:
$R=P - E_t$
where
R is the net precipitation which may be available for infiltration;
P is the mean annual precipitation; and
E_t is the mean annual evapotranspiration.
Areal net precipitation values were obtained from Ituli (1984) for Kenya and from the Water Resources Research Center for Florida. Areal net precipitation values of Kenya are shown in Figure 4. Areal net precipitation values of Florida range between 130 mm/year and 690 mm/year.
The topographic levels are obtained by averaging the topographic levels on each element of an 33 by 38 grid system imposed on a topographic map of the study areas. The square grids are measuring respectively 10.0 km by 10.0 km for the Athi-Tana River Basin, and 7.9 km by 7.9 km for Southern Florida. The topographical data of Kenya are shown in Figure 5. Topographical data of Florida range between 0 and 45 m.

Well withdrawals
To provide Mombasa (Kenya) with the necessary drinking water a pipeline was built between Mzima Springs and Mombasa. In 1995 35.000 m^3/day were pumped up at Mzima springs. Presently, plans exist to multiply the pumping capacity at Mzima springs up to 350.000 m^3/day. We will compare the groundwater flow taking into account both pumping capacities.
In Florida tourism (e.g. Miami) and agricultural activities have led to an explosion of the use of fresh water. While in 1900 no groundwater was pumped up, at least 2.500.000 m^3/day is pumped up today. We will compare the groundwater flow in southern Florida making use of a pumping capacity of respectively 0 m^3/day and 1.000.000 m^3/day.

Additional measurements
Salinity and distance to the mean high water line (spring tide) were measured for 104 boreholes along the Kenyan coast. Those salinities and distances were related to the groundwater flow estimated by the mathematical model. Individual relations between groundwater flow and respectively salinity and distance to the mean high water line (spring tide) were studied making use

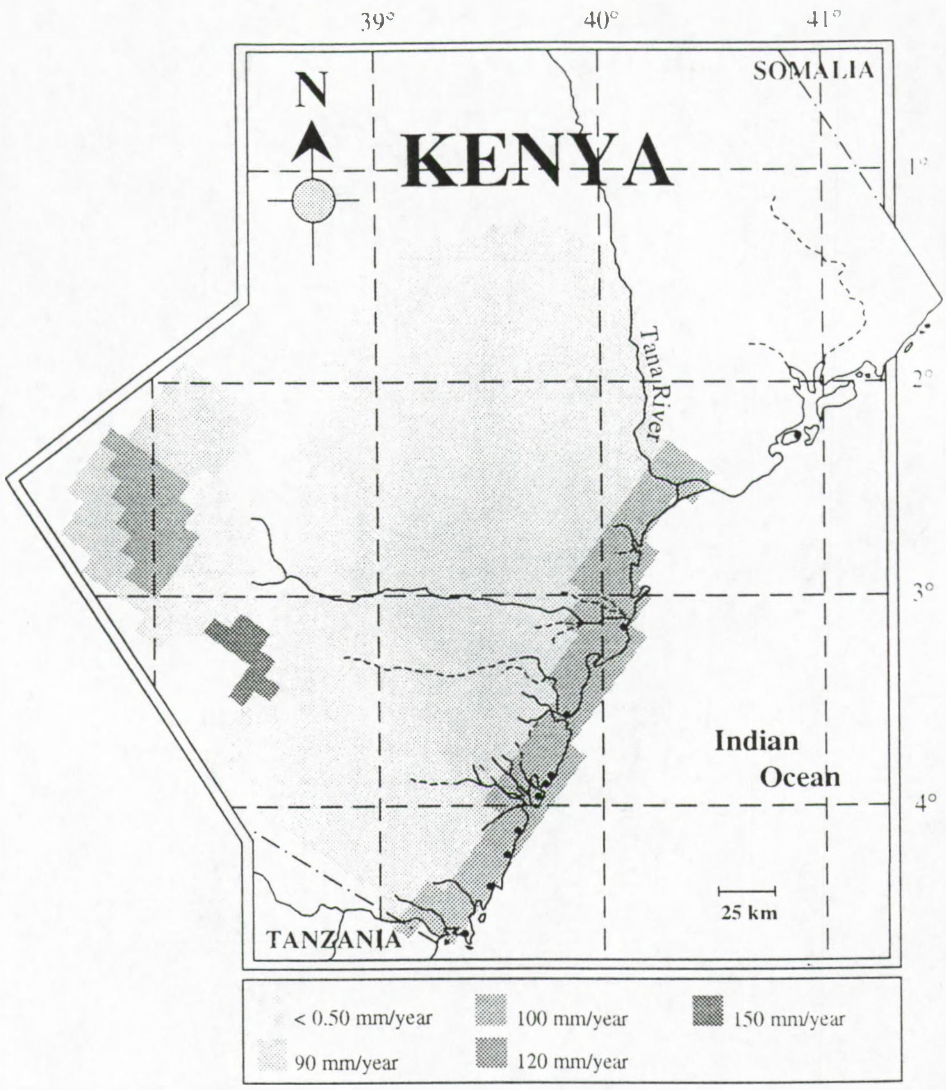


Figure 4. Zones with equal mean areal net precipitation (mm/year) in the study area (Kenya).

