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Annexe 1

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GROFLO Final Report Part 1

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

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

COORDINATOR

NETHERLANDS INSTITUTE OF ECOLOGY
CENTRE FOR ESTUARINE AND COASTAL ECOLOGY
P.O. BOX 140
4400 AC YERSEKE
THE NETHERLANDS

PROF. DR. HEMMINGA MARTEN
E-M : hemminga@cemo.nioo.knaw.nl
TEL : 31-113-577472
FAX : 31-113-573616

CONTRACTORS

KENYA MARINE AND FISHERIES RESEARCH INSTITUTE
P.O. BOX 81651
MOMBASA
KENYA

DR. KAZUNGU JOHNSON
E-M : jkazungu@recoscix.com
TEL : 254-11-475151
FAX : 254-11-472215

FREE UNIVERSITY OF BRUSSELS
INSTITUTE OF ENVIRONMENTAL RESEARCH
PLEINLAAN 2
1050 BRUSSELS
BELGIUM

PROF. DR. TACK JURGEN
E-M : jtack@vub.ac.be
TEL : 32-2-6293410
FAX : 32-2-6293403

UNIVERSITY OF DAR ES SALAAM
INSTITUTE OF MARINE SCIENCES
P.O. BOX 668
ZANZIBAR
TANZANIA

DR. MTOLERA MATERN
E-M : mtolera@zims.udsm.ac.tz
TEL : 255-54-30741
FAX : 255-54-33050

STOCKHOLM UNIVERSITY
DEPARTMENT OF ZOOLOGY

10691 STOCKHOLM
SWEDEN

DR. JOHNSTONE RON
E-M : ron.johnstone@awtensight.nsw.gov.au
TEL : 61-2-93340735
FAX : 61-2-93340948

EDUARDO MONDLANE UNIVERSITY
DEPARTMENT OF BIOLOGICAL SCIENCES
P.O. BOX 257
MAPUTO
MOZAMBIQUE

MR. GOVE DOMINGOS
E-M : idomio@biologia.uem.mz
TEL : 258-1-490009
FAX : 258-1-492176

UNIVERSITY OF LISBON
GUIA MARINE LABORATORY
ESTRADA DO GUINCHO
2750 CASCAIS
PORTUGAL

DR. PAULA JOSE
E-M : jpaula@fc.ul.pt
TEL : 351-1-4869211
FAX : 351-1-4869720

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Abstract

Objectives

To assess the significance of changing inputs of groundwater - and the anthropogenic substances it contains - for Eastern African nearshore ecosystems

To meet the general objective of the project, three more specific objectives were pursued:

(1) To construct a model of groundwater flow along the Eastern African coast.

(2) To elucidate differences in nearshore community structures and ecosystem functions in relation to groundwater outflow.

(3) To elucidate the importance of groundwater as a vector of anthropogenic inputs into the coastal zone.

Activities and methodologies

The project consisted of three work packages.

Work package 1: Constructing a model of groundwater flow along the Eastern African coast

Work package 2: Elucidating differences in nearshore community structures and ecosytem functions in relation to groundwater outflow

(a) Groundwater flow and the productivity and vitality of lagoon seagrasses

(b) Groundwater flow and macrobenthos in seagrass systems

(c) Search for changes in groundwater flow as recorded by elemental changes in biogenic carbonates

Work package 3: Elucidating the importance of groundwater as a vector of anthropogenic inputs into the coastal zone

(a) Groundwater inputs of pollutants into the coastal zone

(b) Effects of pollutants on microbial remineralisation and community metabolism

(c) Effects of pollutants on community structure

(d) Socio-economic studies

Results obtained

The general conclusion of the GROFLO project is that the East African nearshore coastal ecosystem is affected by the amount of groundwater outflow and by its quality. The data collected showed a strong impact of groundwater outflow on a number of components of the back-reef lagoon ecosystem. Sites with high groundwater outflow displayed a lower seagrass species diversity than sites with low groundwater outflow. Seagrasses are “structuring species”, which means that they constitute an important component of the system. Changes in seagrass vegetation can affect the whole ecosystem. Results also indicate that anthropogenically induced 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 was indicative of groundwater discharge. And, a proliferation of green macroalgae was observed at the beach sites with groundwater influence. 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 rates and groundwater quality.

The socio-economic studies provided valuable baseline data on water usage patterns. Analysis of the water quality of the wells yielded results on levels of contamination with micro-oganisms, nutrients and pesticides that call for caution. The results will be coveyed to the local administrators.

The groundwater model that was developed during the GROFLO project, proved to be an an indispensable tool for the field studies. The model is now available on CD-ROM, and can be obtained from VUB. It can be a valuable aid to coastal managers, e.g. for use in Environmental Impact Studies to predict effects of changes in groundwater use on the outflow rates into the coastal zone.

Final Summary Report

Contents

Objectives

Not only in riverine areas, but everywhere along the coast a dynamic balance exists between the seaward outflow of groundwater and salt water intrusion into coastal freshwater aquifers. Groundwater is a resource of enormous significance. In the Eastern African coastal zone, withdrawal of groundwater occurs in many places to supply an increasing number of beach hotels and settlements of the local population. Concomitant with a decrease in groundwater levels, due to withdrawal, it is also likely that these waters exhibit elevated nutrient and pollutant concentrations. This is largely due to poor soil conservation and agricultural practices as well as inappropriate disposal of effluents into pits or sink holes.

Despite this increasing anthropogenic pressure on groundwater reservoirs, little information exists regarding the importance of groundwater for ecological processes and structures in the nearhore environment. However, it can be expected that the diffuse groundwater outflow in non-riverine coastal areas will potentially affect nearshore marine ecosystems by (1) moderating saline conditions; (2) by delivering nutrients such as N,P, Si used by primary producers; (3) by delivering pollutants.

The key objective of the GROFLO project is:

To assess the significance of changing inputs of groundwater - and the anthropogenic substances it contains - for Eastern African nearshore ecosystems

To meet the general objective of the project, three more specific objectives were pursued:

(1) **To construct a model of groundwater flow along the Eastern African coast.**

(2) **To elucidate differences in nearshore community structures and ecosysytem functions in relation to groundwater outflow.**

(3) **To elucidate the importance of groundwater as a vector of anthropogenic inputs into the coastal zone.**

Activities and methodologies

The following abbreviations are used for the GROFLO partners:

KMFRI: Kenya Marine and Fisheries Research Institute
NIOO-CEMO: Netherlands Institute of Ecology, Centre for Estuarine and Coastal Ecology
VUB: Free University, Institute of Environmental Research
IMS: University of Dar es Salaam, Institute of Marine Sciences
SU: Stockholm University, Department of Zoology
GML: University of Lisbon, Guia Marine Laboratory
UEM: Eduardo Mondlane University, Department of Biological Sciences

The project consisted of three work packages.

Work package 1: Constructing a model of groundwater flow along the Eastern African coast

This part was the responsibility of **VUB** in cooperation with **KMFRI**, **IMS** and **UEM**. Modelling of the groundwater flow was done in two phases. In the first 4-month phase, groundwater models were made on coarse grids. The models presented a general idea of groundwater outflow in the coastal zone which allowed localisation of the sites for ecological studies during the first GROFLO workshop. In the second phase more detailed models were made by **VUB** based on topographic data obtained in cooperation with **KMFRI**, **IMS** and **UEM**.

Local hydrological fieldwork to calibrate the model was carried out by **KMFRI** and **VUB**. The data on groundwater-outflow rates provided by the model were used by all GROFLO partners for interpretation of the ecological data.

Work package 2: Elucidating differences in nearshore community structures and ecosytem functions in relation to groundwater outflow

(a) Groundwater flow and the productivity and vitality of lagoon seagrasses

The work on seagrasses was the responsibility of **NIOO-CEMO** in cooperation with **KMFRI**, **IMS** and **UEM/GML**. The relation between seagrasses and groundwater outwelling in nearshore lagoons was studied. Seagrass species composition and coverage were determined. At several plots along transects, above-ground biomass and shoot density were also measured. The importance of groundwater as a source of nutrient input was studied by determining stable nitrogen isotopes ($\delta^{15}N$) in seagrass leaves. Seagrass leaf growth rates were measured by **NIOO-CEMO** and **UEM. NIOO-CEMO** investigated if signs of meadow deterioration can be detected in reef lagoons as a result of changed groundwater flow and quality near concentrations of beach hotels by determining age structure, and shoot recruitment and mortality rates from leaf scars on seagrass stems.