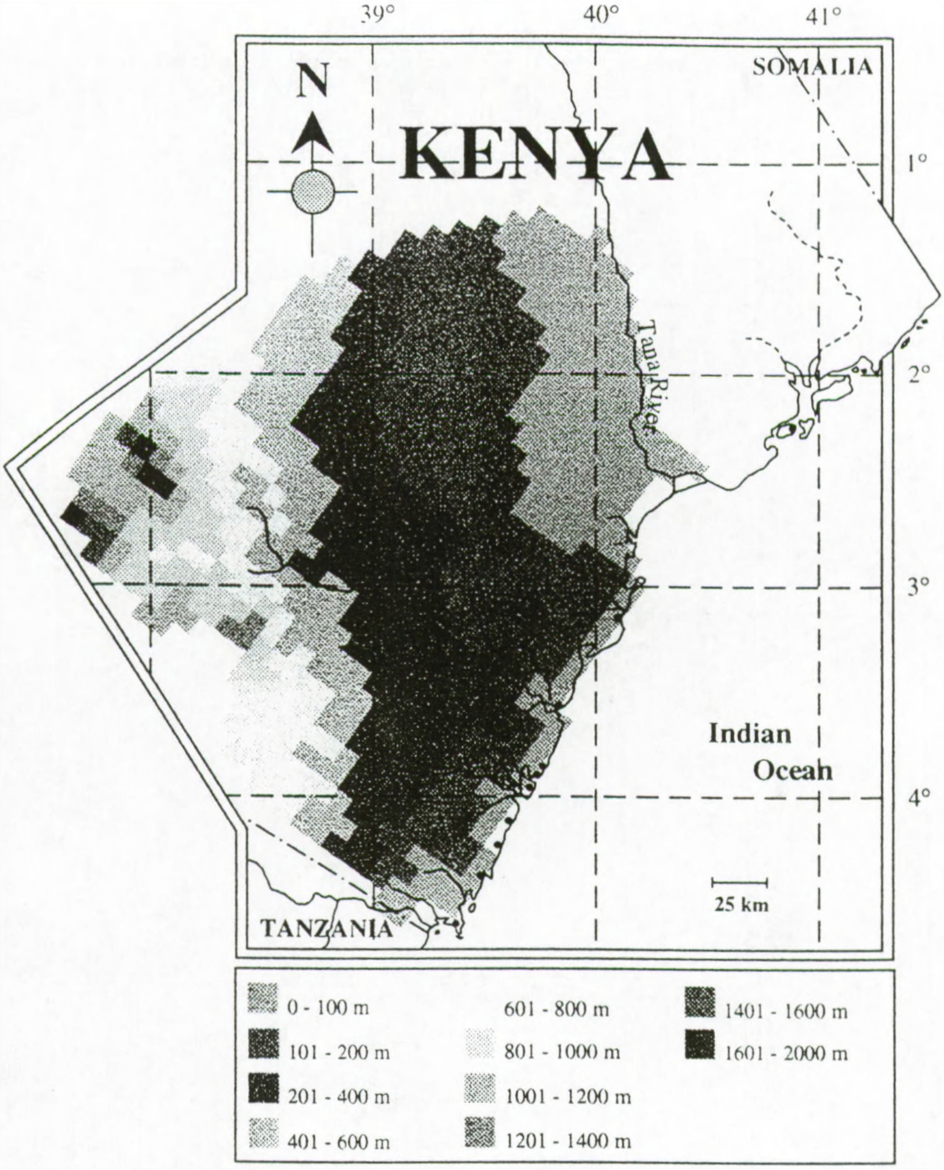


Figure 5. Zones with equal mean topographic levels (m) in the study area (Kenya).

of a Spearman rank correlation coefficient.
The possibility to use groundwater outflow to predict the presence/absence of mangroves along the coastal zone of Kenya was tested with a χ^2-test comparing the number of squared grids with groundwater flow higher than a certain value (expected) with the number of squared grids with as well a high groundwater flow as with the mangrove ecosystem being present (observed).

Results

Figure 6 gives the results of the mathematical model for the groundwater flow in Kenya when 35.000 m^3/day is pumped up at Mzima springs. The arrows show the direction of the groundwater flow, while the colours represent the magnitude of the groundwater flow, which is expressed as the total flux over the aquifer, i.e. flux times aquifer tickness. A vector representation of the groundwater flow along the coastal zone is given in Figure 7. Only groundwater flow vectors with a groundwater flow ≥ 1 m^2/day are shown. Figure 8 shows groundwater flow vectors along the Kenyan coast when every day 350.000 m^3 of groundwater is pumped up at Mzima springs.
Figure 9 and 10 show respectively groundwater flow in South Florida at the beginning of the century and in 1994.
Figure 11 shows the relationship between salinity, distance to the mean high water line (spring tide) and groundwater flow. Boreholes with a salinity lower than 1‰ were not used in the graph. With one exception all salinities higher than 1‰ were measured at locations where the groundwater model predicts a groundwater flow smaller than 1 m^2/day. When the distance is kept constant, salinities show a clear Spearman rank correlation with groundwater flow (Table 1). Also salinities show very high correlations (Spearman rank correlation coefficient) with the distance to the mean water line (spring tide), when measured in a region with constant groundwater flow (Table 2).
Comparing the number of cells with a groundwater flow higher than 1 m^2/day with the number of cells where the groundwater flow is higher than 1 m^2/day and where the mangrove forest is present, a χ^2 test shows no significant differences.