(b) Groundwater flow and macrobenthos in seagrass systems

The assessment of the macrobenthic community structures were carried out on Zanzibar Island (Tanzania) and Inhaca Island (Mozambique). **GML** and **UEM** were responsible for the coordination and evaluation of this part of the work. Consequently, the first sampling campaingns and initial analyses were carried out in Mozambique. In the second phase of the work, **IMS** carried out sampling surveys on Zanzibar Island (Tanzania), in interaction with **GML/UEM**.

Sampling was performed on a seasonal basis. The recovered animals were identified and assigned to family groups, and their abundance and biomasses worked out. The influence of groundwater was assessed by plotting in a comparative way the curves of dominance, abundance and biomass (ABC curves).

(c) Search for changes in groundwater flow as recorded by elemental changes in biogenic carbonates

This part of the project was carried out by **VUB** in cooperation with **KMFRI**. The purpose of the work was to investigate the potential of tropical mollusc shells to record and archive environmental conditions. Molluscs will store information in their shells which can be retrieved by analysing shells along a growth axis, which is equivalent to a time axis. Mollusc shells were investigated with respect to the occurrence of isotopes of a number of chemical elements to study changes in relation to different levels of freshwater efflux. Secondly, historical changes in the biogenic carbonates of these species, collected from various sites, were studied by analysing carbonate deposits of increasing age. Mollusc shells were analysed by Laser Ablation - ICP-MS along growth for trace metals (Pb, Cu, Zn, Co) and by isotope radio mass spectrometry for $\delta^{18}O$ and $\delta^{13}C$.

Work package 3: Elucidating the importance of groundwater as a vector of anthropogenic inputs into the coastal zone

(a) Groundwater inputs of pollutants into the coastal zone

Part of this study was carried out on Zanzibar Island by **IMS** in close cooperation with **SU**. Groundwater samples were collected on a seasonal basis and chemically analysed for nutrients and polyaromatic hydrocarbons (PAH), PCB's, DDT, and a range of pesticides. PH, PCB and pesticide analyses were conducted on sediment samples taken from the selected coastal sites for further assessment of the impact of groundwater pollution.

In Kenya, **KMFRI** determined dissolved inorganic nutrient levels of the nearshore coastal waters and sediment where groundwater outflow occurs, to assess the influence of groundwater on lagoonal water quality. In addition, the spatial and temporal variability in the level of bacterial contamination in ground and lagoonal waters in the study areas was determined. As indicators of microbial contamination levels, faecal coliforms, *E. coli* and faecal *Streptococci* were enumerated.

(b) Effects of pollutants on microbial remineralisation and community metabolism

These studies were carried out by **KMFRI** and **SU/IMS**, on in Kenya and on Zanzibar Island, respectively. Nutrient regeneration process measurements were carried out in areas receiving anthropogenic inputs (via groundwater or otherwise) and in control areas which receive unpolluted groundwater. Microbial process measurements include measurement of denitrification, nitrification, and ammonification rates.

(c) Effects of pollutants on community structure

Estimations were made of macrophyte community structure (including epiphytic cover), and sediment meiofauna population structure, to compare sites receiving groundwater with and without anthropogenic contamination, and between these sites and sites receiving non-groundwater anthropogenic inputs. These studies were carried out by **IMS**, **KMFRI** and **UEM/GML**. Species composition, coverage and biomass of algae and seagrasses was determined along transects. The effect of low pH and salinity (measured in sites with groundwater) on macrophyte productivity was determined by IMS. The epiphytic load on seagrasses was determined by **KMFRI** and **UEM/GML**

IMS/SU studied meiofaunal community structure on Zanzubar Island. Animals were identified to major taxa. Multidimensional scaling ordination was done to distinguish between sites receiving fresh water and those of normal saline conditions.

KMFRI and **UEM** also investigated plankton distribution and productivity in lagoons receiving polluted and unpolluted groundwater. **KMFRI** collected plankton samples for species composition. Chlorophyll-a and B.O.D. samples were collected and analysed. **UEM** took zooplankton samples for identification to major taxonomic groups only, since local species are still not described.

(d) Socio-economic studies

Although not included in the technical annex, the original proposal contained a modest investigation of the uses of groundwater in the coastal zone of Zanzibar. **SU/IMS** examined water usage patterns for different villages on Zanzibar Island. In addition, **UEM** did a comparable study on Inhaca Island. At both locations, the quality of the water was investigated as well. In Kenya, **KMFRI** studied the potability, nutrient levels and microbiological water quality of a number of boreholes and wells along the coast.

Results achieved

Work package 1: Constructing a model of groundwater flow along the Eastern African coast

A groundwater model for the Kenyan coast, Zanzibar island (Tanzania) and Inhaca island (Mozambique) was developed on the basis of existing data on aquifers and the water balance in Eastern Africa coastal areas and on hydrological field data gathered during this project. The results of this modellisation will be distributed through the World Wide Web and a CD-ROM with interactive groundwater flow maps. The coarse-grid groundwater model showed a very clear correlation between groundwater flow and the distribution of the mangroves along the Kenyan coast. At those locations, salinity measured in boreholes was lower than 1‰, which confirmed the predicted groundwater outflow.

The study showed the importance of grid size to link groundwater models to ecological data. Significant differences in groundwater flow were observed at the same site in function of the grid size used in the model. Those differences can be explained by a change in the mean groundwater flow at a certain point when the grid size is changing. When we compared the different grid sizes with the distribution of the mangrove ecosystem, we came to optimal grid sizes to explain ecological processes: 5x5 km for the Kenyan coast, 2x2 km for Zanzibar island and 750x750 m for Inhaca island. The differences in grid size used are comparable with the differences in catchment areas of the three study areas. Whether there is indeed a positive correlation between grid size and catchment area should be the focus of future research.

Local hydrological fieldwork in Kenya showed groundwater dynamics that indicate relatively large volumes of groundwater discharge. From estimations of groundwater volume fluxes, it was established that groundwater volume is roughly equivalent to 2 and 10% of the total lagoon volume. This shows that there is enormous supply of groundwater to coastal beaches and lagoons. Groundwater is therefore an important component of the coastal nearshore environment.

Work package 2: Elucidating differences in nearshore community structures and ecosytem functions in relation to groundwater outflow

(a) Groundwater flow and the productivity and vitality of lagoon seagrasses

Studies on seagrass species diversity and abundance showed that sites with a relative high groundwater outflow displayed a lower species diversity than sites with a relative low groundwater outflow. *Thalassodendron ciliatum* dominated at sites with high groundwater outflow rates, while *Thalassia hemprichii* showed higher coverage at sites with low groundwater outflow. Porewater salinities were significantly lower at locations with high groundwater-outflow rates indicating supply of freshwater. Stable nitrogen isotope signatures of seagrass leaves showed a significant increase with increased groundwater-outflow rates. This suggests that the nitrogen source for these plants was, at least for a part, groundwater. In addition, lagoons with high population densities had highest $\delta^{15}N$ values, indicative of anthropogenic nitrogen inputs. Differences in optimum salinity for growth between species, and competition for nitrogen, may explain the observed pattern in species diversity and abundance.

All *T. ciliatum* populations in the present study appeared to be either expanding or in steady state. This suggests that the environmental quality of the back-reef lagoons is still suitable for seagrass development, which is indicative of a healthy ecosystem. 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.

At Inhaca Island (Mozambique), there was no strong evidence of groundwater outflow at the study areas, due to the fact that catchment area of the island is too small to produce large aquifers. Nevertheless, measurement of slightly reduced porewater salinity and enhanced nutrient concentrations suggest diffuse groundwater outflow at the *T. ciliatum* meadow.

The present study suggests that changes in the amount or quality of groundwater outflow along the East African coast will affect the seagrass species composition in lagoons. Specifically, the occurrence of *T. hemprichii* and *T. ciliatum* are likely to be affected. At present, information on the function of these species in the ecosystem of back-reef lagoons is absent, which impedes predictions of possible consequences.

(b) Groundwater flow and macrobenthos in seagrass systems

On Inhaca Island (Mozambique), macrofauna biomass showed marked fluctuations between seasons with more homogeneous values during the dry season and a very high variability during the wet season. The ecological disturbance presented by the different communities sampled in the dry and wet season in the studied mangrove area were not related with anthropogenic pollution factors. The natural disturbance was a result of high stress due to low oxygen, high salinity and temperature levels mainly during the dry season.

On Zanzibar Island, polychaetes were the most prevalent and were taken as the most representative macrobenthos group. A comparison of polychaete densities from different study sites indicates no significant differences between seawater and freshwater influenced areas. However, when the freshwater influenced sites are compared, one site appears to have the lowest density. The groundwater reaching this area drains from an intensively rice cultivated area which contains agrochemicals which could be responsible for the low polychaete numbers at the groundwater sites. The high amounts of DDT, possibly originating from house fumigation, has been measured at this site.

(c) Search for changes in groundwater flow as recorded by elemental changes in biogenic carbonates

Analysis of an *Isognomon* shell for a series of minor and trace elements, including Ba, Rare Earth Elements, and trace metals showed clear differences between sites. These can be attributed to differences in freshwater flow and proximity of pollution source. Analysis of some major and trace elements, $\delta^{18}O$ and $\delta^{13}C$ along the growth axis of shells provided information on seasonal evolution of environmental parameters such as sea surface temperature and freshwater run-off. Systems with predominance of surface run-off over groundwater flow clearly differentiate from systems where freshwater supply is mainly via the latter process. It can be concluded that bivalve shells are potentially powerful archives of environmental change, especially if possibilities exist to obtain historic specimens and compare these with modern ones.

Work package 3: Elucidating the importance of groundwater as a vector of anthropogenic inputs into the coastal zone

(a) Groundwater inputs of pollutants into the coastal zone

Pesticides (lindane and DDT), originating from agricultural areas and/or sewage systems, were detected in different sites on Zanzibar Island receiving groundwater. DDT, that is associated with fumigation in townships, has been found at two groundwater sites. Low levels of DDT were also detected at a saline site, possibly as a result of dilution effect of the groundwater.

On Zanzibar Island, high levels of ammonia were detected in two groundwater sites, but phosphate concentrations were generally low at all sites. The booming tourist development in the area may be a possible source of higher nutrient levels in the groundwater. A groundwater site in a mangrove bay showed very low ammonia levels, while the groundwater source had the highest groundwater ammonia levels. This may point to the importance of mangrove stands as a filtering system of land based pollution and that macrophytes benefit from such nutrients indirectly.

In Kenya, results showed considerable additional contribution of nutrients from streams associated with groundwater outflow. Concentrations in the streams were way above oceanic values. Nitrate was found to be the most dominant form of dissolved nitrogen contributed by the groundwater. These nutrient additions resulted in elevated nutrient values in the lagoonal water column, with those stations next to the beach having relatively higher nutrient concentrations compared to those stations in offshore deep lagoonal waters.

A higher number of microbiota indicator organisms were enumerated in the groundwater collected from the seepage points in Kenya (on the beach before mixing with the seawater) than in the seawater in the lagoons. This is an indication that groundwater is generally more contaminated than lagoonal water but once groundwater mixes with seawater, indicator organisms are exposed to the antiseptic properties of seawater leading to die-offs of these organisms. Groundwater may not be the only source of contamination of the lagoonal waters. Discharges from beach establishments adjacent to these transects may be significant sources of faecal or raw sewage pollution as compared to the groundwater sources.

(b) Effects of pollutants on microbial remineralisation and community metabolism

In Kenya, relatively low nitrification rates were observed in the sediments within the study areas indicating unfavourable nitrification conditions. On Zanzibar Island, mean nitrogen fixation rates decreased as when moving further away from the source of groundwater.

(c) Effects of pollutants on community structure

<u>Macro- (and micro-) algae, seagrasses and epiphytes:</u>

On Zanzibar Island, groundwater sites were characterised by luxurious growth of green algae and low numbers of macroalgal species. The species diversity increased with distance from the freshwater site. *Ulva pertusa* was only found at groundwater release points. Low salinity detrimental to *Gracilaria salicornia* and cultured *Eucheuma denticulatum*. Groundwater sites had higher number of benthic microalgal species than normal saline sites. The biomass were also highest in freshwater sites

In Kenya, results of macroalgae investigations at the two lagoons indicated that the impacts of groundwater are obvious by the proliferation of green algae at the beach sites where freshwater influence is highest. However, the high diversity of other algae groups like the red algae indicate that any effects of eutrophication by the groundwater at the study sites may be termed as mild eutrophication. The epiphytic load was slightly higher on the *Thalassodendron ciliatum* stems at one site during the rainy months. This peak in the rainy months suggests the influence of nutrient-rich water particularly at that site where the groundwater outflow effect was highest.

On Inhaca Island (Mozambique), no groundwater effect was detected neither with respect to environmental parameters, nor with respect to species composition, percentage cover, biomass and growth of sea-grass and epiphytes. The reason for this can be due to the small area of the island, which implies a small catchment area and small reservoir of groundwater.

<u>Phytoplankton:</u>

In Kenya, phytoplankton species composition, cell abundance and diversity were affected by different levels of anthropogenic input into the lagoons. The species *Oscillatoria* was associated with high nutrients and was abundant in nearshore stations receiving higher nutrients. Though phytoplankton cell abundance was more or less similar in the lagoons during wet and dry seasons, a gradient in abundance was observed from the beach to reef stations with higher values being obtained from the beach and middle stations as compared to the reef which were located away from the beach. Chlorophyll-a and B.O.D values were directly influenced by groundwater seepage into the lagoon. Higher values were obtained at nearshore beach stations as compared to the reef stations due higher amounts of nutrients at the beach sites.

Zooplankton:

The effects of groundwater into the studied lagoons in Kenya was reflected in zooplankton species composition. The presence of "indicator species", more specifically mysids, at particular spots and throughout the year, was indicative of groundwater discharge. The higher numbers of indicator species observed near the beach was a reflection of the slightly more nutritious waters with lower salinity at the beach than next to the reefs. Relatively higher density of fish eggs and larvae occurring at the mid-stations of the two lagoons also reflected the importance of these lagoons as nursery grounds. These areas, which also had seagrass cover, provided good habitat for meroplankters like: amphipods, isopods, squid larvae and juvenile fish.

On Inhaca Island (Mozambique), hydrographic conditions (water temperature and salinity) are homogeneous throughout the studied bay, which indicates good mixing and very low impact of groundwater discharge in the bay. Zooplankton abundance was generally similar all the year round, except for brachyura and some gastropod larvae. There was no relation between water temperature and salinity with zooplankton abundance. A groundwater effect was not detected in the zooplankton abundance and composition in the studied bay, which may be due to the small catchment area of the island. This implies small differences in groundwater outflow rates as can be seen in the model.

Meiofauna:

Results on meiofauna obtained on Zanzibar Island at fresh water sites did not clearly separate from the saline sites and lack any clear pattern. This is considered to be due to the nature of the freshwater input in the intertidal areas where the tidal waters dilute the impact of the incoming groundwater for a large part of the day.

(d) Socio-economic studies

Water usage patterns:

On Zanzibar Island, the majority of water in the villages is used for sanitary purposes, followed by cooking, and drinking, and then washing dishes or clothes, only little is used for cleaning or feeding animals. The amount of water used on average was calculated at 33 $l\ d^{-1}$ for children and 55 $l\ d^{-1}$ for adults. The overall weighted average water use of a tourist on the East Coast was calculated at 674 $l\ d^{-1}$. This is 15 times the average demand of local residents. A major proportion of the sewage from villages is leaking into the ground. As wells are often located close to houses, the amount of nutrients leaching into the groundwater and/or into the ocean could therefore be substantial. However, 40% of the hotels and guesthouses interviewed, stated that they had open tanks leaking into fissures and caves.

On Inhaca Island (Mozambique), the majority of water is used for laundry, followed by showering, cooking and drinking, and washing dishes and others. Almost nothing is used for watering the plants, since the main type of agriculture practiced in the island relies only on rainwater. The amount of water used per person per day was similar among the studied villages and about half the amount consumed on Zanzibar Island. The water consumption at Hotel Inhaca was more than four times as much as in the villages.