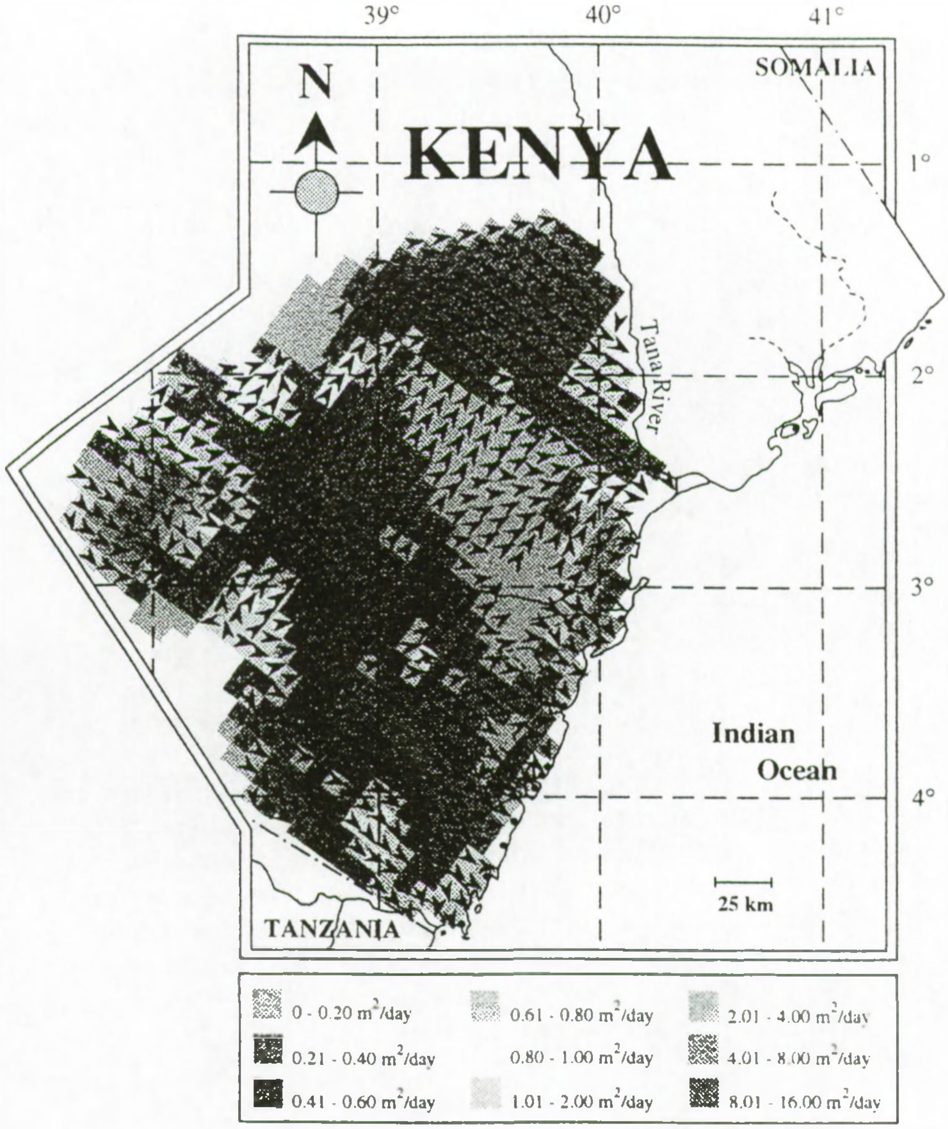


Figure 6. Groundwater flow: graphical output of the model. Arrowheads show the direction of the groundwater flow. Background colours indicate the size of the groundwater flow (m^2/day).

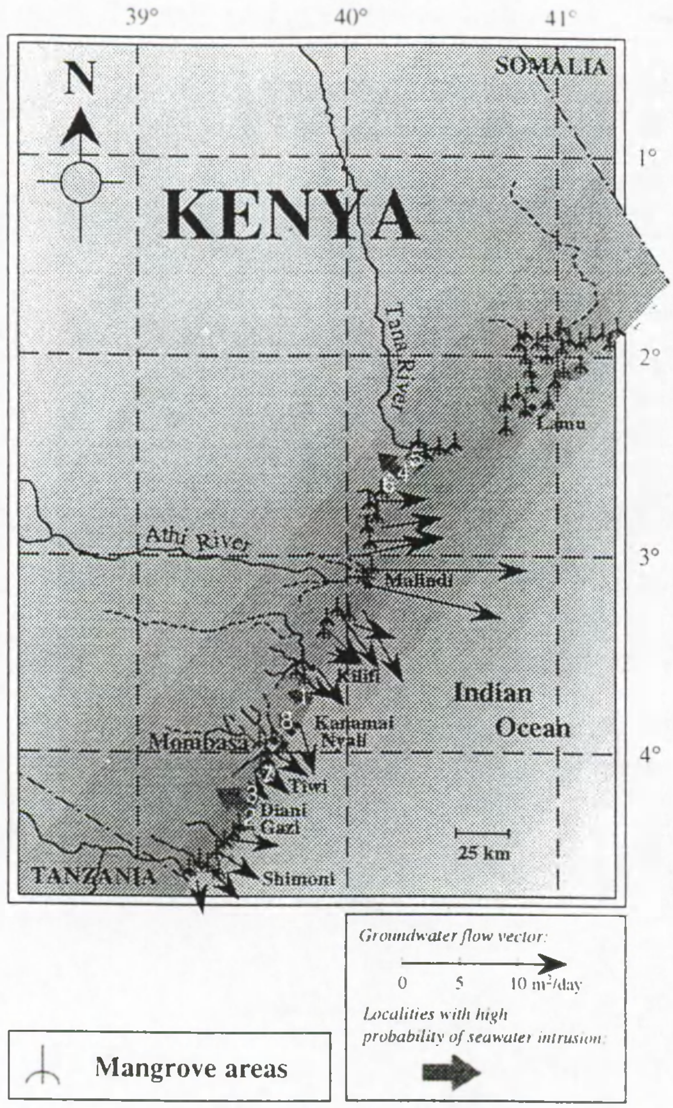


Figure 7. Groundwater flow: graphical output (vectorial) of the actual situation along the Kenyan coast between the Tanzanian border and Tana River. Only those areas with groundwater flow higher than 1 m^2/day and regions with a high probability of seawater intrusion are indicated. Numbers 1 to 8 refer to salinity measurements at different distances from the coast (see Fig. 11).