Water quality:

In Kenya, examination of the nutrient concentrations in the boreholes/wells neighbouring the two study plots indicated highly elevated levels. Nitrate-Nitrogen formed the most dominant (ca. 95%) source of dissolved inorganic nitrogen in all the wells investigated. The high nutrient concentrations could be a reflection of the population pressures and the usage of pit - latrines as main source of sewage disposal by coastal communities. The results of analysis of nutrients in wells on Zanzibar Island also show a predominance of nitrate and nitrite over ammonia and phosphate. On Inhaca Island (Mozambique), nutrient concentrations in well water were far below the acceptable limits for human consumption indicating that, regarding the chemical component, groundwater of Inhaca Island is still potable. There are no significant differences among the studied villages concerning the chemical composition of the water. This indicates that human impact in chemical terms is low.

In terms of microbiological contamination, boreholes/wells of the densily populated site in Kenya had about four times more counts of contamination indicator species than the other sites boreholes. The majority of the groundwater from the boreholes and wells in the studied areas is not potable as the levels of faecal coliforms, *E. coli* and faecal streptococci exceed those recommended by the Kenya Bureau of Standards and EEC guide. From all wells sampled in the villages on Inhaca Island, 84 % showed values of faecal coliforms that are higher than the maximum acceptable value. Reasons for this can be that the majority of families in the island do not have toilets. The lowest contanimation was observed in the economic center of the island, which is the most urbanised village. The existence of latrines for every house significantly diminishes the faecal contamination of the water through runoff.

Conclusions

The general conclusion of the GROFLO project is that the East African nearshore coastal ecosystem is affected by the amount of groundwater outflow and by its quality. The data collected 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. The epiphytic load on seagrass stems was slightly higher at groundwater outflow sites. Seagrasses are "structuring species", which means that they constitute an important component of the system. Changes in seagrass vegetation can affect the whole ecosystem. Results also indicate that anthropogenically induced 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 rates and groundwater quality.

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. 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. Determination of pesticide levels in bays, rivers and streams on Zanzibar Island showed that lindane was present at all sampling sites. DDT was more closely associated with townships rather than agricultural areas and may be a result of fumigation of houses. The results on micro-organisms, nutrients and pesticides will be coveyed to the local administrators.

The groundwater model that was developed during the GROFLO project, proved to be an an indispensable tool for the field studies. The model is now available on CD-ROM, and can be obtained from VUB upon request. It can be a valuable aid to coastal managers, e.g. for use in Environmental Impact Studies to predict effects of changes in groundwater use on the outflow rates into the coastal zone.

The main benefit of the GROFLO project is the generation of baseline data on the relation between groundwater outflow and the functioning of Eastern African nearshore ecosystems. A second benefit of the project is collaboration and training. The GROFLO project has been a multi-disciplinary study which has facilitated collaboration between scientists within and outside the Eastern African Region. The project has also demonstrated how North-South scientific collaboration should develop with the view to transfer expertise and facilite on-the-job-training. Summarizing, the GROFLO project can be rated as a success in that its results are relevant to solving management questions, and because the project has a long term benefit to recipient countries/institutions in terms of expertise.

Publications and students

Publications in peer reviewed scientific journals and books

Gössling S. and Ron W. Johnstone, R.W. Causes and Consequences of Groundwater Use on a Tropical Island: Zanzibar, Tanzania. Submitted to Ambio.

Johnstone, R.W. and Gössling, S. Sustainable management of groundwater resources on a tropical island: issues and dilemmas. Submitted to Coastal Management.

Johnstone, R.W. The role of groundwater as a vector for nutrient enrichment in a tropical coastal ecosystem; Zanzibar, Tanzania. To be submitted Marine Ecology Progress Series.

Kamermans, P., M.A. Hemminga, J.F. Tack, M. A. Mateo, N. Marbà, M. Mtolera, J. Stapel and A. Verheyden. Groundwater effects on diversity and abundance of lagoonal seagrasses in Kenya and on Zanzibar Island (East Africa). To be submitted to Limnology and Oceanography.

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More papers are in preparation.

MSc and PhD students

Ricardo Costa, MSc student, Portugal
Emília Fumo, MSc student, Mozambique
Erik Hansson, MSc student, Sweden
Johan Hast, MSc student, Sweden

Pedro Fidalgo, PhD student, Portugal
Stefan Gosseling, PhD student, Sweden
Domingos Gove, PhD student, Mozambique
Aviti Mmochi, PhD student, Tanzania
Anouk Verheyden, PhD student, Belgium

Consolidated Scientific Report

Contents

Objectives

Not only in riverine areas, but everywhere along the coast a dynamic balance exists between the seaward outflow of groundwater and salt water intrusion into coastal freshwater aquifers. Groundwater is a resource of enormous significance. In the Eastern African coastal zone, withdrawal of groundwater occurs in many places to supply an increasing number of beach hotels and settlements of the local population. Concomitant with a decrease in groundwater levels, due to withdrawal, it is also likely that these waters exhibit elevated nutrient and pollutant concentrations. This is largely due to poor soil conservation and agricultural practices as well as inappropriate disposal of effluents into pits or sink holes.

Despite this increasing anthropogenic pressure on groundwater reservoirs, little information exists regarding the importance of groundwater for ecological processes and structures in the nearhore environment. However, it can be expected that the diffuse groundwater outflow in non-riverine coastal areas will potentially affect nearshore marine ecosystems by (1) moderating saline conditions; (2) by delivering nutrients such as N,P, Si used by primary producers; (3) by delivering pollutants.

The key objective of the GROFLO project is:

To assess the significance of changing inputs of groundwater - and the anthropogenic substances it contains - for Eastern African nearshore ecosystems

To meet the general objective of the project, three more specific objectives were pursued:

(1) **To construct a model of groundwater flow along the Eastern African coast.** Existing data on aquifers and the water balance and hydrological field data were collected with the aim to construct a model of groundwater outflow in three Eastern African coastal areas (Fig. 1) that will allow a prediction of the response of the hydrological system to anthropogenic disturbances.

(2) **To elucidate differences in nearshore community structures and ecosystem functions in relation to groundwater outflow.** Community structures in nearshore habitats were studied in relation to different levels of groundwater outflow and quality. The effect of different levels of groundwater outflow on the productivity and population dynamics of some species of commercial value were examined. Sophisticated techniques in the field of population dynamics were applied to detect historical changes in the primary productivity and vitality of seagrass meadows and in chemical characteristics of molluscs and corals in relation to changes in groundwater outflow in recent years.

(3) **To elucidate the importance of groundwater as a vector of anthropogenic inputs into the coastal zone.** Little insight exists into the significance of groundwater as a vector for anthropogenic pollutants to the coastal zone. Accordingly, it was unclear as to whether such transport can lead to measurable increases in pollutant levels in coastal waters or whether they can influence coastal ecosystems. Therefore, part of the research efforts in the present study were aimed at elucidating these points.

Kenya: Southern half of coast

Tanzania: Zanzibar Island

Mozambique: Inhaca Island

Fig. 1. Location of GROFLO study sites in East Africa.

Activities and methodologies

The following abbreviations are used for the GROFLO partners:

KMFRI: Kenya Marine and Fisheries Research Institute
NIOO-CEMO: Netherlands Institute of Ecology, Centre for Estuarine and Coastal Ecology
VUB: Free University, Institute of Environmental Research
IMS: University of Dar es Salaam, Institute of Marine Sciences
SU: Stockholm University, Department of Zoology
GML: University of Lisbon, Guia Marine Laboratory
UEM: Eduardo Mondlane University, Department of Biological Sciences

The project consisted of three work packages.

Work package 1: Constructing a model of groundwater flow along the Eastern African coast

This part was the responsibility of **VUB** in cooperation with **KMFRI**, **IMS** and **UEM**. Modelling of the groundwater flow was done in two phases. In the first 4-month phase, groundwater models were made on grids of 8 x 8 km for Kenya, 2.5 x 2.5 km for Zanzibar Island (Tanzania) and 0.5 x 0.5 km for Inhaca Island (Mozambique). The models presented a general idea of groundwater outflow in the coastal zone which allowed localisation of the sites for ecological studies during the first GROFLO workshop held in Mombasa in March 1997. In the second phase more detailed models with grids of upto 100 x 100 m were made by **VUB** based on topographic data obtained in cooperation with **KMFRI**, **IMS** and **UEM**.

Local hydrological fieldwork (such as determination of beach groundwater table levels, discharge rates and salinity of boreholes) was carried out by **KMFRI** and **VUB**. The data on groundwater-outflow rates provided by the model were used by all GROFLO partners for interpretation of the ecological data.

Work package 2: Elucidating differences in nearshore community structures and ecosytem functions in relation to groundwater outflow

(a) Groundwater flow and the productivity and vitality of lagoon seagrasses

The work on seagrasses was the responsibility of **NIOO-CEMO** in cooperation with **KMFRI**, **IMS** and **UEM/GML**. The relation between seagrasses and groundwater outwelling in nearshore lagoons was studied. Seagrass species composition and coverage were determined from photographs taken along transects. At several plots along each transect, above-ground biomass and shoot density were also measured. The importance of groundwater as a source of nutrient input was studied by determining stable nitrogen isotopes ($\delta^{15}N$) in seagrass leaves. Seagrass leaf growth rates were measured by **NIOO-CEMO** (reconstruction technique) and **UEM** (leaf marking technique). **NIOO-CEMO** investigated if signs of meadow deterioration can be detected in reef lagoons as a result of changed groundwater flow and quality near concentrations of beach hotels by determining age structure, and shoot recruitment and mortality rates from leaf scars on seagrass stems.

(b) Groundwater flow and macrobenthos in seagrass systems

The assessment of the macrobenthic community structures were carried out on Zanzibar Island (Tanzania) and Inhaca Island (Mozambique). **GML** and **UEM** were responsible for the coordination and evaluation of this part of the work. Consequently, the first sampling campaingns and initial analyses were carried out in Mozambique. In the second phase of the work, **IMS** carried out sampling surveys on Zanzibar Island (Tanzania), in interaction with **GML/UEM**.

Sampling was performed on a seasonal basis. Sampling was conducted during spring low tides, using a metallic corer. The substrate core was wet sieved (mesh size I mm). Bengal-Rose as a dye, 4% formalin as fixative, and Ludox colloidal silica for macrobenthos extraction were used. The recovered animals were identified and assigned to family groups, and their abundance and biomasses worked out. The influence of groundwater was assessed by plotting in a comparative way the curves of dominance, abundance and biomass (ABC curves).

(c) Search for changes in groundwater flow as recorded by elemental changes in biogenic carbonates

This part of the project was carried out by **VUB** in cooperation with **KMFRI**. The purpose of the work was to investigate the potential of tropical mollusc shells to record and archive environmental conditions. Molluscs will store information in their shells in a chronological order rather than integrating the signal as is the case for soft tissue. This information can be retrieved by analysing shells along a growth axis, which is equivalent to a time axis. Shells are easily preserved over considerable (even historic) time scales and they are less prone to contamination during sampling and storage, compared to soft tissue samples.

Mollusc shells were investigated with respect to the occurrence of isotopes of a number of chemical elements to study changes in relation to different levels of freshwater efflux. Secondly, historical changes in the biogenic carbonates of these species, collected from various sites, were studied by analysing carbonate deposits of increasing age. Mollusc shells were analysed by Laser Ablation - ICP-MS along growth axes of the banded carbonate substrate. During ICP-MS analysis, information was gathered on trace metals (Pb, Cu, Zn, Co) reflecting the antropogenic stress on these environments. Separate cut-outs were prepared for $\delta^{18}O$ and $\delta^{13}C$ analysis by isotope radio mass spectrometry.

Work package 3: Elucidating the importance of groundwater as a vector of anthropogenic inputs into the coastal zone

(a) Groundwater inputs of pollutants into the coastal zone

Part of this study was carried out on Zanzibar Island by **IMS** in close cooperation with **SU**. Groundwater samples were collected on a seasonal basis and chemically analysed for nutrients and polyaromatic hydrocarbons (PAH), PCB's, DDT, and a range of pesticides. PH, PCB and pesticide analyses were conducted on sediment samples taken from the selected coastal sites for further assessment of the impact of groundwater pollution. Pesticides from water samples were extracted by shaking with dichloromethane. Dried sediment samples were ground with sodium sulphate and the resulting powder was extracted by a mixture of cyclohexane and acetone. Pesticide residue analysis was done using a SE-30 column and electron capture detector (ECD) and OV-1701 nitrogen/phosphorus detector (NPD). Ammonia, phosphate, oxygen and pH were also analysed.

In Kenya, **KMFRI** determined dissolved inorganic nutrient levels of the nearshore coastal waters and sediment where groundwater outflow occurs, to assess the influence of groundwater on lagoonal water quality. In addition, the spatial and temporal variability in the level of bacterial contamination in ground and lagoonal waters in the study areas was determined. As indicators of microbial contamination levels, faecal coliforms, *E. coli* and faecal *Streptococci* were enumerated.

(b) Effects of pollutants on microbial remineralisation and community metabolism

These studies were carried out by **KMFRI** and **SU/IMS**, on in Kenya and on Zanzibar Island, respectively. Nutrient regeneration process measurements were carried out in areas receiving anthropogenic inputs (via groundwater or otherwise) and in control areas which receive unpolluted groundwater. Microbial process measurements include measurement of denitrification, nitrification, and ammonification rates.

(c) Effects of pollutants on community structure

Estimations were made of macrophyte community structure (including epiphytic cover), and sediment meiofauna population structure, to compare sites receiving groundwater with and without anthropogenic contamination, and between these sites and sites receiving non-groundwater anthropogenic inputs. These studies were carried out by **IMS**. Macrophyte species composition and biomass were studied at sites with and without (controls) groundwater. Additional sampling were at 1.5 - 2 km away from the borehole and along the reefs. The effect of low pH and salinity (measured in sites with groundwater) on macrophytes were established using a dose-response curve of photosynthetic oxygen evolution, measured as a function of photon flux densities using the Illuminova light dispensing system. In vivo chlorophyll fluorescence was also measured using a Plant Efficiency Analyser. The productivity of seagrasses and macroalgae, including the economically important Rhodophyte *Eucheuma denticulatum*, was assessed. Biomass of microphytobenthos was estimated by determining the amount of chlorophyll *a* in the upper 2 cm sediment. Species composition was also assessed.

After the start of the project, this work package was extended with studies on macrophytes by **KMFRI**. Permanent line transects were established, perpendicular to the beach in the study areas and sampling was undertaken during the low spring tide periods. Species composition of algae and seagrasses was determined along transects. Percentage cover in the field of algae was obtained using a quadrat. Algae were cropped for biomass estimates. The line intercept transect method was used to evaluate algal composition in transects. **UEM/GML** determined seagrass species composition, percentage cover and biomass along transects.

The epiphytic load on seagrasses was determined by **KMFRI** and **UEM/GML**. The epiphytic load was considered to be an estimate of the dry weight of epiphytes per sampling area. The seagrass and epiphytes were separated and dried. The epiphyte/seagrass ratio was calculated.

IMS/SU studied meiofaunal community structure on Zanzubar Island. A polycarbonate tube was used to sample sediments (5 cm deep/ 10 cm deep). Sampling was done during spring low tide and samples were analysed for meiobenthos counts, sediment organic content and mean grain size. Samples for meiobenthos counts were washed over a sieve (mesh size 40 µm) and animals extraction was facilitated by Ludox MT 40 (colloidal silica). Animals were identified to major taxa, and counted under a stereo dissecting microscope. Multidimensional scaling ordination was done to distinguish between sites receiving fresh water and those of normal saline conditions.

KMFRI and **UEM** also investigated plankton distribution and productivity in lagoons receiving polluted and unpolluted groundwater. **KMFRI** collected plankton samples using a 25 µm (phytoplankton) and 332 µm (zooplankton) mesh size plankton nets during low tide. Collected samples were preserved in 5% formalin, labeled and reserved for laboratory analysis. Species composition was analysed. Chlorophyll-a and B.O.D. samples were collected and analysed. **UEM** took zooplankton samples twice a month, through a year. The timing of sampling was during the neap tides. The high-tide period was chosen because during low tide the low depth of the water column did not permit effective zooplankton trawls to be performed. Two plankton nets (125 and 330 µm) were used for zooplankton samples. Samples were fixed and preserved in buffered 4% formaldehyde. Identification was made to major taxonomic groups only, since local species are still not described.

(d) Socio-economic studies

Although not included in the technical annex, the original proposal contained a modest investigation of the uses of groundwater in the coastal zone of Zanzibar. **SU/IMS** examined water usage patterns for different villages on Zanzibar Island. In addition, **UEM** did a comparable study on Inhaca Island. At both locations, the quality of the water was investigated as well. In Kenya, **KMFRI** studied the potability, nutrient levels and microbiological water quality of a number of boreholes and wells along the coast.