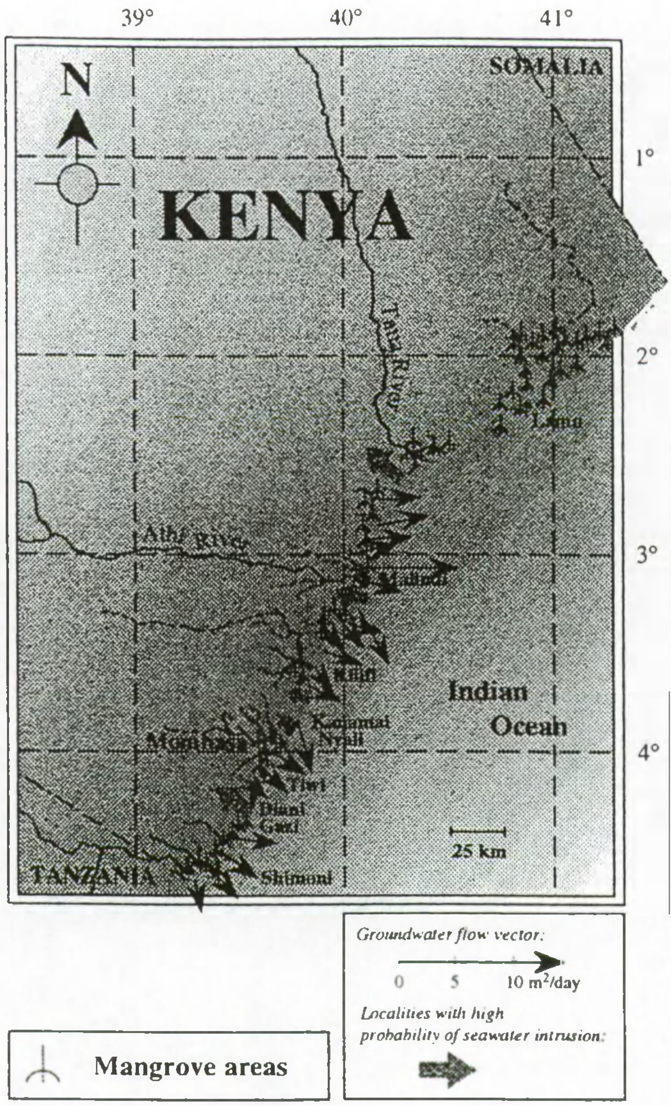


Figure 8. Groundwater flow: graphical output (vectorial) of the modelled situation along the Kenyan coast between the Tanzanian border and Tana River when 350.000 m^3/day is pumped at Mzima springs. Only those areas with groundwater flow higher than 1 m^2/day and regions with a high probability of seawater intrusion are indicated.

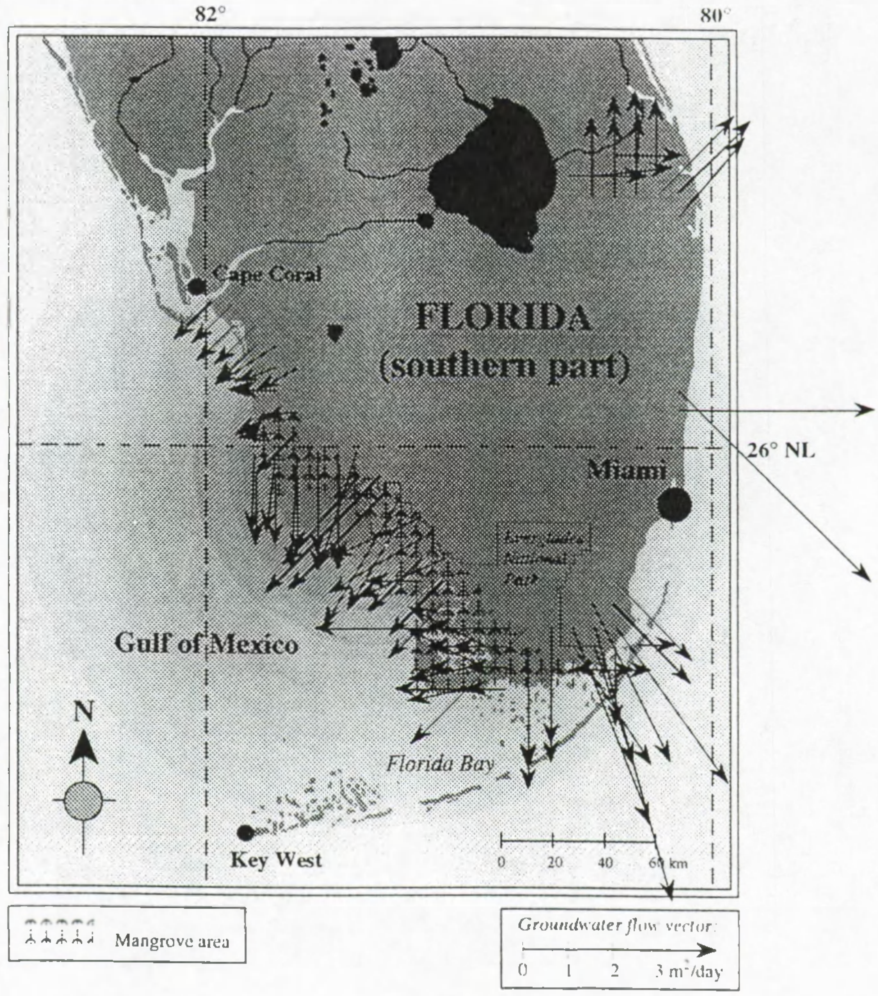


Figure 9. Groundwater flow: graphical output (vectorial) of the groundwater flow situation in the southern part of Florida in the beginning of the 19th century. In the western part of the study region groundwater flow is high in the direction of the Gulf of Mexico. In the eastern part there are only a few areas with high groundwater flow.

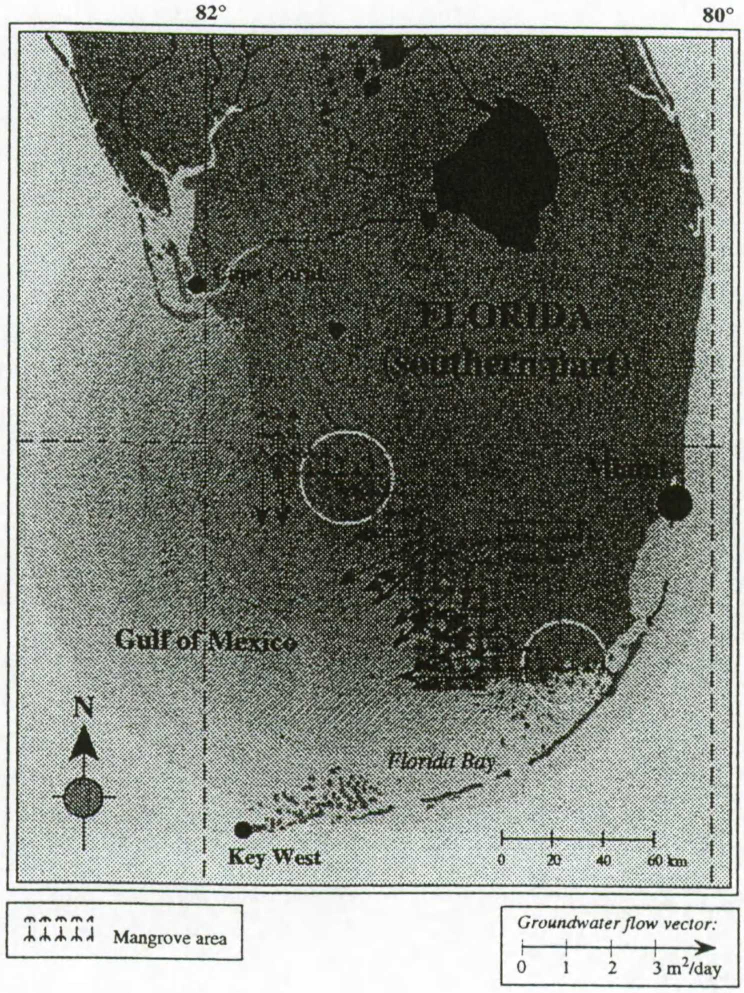


Figure 10. Groundwater flow: graphical output (vectorial) of the groundwater flow in the southern part of Florida based on actual data (Feb. 1994).