Results achieved

Work package 1: Constructing a model of groundwater flow along the Eastern African coast

A groundwater model for the Kenyan coast, Zanzibar island (Tanzania) and Inhaca island (Mozambique) was developed on the basis of existing data on aquifers and the water balance in Eastern Africa coastal areas and on hydrological field data gathered during this project. The results of this modellisation will be distributed through the World Wide Web and a CD-ROM with interactive groundwater flow maps.

The coarse-grid groundwater model showed a very clear correlation between groundwater flow and the distribution of the mangroves along the Kenyan coast. At those locations, salinity measured in boreholes was lower than 1‰, which confirmed the predicted groundwater outflow. To reach a model resolution of less then 200x200 m as foreseen in the project proposal, the Kenyan coastal zone was modeled between the coastal line and a parallel line 20 km inland. At the same time the Kenyan coast was divided in three sub-basins: (1) between Tana River and Malindi, (2) between Malindi and Mombasa, and, (3) between Mombasa and Vanga. Those sub-basins are bordered by no flow boundaries (rivers). On the landside we used the flow conditions as calculated by the coarse-grid model. In the cases of Zanzibar island (Tanzania) and Inhaca island (Mozambique) the maximum of 499 rows and 499 columns used by the model was sufficient to model the groundwater flow up to a resolution of less than 200x200 meters.

The study shows the importance of grid size to link groundwater models to ecological data. Significant differences in groundwater flow were observed at the same site in function of the grid size used in the model. Those differences can be explained by a change in the mean groundwater flow at a certain point when the grid size is changing. More important is the question how to link our results to ecological phenomenons. The ecology of estuarine ecosystems is especially influenced by groundwater outflow. Groundwater flow and groundwater outflow are two completely different processes. However, groundwater flow can be an indication of the quantity of groundwater outflow. Groundwater outflow is most often very localized. However, due to current and tidal movement the groundwater outflow at one point is spread over a much bigger area.

When we compared the different grid sizes with the distribution of the mangrove ecosystem, we came to optimal grid sizes to explain ecological processes: 5x5 km for the Kenyan coast (Fig. 2a), 2x2 km for Zanzibar island (Fig. 2b) and 750x750 m for Inhaca island (Fig. 2c). The differences in grid size used are comparable with the differences in catchment areas of the three study areas. Whether there is indeed a positive correlation between grid size and catchment area should be the focus of future research.

Local hydrological fieldwork in Kenya showed groundwater dynamics indicating that both study sites selected by KMFRI receive relatively large volumes of groundwater discharges. There were clear indications that rainfall also periodically replenishes (to a certain extent) groundwater aquifers in the region. At the site with relatively lower discharge rates, groundwater salinity could go down to ca. 5 PSU in the rainy season (from ca. 26 PSU in dry season) while at the other site, the lowest salinities recorded hardly went below 21 PSU. Within the water column, these groundwater streams moderate the lagoonal water salinity by creating a band of low salinity waters along the shore throughout the year. Circulation characterized by low currents speed (< 0.35 m/s) during low tide, and onshore winds which generate longshore currents, help in trapping the low salinity water along the coast. At high tide, intensive mixing occurs leading to disappearance of the low salinity band only to re-appear again during the subsequent low tide.

From estimations of groundwater volume fluxes, it was established that groundwater volume is roughly equivalent to 2 and 10% of the total lagoon volume. This shows that there is enormous supply of groundwater to coastal beaches and lagoons. Groundwater is therefore an important component of the coastal nearshore environment.

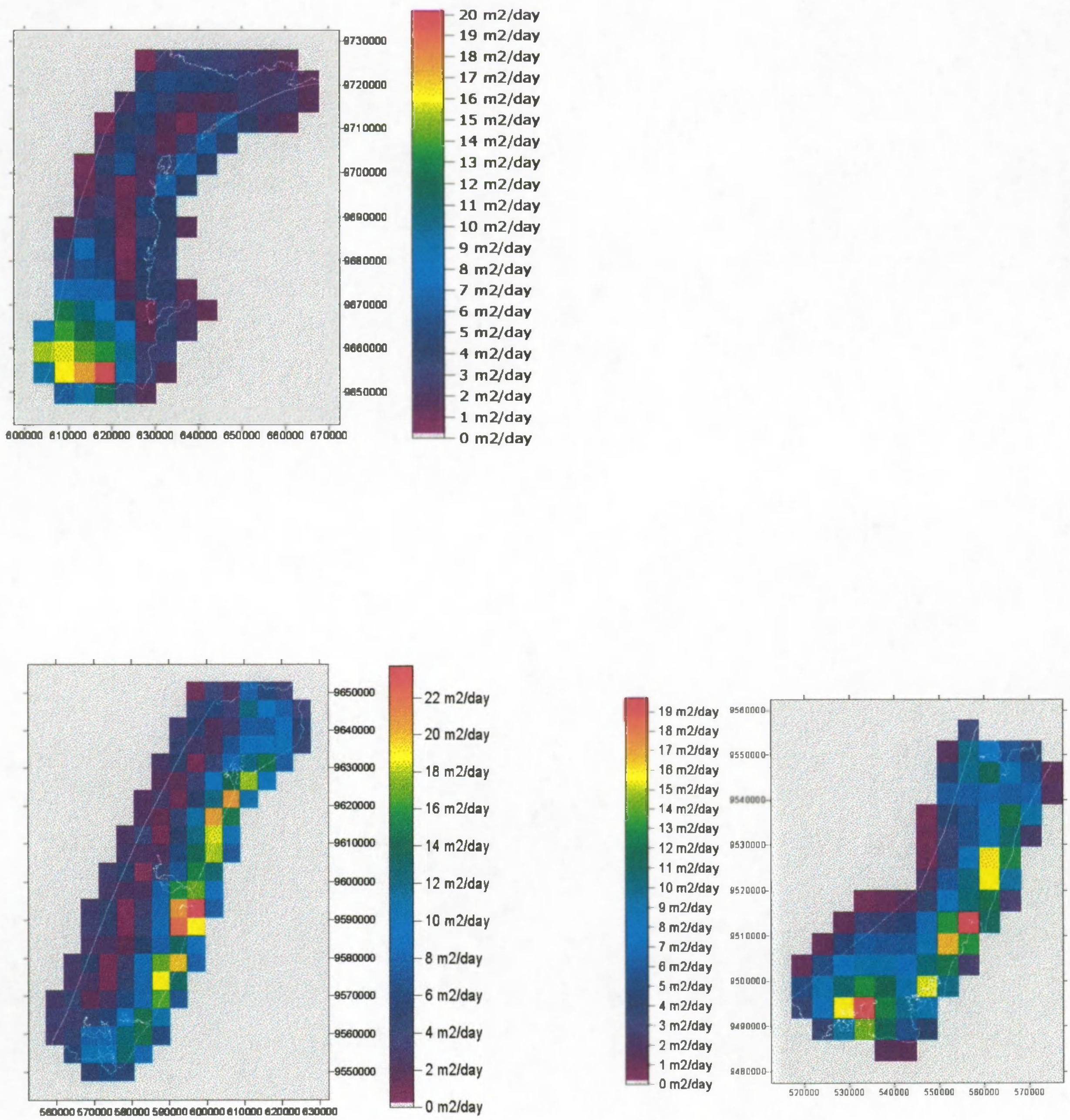


Fig. 2a. Kenya: groundwater flow velocities ($m^2.day^{-1}$) in the areas between Tana River and Malindi (top panel), between Malindi and Mombasa (left panel), and between Mombasa and Vanga (right panel) (grid size: 5x5 km).

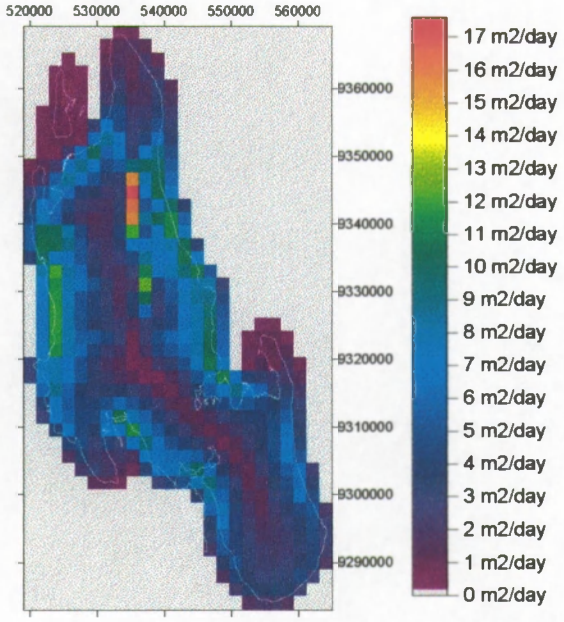


Fig. 2b. Tanzania: groundwater flow velocities ($m^2.day^{-1}$) on Zanzibar island (grid size: 2x2 km).

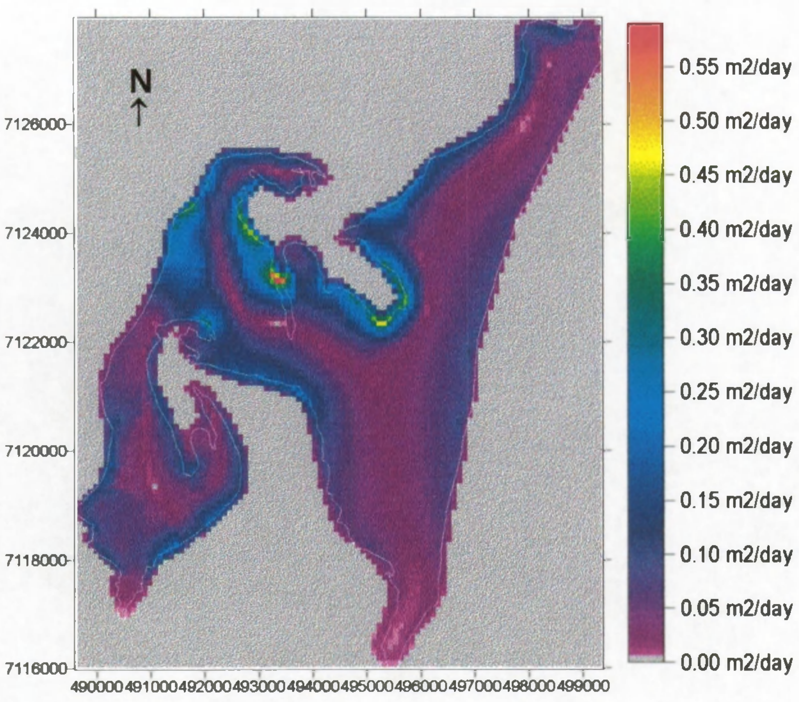


Fig. 2c. Mozambique: groundwater flow velocities ($m^2.day^{-1}$) on Inhaca island (grid size: 100x100 m).

Work package 2: Elucidating differences in nearshore community structures and ecosytem functions in relation to groundwater outflow

(a) Groundwater flow and the productivity and vitality of lagoon seagrasses

Seagrass species diversity and abundance were studied in five Kenyan and three Zanzibar back-reef lagoons with contrasting groundwater-outflow rates. The selection of the lagoons was based on the groundwater flow model. Sites with a relative high groundwater outflow displayed a lower species diversity than sites with a relative low groundwater outflow (Fig. 3). *Thalassodendron ciliatum* dominated at sites with high groundwater outflow rates, while *Thalssia hemprichii* showed higher coverage at sites with low groundwater outflow. Porewater salinities were significantly lower at locations with high groundwater-outflow rates indicating supply of freshwater. Stable isotope signatures of seagrass leaves showed a significant increase with increased groundwater-outflow rates. This suggests that the nitrogen source for these plants was, at least for a part, groundwater. In addition, lagoons with high population densities had highest $\delta^{15}N$ values, indicative of anthropogenic nitrogen inputs. Differences in optimum salinity for growth between species, and competition for nitrogen, may explain the observed pattern in species diversity and abundance. From our observations, we hypothesize that reduced salinity and enhanced nutrient supply favour development of *T. ciliatum*, while normal salinity and low nutrient supply give *T. hemprichii* competitive advantage.

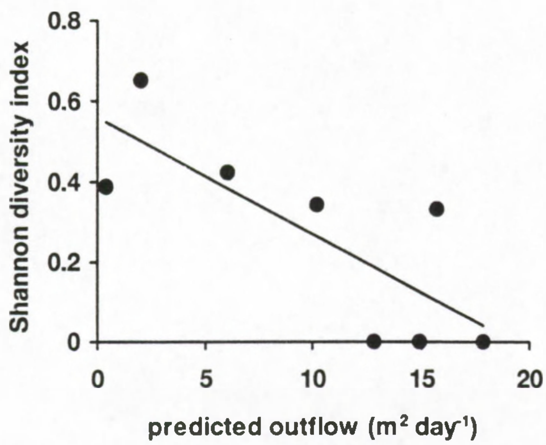


Fig. 3. Groundwater outflow as predicted by the model related to the Shannon diversity index for seagrasses per transect (n = 1). Line of best fit is indicated, τ = -0.64, p = 0.026.

All *T. ciliatum* populations in the present study appeared to be either expanding or in steady state. This suggests that the environmental quality of the back-reef lagoons is still suitable for seagrass development, which is indicative of a healthy ecosystem. 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.

At Inhaca Island (Mozambique), there was no strong evidence of groundwater outflow at the study areas, due to the fact that catchment area of the island is too small to produce large aquifers. Nevertheless, measurement of slightly reduced porewater salinity and enhanced nutrient concentrations suggest diffuse groundwater outflow at the *T. ciliatum* meadow.

The present study suggests that changes in the amount or quality of groundwater outflow along the East African coast will affect the seagrass species composition in lagoons. Specifically, the occurrence of *T. hemprichii* and *T. ciliatum* are likely to be affected. At present, information on the function of these species in the ecosystem of back-reef lagoons is absent, which impedes predictions of possible consequences.

(b) Groundwater flow and macrobenthos in seagrass systems

On Inhaca Island (Mozambique), macrofauna biomass showed marked fluctuations between seasons with more homogeneous values during the dry season and a very high variability during the wet season. The ecological disturbance presented by the different communities sampled in the dry and wet season in the studied mangrove area were not related with anthropogenic pollution factors. The natural disturbance was a result of high stress due to low oxygen, high salinity and temperature levels mainly during the dry season. Biological interactions have an important influence and should be taken into account. The degree of disturbance detected in these communities does not seem to be related to the level of groundwater influence in the studied stations. There was no relation between salinity and maturation of sea cucumbers.

On Zanzibar Island, polychaetes were the most prevalent and were taken as the most representative macrobenthos group. A comparison of polychaete densities from different study sites indicates no significant differences between seawater and freshwater influenced areas. However, within one site, more polychaetes were found closer to the groundwater outlet points than at sites further away. When the freshwater influenced sites are compared, one site appears to have the lowest density. The groundwater reaching this area drains from an intensively rice cultivated area which contains agrochemicals which could be responsible for the low polychaete numbers at the groundwater sites. The highest amount of DDT, possibly originating from house fumigation, has been measured at this site. Another site was consistently having extremely low numbers or no macrobenthos at all. This site is basically a large freshwater outflow area and drains from a sugarcane plantation and rice farms. The hypersalinity of the interstitial waters in this area (60-100‰) may also contribute to the low macrobenthos numbers. It is possible that the polychaete communities here are stressed.

(c) Search for changes in groundwater flow as recorded by elemental changes in biogenic carbonates

We focused our attention on shells of *Isognomon* sp. a bivalve common to the East African coast, which has an eulittoral and estuarine distribution. *Isognomon* is also common in mangrove settings where it occurs attached to stilt roots. We analysed whole shells for a series of minor and trace elements, including Ba, Rare Earth Elements, and trace metals. Differences between sites are clearly visible and can be attributed to differences in freshwater flow and proximity of pollution source. We also analysed shells on a micro-scale along their growth axis for some major and trace elements, $\delta^{18}O$ and $\delta^{13}C$. This provided information on seasonal evolution of environmental parameters such as sea surface temperature and freshwater run-off. Systems with predominance of surface run-off over groundwater flow clearly differentiate from systems where freshwater supply is mainly via the latter process. It can be concluded that bivalve shells are potentially powerful archives of environmental change, especially if possibilities exist to obtain historic specimens and compare these with modern ones.