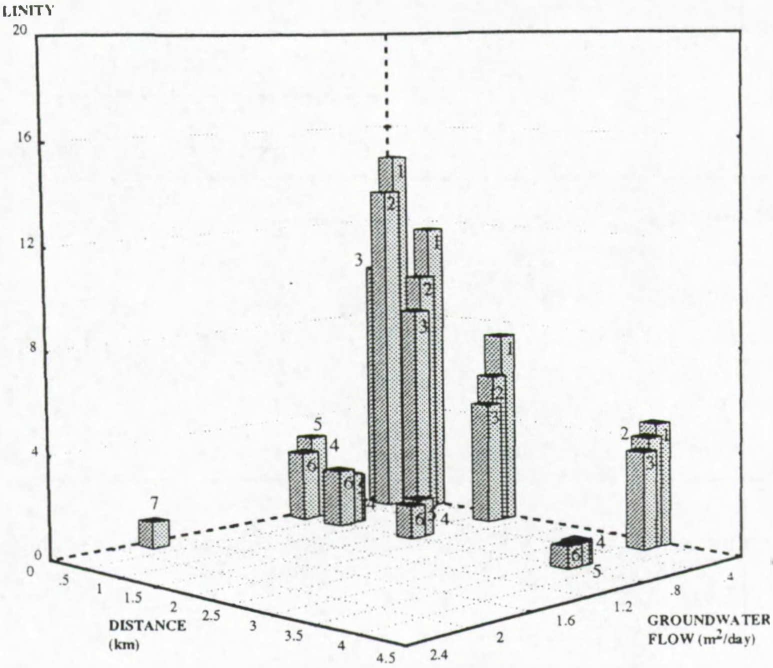


Figure 11. Relation between salinity (‰), distance to the mean high water line (spring tide) (km) and groundwater flow (m^2/day). Measurements taken in 104 boreholes along the Kenyan coast. Boreholes with a salinity lower than 1‰ were not added to the graph. Numbers 1 to 8 refer to places along the Kenyan coast as given in Figure 7.

	Groundwater flow	
	Spearman R	N
Salinity (0.5 km)	-.78*	26
Salinity (1 km)	-.73*	26
Salinity (2 km)	-.74*	26
Salinity (4 km)	-.74*	26

Table 1. Spearman Rank Correlation Coefficient between groundwater flow and salinity (distance to the mean high water line at spring tide kept constant).

	Distance	
	Spearman R	N
Salinity (0.242 m^2/day)	-1*	4
Salinity (0.312 m^2/day)	-1*	4
Salinity (0.354 m^2/day)	-1*	4
Salinity (0.886 m^2/day)	-1*	4
Salinity (0.904 m^2/day)	-1*	4
Salinity (0.963 m^2/day)	-1*	4
Salinity (2.030 m^2/day)		1

Table 2. Spearman Rank Correlation Coefficient between distance to the mean high water line at spring tide and salinity (groundwater flow kept constant).

Discussion and conclusions

The coastal zone of Kenya is characterised by moderately high groundwater flow ranging between 0.31 and 12.8 m^2/day (average value: 4 m^2/day). The high groundwater flow is due to high potential gradients, high infiltration capacity of the geologic formations and high precipitation received by the area.
The elevation of the coastal belt ranges between 0 and 76 m. Piezometric heads as calculated from the model range between 0 and 48 m. In general those piezometric heads reflect the field situation: wells in the coastal belt strike water between 5 and 15 m.
High discharge of fresh groundwater into the sea is in conformity with Cashwell and Bakers 's (1953) assertion that close to the shores, in some points, seepage of freshwater occurs. Seawater seepage is reported in several areas along the Kenyan coast (Isaac and Isaac, 1968; Knutzen and Jasuund (1979); Ruwa and Polk, 1986; Ruwa, 1993).
Figure 7 shows a very clear correlation between groundwater flow and the distribution of the mangroves along the coast. This correlation is confirmed

by the result of the χ^2 test comparing the number of cells with a groundwater flow higher than 1 m^2/day with the number of cells where the mangrove forest is present and the groundwater flow is higher than 1 m^2/day. The value of 1 m^2/day was chosen on the basis of Figure 11. Only 1 out of 104 boreholes had a salinity larger than 1‰ in case the groundwater flow was more than 1 m^2/day. Figure 11 also shows that places with groundwater flow lower than 1 m^2/day are highly susceptible to seawater intrusion. This is much higher than the theoretical value of 0.22 m^2/day mentioned by Ituli (1984). Areas with a groundwater flow lower than 1 m^2/day are indicated in Figure 7 by red arrows.

Figure 11 shows the relation between salinity, or seawater intrusion, groundwater flow and the distance to the coast. Those three variables are clearly correlated with each other (Table 1 and 2). Salinity decreases exponentially with an increasing distance from the coast and with an increasing groundwater flow. Numbers 1 to 7 on Figure 11 correspond with identical numbers on the map of Kenya (Fig. 7). Number 8 indicates a region with local seawater intrusion, probably caused by pumping up large volumes of groundwater by a local cement factory. However, we were not able to get the necessary information from the local responsibles to confirm this hypothesis.

To solve the drinking-water problem of Mombasa, plans exist to pump up more water at Mzima Springs. Pumping of huge amounts of water will lead to an alteration of the regional groundwater flow along the coast. At the moment groundwater is pumped at a rate of 35.000 m^3/day. If this amount would be raised to the planned 350.000 m^3/day the groundwater flow in the region of Malindi and in the region south of Tana River would decrease drastically (Fig. 8). As a consequence, the probability of seawater intrusion would increase in both regions, and the existing mangrove forests would be endangered, because seawater intrusion would lead to the destruction of the ecosystem.

To prove the capability of the model to predict the destruction of the mangrove forest due to lower groundwater flows, we tested the model for the southern part of Florida, with a special interest to the Everglades National Park. The groundwater flow in the beginning of the century was compared to the situation in 1994. Figure 9 (beginning of this century) shows large groundwater outflow in the southern and western part of the region. In Figure 10 (situation 1994) the groundwater flow in the whole area has dropped drastically, because of urbanisation, tourism and agriculture. In

those places where groundwater flow fell below 1 m^2/day, mangroves are dying, as indicated by the yellow circles in Figure 10.
The complete absence of groundwater flow in the south-eastern part of the park together with the diminished surface water flow (Holloway, 1994; Fennema *et al.*, 1994), also explanains the doubling of the salinity in Florida Bay and the sea grass die-off in this bay (Mairson, 1994).
Hence, this study shows a clear relation between the distribution of the mangrove ecosystem and groundwater flow. Groundwater modellisation seems to be a proper tool to evaluate the effects of massive pumping of groundwater. The model also shows how human activities as far as several hundreds of kilometres inland can destroy vast areas of mangroves by changing the groundwater flow. The model predicts and/or confirms the destruction of large mangrove areas in Kenya and the Everglades (Florida-USA). The present authors believe at least one variable must be added to the list of seven basic conditons (Chapman, 1975, 1977, 1984) for the existance of extensive mangrove forests: presence of fresh water.

Acknowledgements

This research was carried out in the framework of the Kenya Belgium Project in Marine Sciences. We are indebted to director, Dr. E. Okemwa and his staff of the Kenya Marine and Fisheries Research Institute for their positive cooperation, and to the Water Resources Research Center (Florida) for the use of their hydrological data. We thank Professor Dr. F. De Smedt and Dr. O. Batelaan for their cooperation on the hydrological part of this study and for their positive criticism on the drafts of this paper.

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Annex III. Questionnaires

Contents

QUESTIONNAIRE

(One form to be completed <u>for each participating organisation</u>)

IDENTIFICATION OF INSTITUTION:

NAME: KENYA MARINE & FISHERIES RESEARCH INSTITUTE (KMFRI)

ADDRESS: P.O. BOX 81651
MOMBASA – KENYA

FAX: 254-11-475157 TEL: 254-11-475157 e-mail: ....

1. HUMAN RESOURCES

SCIENTIFIC PERSONNEL PARTICIPATING IN THE PROJECT ALREADY EMPLOYED BY THE INSTITUTION

a. Scientific personnel having completed full university education (graduate/post-graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Kazungu, J. M.	Chief Scientist	Ph. D.	30
Mwangi, S.	Researcher	M. Sc.	"
Kitheka, J.	"	"	"
Mwaluma, J.	"	"	"
Mwashote, B.	"	"	"
Uku, J.	"	"	"
Wawiye, P.	"	"	"

b. Number of technicians (having completed full secondary education/non-graduate) in man months ....180... Months

Scientific Personnel Specifically Employed by the Institution to Participate in the Project

a. Scientific personnel having completed full university education (graduate/post-graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
....			
....			
....			
....			

b. Number of technicians (having completed full secondary education/non-graduate) in man months .... Months

VISITING PERSONNEL PARTICIPATING IN THE PROJECT, BUT NOT EMPLOYED BY THE INSTITUTION
(Status: Fellow, stagiaire, student, visiting scientists, etc.)

a. Long term (more than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANISATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT	FINANCIALLY SUPPORTED BY THE PROJECT?
....						
....						
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....						

b. Short term (less than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANISATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT	FINANCIALLY SUPPORTED BY THE PROJECT?
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....						
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....						

2. DURABLE EQUIPMENT

(Specify type and value of equipment purchased for the project - only for pieces of equipment of a value higher than 500/item)

TYPE	VALUE (specify currency)	EU CONTRIBUTION
Well Data logger	Kshs. 296,208.00	100%
....		
....	....	....
....		

QUESTIONNAIRE

(One form to be completed <u>for each participating organisation</u>)

IDENTIFICATION OF INSTITUTION:

NAME: Netherlands Institute of Ecology
Centre for Estuarine and Coastal Ecology

ADDRESS: P.O. Box 140
4400 AC Yerseke
The Netherlands
fax: +31-113-573616 tel: +31-113-577472
email: hemminga@cemo.nioo.knaw.nl

1. HUMAN RESOURCES

SCIENTIFIC PERSONNEL PARTICIPATING IN THE PROJECT ALREADY EMPLOYED BY THE INSTITUTION

a. Scientific personnel having completed full university education (graduate/post graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Prof. Dr. Marten Hemminga	Researcher	Ph.D. (Marine Botany)	4

b. Number of technicians (having completed full secondary education/non graduate) in man months ....../ Months

SCIENTIFIC PERSONNEL SPECIFICALLY EMPLOYED BY THE INSTITUTION TO PARTICIPATE IN THE PROJECT

a. Scientific personnel having completed full university education (graduate/post graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Dr. Pauline Kamermans	Researcher	Ph.D. (Coastal Ecology)	22

b. Number of technicians (having completed full secondary education/non graduate) in man months

VISITING PERSONNEL PARTICIPATING IN THE PROJECT, BUT NOT EMPLOYED BY THE INSTITUTION
(Status: Fellow, stagiaire, student, visiting scientist, etc)

a. Long term (more than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man months)	FINANCIALLY SUPPORTED BY THE PROJECT

b. Short term (less than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man days)	FINANCIALLY SUPPORTED BY THE PROJECT

2. DURABLE EQUIPMENT

(Specify type and value of equipment purchased for the project – only for pieces of equipment of a value higher than 500/item)

TYPE	VALUE (Specify currency)	EU CONTRIBUTION
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QUESTIONNAIRE

(One form to be completed for each participating organisation)

IDENTIFICATION OF INSTITUTION:

NAME: VRIJE UNIVERSITEIT BRUSSEL - INSTITUTE OF ENVIRONMENTAL RESEARCH

ADDRESS: PLEINLAAN 2

1050 BRUSSELS BELGIUM

FAX: 02/6293403 TEL: 02/6293410 e-mail: J.TACK@VUB.AC.BE

1. HUMAN RESOURCES

SCIENTIFIC PERSONNEL PARTICIPATING IN THE PROJECT ALREADY EMPLOYED BY THE INSTITUTION

a. Scientific personnel having completed full university education (graduate/post-graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
TACK JURGEN	RESEARCHER	ECOHYDROLOGY	12
VERHEYDEN ANOUCK	"	ECOLOGY	6
GILLIKIN DAVID	"	GEOLOGY	2

b. Number of technicians (having completed full secondary education/non-graduate) in man months ... 6 ... Months

SCIENTIFIC PERSONNEL SPECIFICALLY EMPLOYED BY THE INSTITUTION TO PARTICIPATE IN THE PROJECT

a. Scientific personnel having completed full university education (graduate/post-graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
VERHEYDEN . ANOUCK	RESEARCHER	ECOLOGY	7 MONTHS
....			
....			
....			

b. Number of technicians (having completed full secondary education/non-graduate) in man months ~~......~~ Months

VISITING PERSONNEL PARTICIPATING IN THE PROJECT, BUT NOT EMPLOYED BY THE INSTITUTION
(Status: Fellow, stagiaire, student, visiting scientists, etc.)

a. Long term (more than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANISATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT	FINANCIALLY SUPPORTED BY THE PROJECT?
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....						

b. Short term (less than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANISATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT	FINANCIALLY SUPPORTED BY THE PROJECT?
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2. DURABLE EQUIPMENT

(Specify type and value of equipment purchased for the project - only for pieces of equipment of a value higher than 500/item)

TYPE	VALUE (specify currency)	EU CONTRIBUTION
. . . .	. . . .	. . . .
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. . . .	. . . .	. . . .
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QUESTIONNAIRE

(One form to be completed for each participating organisation)

IDENTIFICATION OF INSTITUTION:

NAME: Institute of Marine Sciences

ADDRESS: P.O. Box 668,
Zanzibar - Tanzania

FAX: (054)233050 TEL: (054) 230741 e-mail: ims@zims.udsm.ac.tz

1. HUMAN RESOURCES

SCIENTIFIC PERSONNEL PARTICIPATING IN THE PROJECT ALREADY EMPLOYED BY THE INSTITUTION

a. Scientific personnel having completed full university education (graduate/post-graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Mtolera, M.S.P.	Res. Fellow	Ph.D (Marine Botany	5
Shunula, J.P.	Sen. Res. Fel	Ph.D (Marine Botany	2
Ndaro, S.M.G.	Sen. Lecture	Ph.D. (Meiobenthos)	3
Mmochi, A.J.	Ass. Res. Fel	MSc. (Marine Environment Chemistry)	6

b. Number of technicians (having completed full secondary education/non-graduate) in man months .... Months

SCIENTIFIC PERSONNEL SPECIFICALLY EMPLOYED BY THE INSTITUTION TO PARTICIPATE IN THE PROJECT

a. Scientific personnel having completed full university education (graduate/post-graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
....//.....	Nil	Nil	Nil

b. Number of technicians (having completed full secondary education/non-graduate) in man months .... Months

VISITING PERSONNEL PARTICIPATING IN THE PROJECT, BUT NOT EMPLOYED BY THE INSTITUTION
(Status: Fellow, stagiaire, student, visiting scientists, etc.)

a. Long term (more than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANISATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT	FINANCIALLY SUPPORTED BY THE PROJECT?
....	Nil	Nil	Nil	Nil	Nil	Nil
....						
....						
....						

b. Short term (less than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANISATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT	FINANCIALLY SUPPORTED BY THE PROJECT?
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....						

2. DURABLE EQUIPMENT

(Specify type and value of equipment purchased for the project - only for pieces of equipment of a value higher than 500/item)

TYPE	VALUE (specify currency)	EU CONTRIBUTION
BENTHNIC CHAMBERS	Tshs. 1,893,000/=	100%
SALINOMETER	" 6,387,500/=	100%
AUTO ANALYSER (SPARES)	" 5,218,500/=	100%

QUESTIONNAIRE

(One form to be completed for each participating organisation)

IDENTIFICATION OF INSTITUTION:

NAME: Zoology Department, Stockholm University

ADDRESS: 106 91 Stockholm, Sweden

Tel: +46-8-164010, Fax: +48-8-167715

1. HUMAN RESOURCES

SCIENTIFIC PERSONNEL PARTICIPATING IN THE PROJECT ALREADY EMPLOYED BY THE INSTITUTION

a. Scientific personnel having completed full university education (graduate/post graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Dr Ron Johnstone	Senior Lecturer /Researcher	Ph.D. (Nutrient Dynamics in Aquatic Ecosystems)	24
Dr Emil Olafsson	Lecturer/Researcher	Ph.D. (Meiofauna Ecology)	3

b. Number of technicians (having completed full secondary education/non graduate) in man months ...... 6 Months

SCIENTIFIC PERSONNEL SPECIFICALLY EMPLOYED BY THE INSTITUTION TO PARTICIPATE IN THE PROJECT

a. Scientific personnel having completed full university education (graduate/post graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Dr Emil Olafsson	Lecturer/Researcher	Ph.D. (Meiofauna Ecology)	9

b. Number of technicians (having completed full secondary education/non graduate) in man months

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Martin Ekman	Technician	BSc (Hons)	6

VISITING PERSONNEL PARTICIPATING IN THE PROJECT, BUT NOT EMPLOYED BY THE INSTITUTION
(Status: Fellow, stagiaire, student, visiting scientist, etc)

a. Long term (more than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man months)	FINANCIALLY SUPPORTED BY THE PROJECT
Stefan Gossling	German	Student	Lund University	BSc (Hons)	9	Yes, travel & field costs only
Johan Hast	Swedish	Student	Stockholm University	BSc (Hons)	4	As above.

b. Short term (less than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man days)	FINANCIALLY SUPPORTED BY THE PROJECT
Anna Stockenberg	Swedish	Student	Zoology Department	BSc (Hons)	14	Yes

2. DURABLE EQUIPMENT

(Specify type and value of equipment purchased for the project – only for pieces of equipment of a value higher than 500/item)

TYPE	VALUE (Specify currency)	EU CONTRIBUTION
GPS	380 US$	100%
Digital Camera	1,470 US$	50%
Salinity Meter & Electrode	530 US$	100%

QUESTIONNAIRE

IDENTIFICATION OF INSTITUTION:

NAME: Instituto do Mar

ADDRESS: Laboratório Marítimo da Guia
Estrada do Guincho, 2750 Cascais
Portugal
fax: +351-1-4869720 tel: +351-1-4869211
email: jpaula@fc.ul.pt

1. HUMAN RESOURCES

SCIENTIFIC PERSONNEL PARTICIPATING IN THE PROJECT ALREADY EMPLOYED BY THE INSTITUTION

a. Scientific personnel having completed full university education (graduate/post graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Prof. José Paula	Assistant Professor	Ph.D. (Marine Biology)	5
Prof. L. Saldanha	Full Professor	Ph.D. (Marine Biology)	2

b. Number of technicians (having completed full secondary …… Months
education/non graduate) in man months

SCIENTIFIC PERSONNEL SPECIFICALLY EMPLOYED BY THE INSTITUTION TO PARTICIPATE IN THE PROJECT

a. Scientific personnel:

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Mr. Pedro Fidalgo	Researcher	1st degree in Biology	18
Mr. Ricardo Costa	Researcher	undergraduate student	6

b. Number of technicians (having completed full secondary education/non graduate) in man months

NAME	FUNCTION IN INSTITUTION	QUALIFICATION	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Mr. Milton Alfredo	Technician	Secondary school	4

VISITING PERSONNEL PARTICIPATING IN THE PROJECT, BUT NOT EMPLOYED BY THE INSTITUTION
(Status: Fellow, stagiaire, student, visiting scientist, etc)

a. Long term (more than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATI ON	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man months)	FINANCI ALLY SUPPOR TED BY THE PROJECT
-	-	-	-	-	-	

b. Short term (less than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATI ON	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man days)	FINANCI ALLY SUPPOR TED BY THE PROJECT
-	-	-	-	-	-	-

2. DURABLE EQUIPMENT

(Specify type and value of equipment purchased for the project – only for pieces of equipment of a value higher than 500/item)

TYPE	VALUE (Specify currency)	EU CONTRIBUTION
-	-	-

QUESTIONNAIRE

(One form to be completed for each participating organisation)

IDENTIFICATION OF INSTITUTION:

NAME: Department of Biological Sciences of University Eduardo Mondlane

ADDRESS: Julius Nyerere Avenue, University Campus, Maputo, Mozambique P.O.Box 257.

FAX: +258-1-492176 TEL: +258-1-490009 e-mail: idomio @ biologia.uem.mz/ xipixi @ zebra. uem.mz

1. HUMAN RESOURCES

SCIENTIFIC PERSONNEL PARTICIPATING IN THE PROJECT ALREADY EMPLOYED BY THE INSTITUTION

a. Scientific personnel having completed full university education (graduate/post graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Domingos Z. Gove	Lecturer/Researcher	MSc (Marine Zoology)	23
Angelina Martins	Lecture/Researcher	BSc Honours (Biology)	6

b. Number of technicians (having completed full secondary education/non graduate) in man months ...... 4 Months

SCIENTIFIC PERSONNEL SPECIFICALLY EMPLOYED BY THE INSTITUTION TO PARTICIPATE IN THE PROJECT

a. Scientific personnel having completed full university education (graduate/post graduate):

NAME	FUNCTION IN INSTITUTION	QUALIFICATION Scientific Discipline	DURATION IN MAN MONTHS OF TIME SPENT ON PROJECT (no decimals)
Helena Chavale	Researcher	BSc Honours (Biology)	5
Rabia Abdula	Researcher	BSc Honours (Biology)	4

b. Number of technicians (having completed full secondary education/non graduate) in man months ..... 0 Months

VISITING PERSONNEL PARTICIPATING IN THE PROJECT, BUT NOT EMPLOYED BY THE INSTITUTION
(Status: Fellow, stagiaire, student, visiting scientist, etc)

a. Long term (more than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man months)	FINANCIALLY SUPPORTED BY THE PROJECT
Emília Fumo	Mozambican	Stagiare	Dep. Biol. Sciences	(BSc (Biology)	4	Yes

b. Short term (less than one month)

NAME	NATIONALITY	STATUS	ORIGINALLY ATTACHED TO WHICH ORGANIZATION	QUALIFICATIONS Scientific Discipline	DURATION OF TIME SPENT ON PROJECT (in man days)	FINANCIALLY SUPPORTED BY THE PROJECT
Adolfo Majaliva	Mozambican	Stagiaire	Dep. Biol. Sciences	BSc (Biology)	7	Yes
Alice da Costa	Mozambican	Stagiaire	Dep. Biol. Sciences	BSc (Biology)	7	Yes
Balidy Henriques	Mozambican	Stagiaire	Dep. Biol. Sciences	BSc (Biology)	7	Yes
Celestino Uamusse	Mozambican	Stagiaire	Dep. Biol. Sciences	BSc (Biology)	7	Yes
Guilhermina Fernandes	Mozambican	Stagiaire	Dep. Biol. Sciences	(BSc (Biology)	7	Yes

2. DURABLE EQUIPMENT

(Specify type and value of equipment purchased for the project – only for pieces of equipment of a value higher than 500/item)

TYPE	VALUE (Specify currency)	EU CONTRIBUTION
1 Computer Pentium 200 MMX, 6.0 GB Hard disk, 32 MB RAM Memory and Diskette Unit 1.44 Mbytes	1980 US$	100%
1 Monitor 15" S/XGA, 2 MB Memory Video, MS Mouse, Mini-Tower Case + 200 Watt P/S	583 US$	100%
1 APC Smart/VS 650 VA UPS	849.2US$	100%
1 CD – ROM 24X Speed	231 US$	100%
1 Sound Blaster 64	302.5US$	100%
1 Pair of 80 Watt Speakers	112.8US$	100%
1 DeskJet Colour Printer 690 c	940.5US$	100%