Work package 3: Elucidating the importance of groundwater as a vector of anthropogenic inputs into the coastal zone

(a) Groundwater inputs of pollutants into the coastal zone

Pesticides (lindane and DDT), originating from agricultural areas and/or sewage systems, were detected in different sites on Zanzibar Island receiving groundwater. DDT, that is associated with fumigation in townships, has been found at two groundwater sites. Low levels of DDT were also detected at a saline site, possibly as a result of dilution effect of the groundwater.

On Zanzibar Island, high levels of ammonia were detected in two groundwater sites, but phosphate concentrations were generally low at all sites (Fig. 4). At one site, the highest levels of ammonia were found during November, when there is no rice farming activities. This may point out the role of the sugar plantations. At the other site, the groundwater has also been established as a source of ammonia to near-shore ecosystems. As the area surrounding the study site is mainly coral rag, the concentrations of nutrients detected here may be explained by the presence of aquifers or underground water streams/river that are inter-linked with agricultural areas. A groundwater site in a mangrove bay showed very low ammonia levels, while the groundwater source had the highest groundwater ammonia levels. This may point to the importance of mangrove stands as a filtering system of land based pollution and that macrophytes benefit from such nutrients indirectly. Ammonia concentrations depended on the season of sampling, highest concentrations measured in the dry season and the lowest ones in the late wet season. The concentrations of ammonia are higher than expected. It is possible that aquifers or underground water streams/river are inter-linked to agricultural areas. The booming tourist development in the area, which has been shown to have a significant influence on the groundwater budget and quality, is also a possible source of higher nutrient levels in the groundwater.

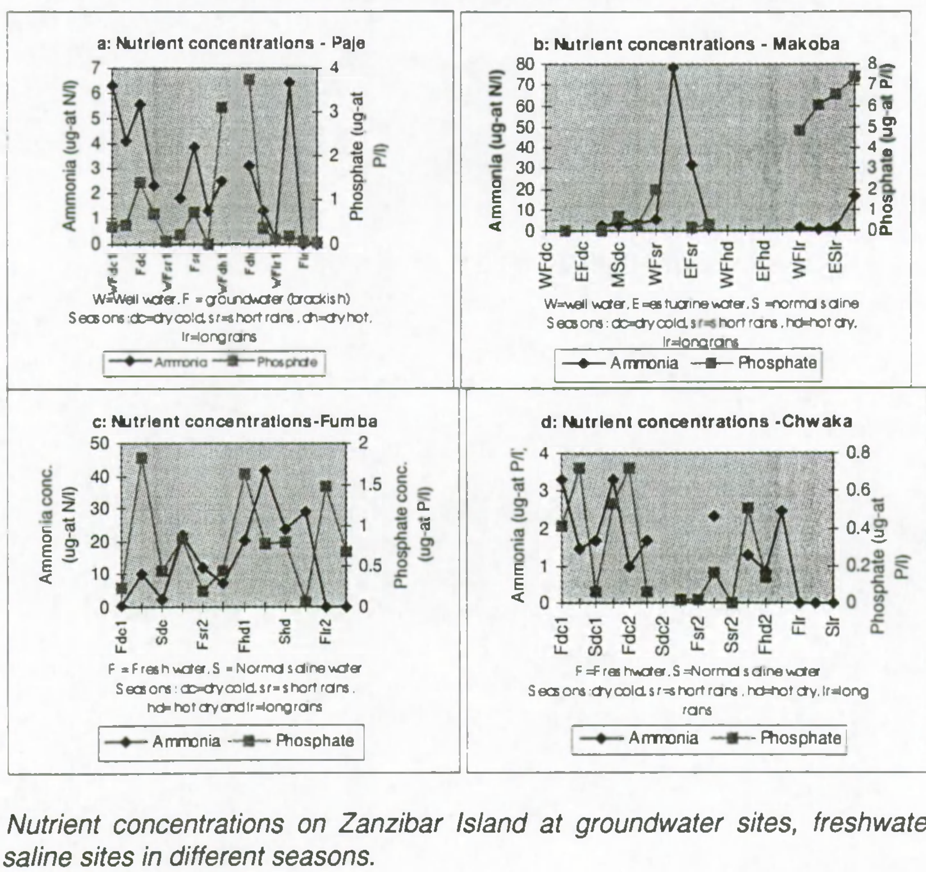


Fig. 4. Nutrient concentrations on Zanzibar Island at groundwater sites, freshwater wells and normal saline sites in different seasons.

In Kenya, results showed considerable additional contribution of nutrients from streams associated with groundwater outflow. Concentrations in the streams were way above oceanic values. Nitrate was found to be the most dominant form of dissolved nitrogen contributed by the groundwater. These nutrient additions resulted in elevated nutrient values in the lagoonal water column, with those stations next to the beach having relatively higher nutrient concentrations compared to those stations in offshore deep lagoonal waters. One lagoon showed a slightly different trend with higher concentrations at offshore stations possibly due to a localized source of nutrient input most probably arising from groundwater outflow near the coral reef. The lagoon without groundwater outflow showed nutrient concentrations in the water that are basically oceanic.

A higher number of microbiota indicator organisms were enumerated in the groundwater collected from the seepage points in Kenya (on the beach before mixing with the seawater) than in the seawater in the lagoons. This is an indication that groundwater is generally more contaminated than lagoonal water but once groundwater mixes with seawater, indicator organisms are exposed to the antiseptic properties of seawater leading to die-offs of these organisms. Groundwater may not be the only source of contamination of the lagoonal waters. Discharges from beach establishments adjacent to these transects may be significant sources of faecal or raw sewage pollution as compared to the groundwater sources.

Data generated in the Kenyan study is indicative of some extent of contamination of lagoonal water by groundwater, surface runoff and occasional direct discharge of raw sewage and waste from beach establishments. In general, the studied lagoonal waters appear safe for swimming and diving. However, though the situation is presently not serious, the continuing rise in population and tourist industry may eventually lead to increased contamination of groundwater and recreational beaches with faecal pathogens resulting in higher health risk to tourists and other visitors.

In general, it is evident that groundwater outflow areas impact strongly on nearshore coastal ecosystems with regard to elevation of anthropogenic associated inputs such as nutrients and microorganisms.

(b) Effects of pollutants on microbial remineralisation and community metabolism

In Kenya, relatively low nitrification rates were observed in the sediments within the study areas indicating unfavourable nitrification conditions. On Zanzibar Island, mean nitrogen fixation rates decreased as when moving further away from the source of groundwater. The mangrove bay site showed the opposite pattern with a marked increase from the edge of the source to 3 m distance. This may be due to an acute impact of the groundwater. However, the groundwater that is being released has a high salinity. Thus, the effect may be due to other factors such as low oxygen tensions in the groundwater or sulphidic compounds in the groundwater. This site consistently gave a strong sulphidic smell during sampling.

(c) Effects of pollutants on community structure

Macro- (and micro-) algae, seagrasses and epiphytes:

On Zanzibar Island, groundwater sites were characterised by luxurious growth of green algae and low numbers of macroalgal species. The species diversity increased with distance from the freshwater site. *Ulva pertusa* was only found at groundwater release points. Macrophytes that were well representated in groundwater sites (the algae *Ulva reticulata, U. fasciata, U. rigida* and *U. pertusa*, and seagrasses *Thalassia hemprichii* and *Thalassodendron ciliatum*) maintained relatively high photosynthetic rates and quantum efficiencies. Low salinity was, however, detrimental to *Gracilaria salicornia* and cultured *Eucheuma denticulatum*. Groundwater sites had higher number of benthic microalgal species than normal saline sites. The biomass was also highest in freshwater sites.

In Kenya, results of macroalgae investigations at the two lagoons indicated that the impacts of groundwater are obvious by the proliferation of green algae at the beach sites where freshwater influence is highest (Fig. 5). However, the high diversity of other algae groups like the red algae indicate that any effects of eutrophication by the groundwater at the study sites may be termed as mild eutrophication. The epiphytic load did not give distinctly significant differences between sites. However, the trend indicates the occurrence of a slightly higher loading on the *Thalassodendron ciliatum* stems at one site during the rainy months. This peak in the rainy months suggests the influence of nutrient-rich water particularly at that site where the groundwater outflow effect was highest.

On Inhaca Island (Mozambique), no groundwater effect was detected neither with respect to environmental parameters, nor with respect to species composition, percentage cover, biomass and growth of sea-grass and epiphytes. The reason for this can be due to the small area of the island, which implies a small catchment area and small reservoir of groundwater, so that the outflow is not relevant in the physical and biological components of the South Bay.

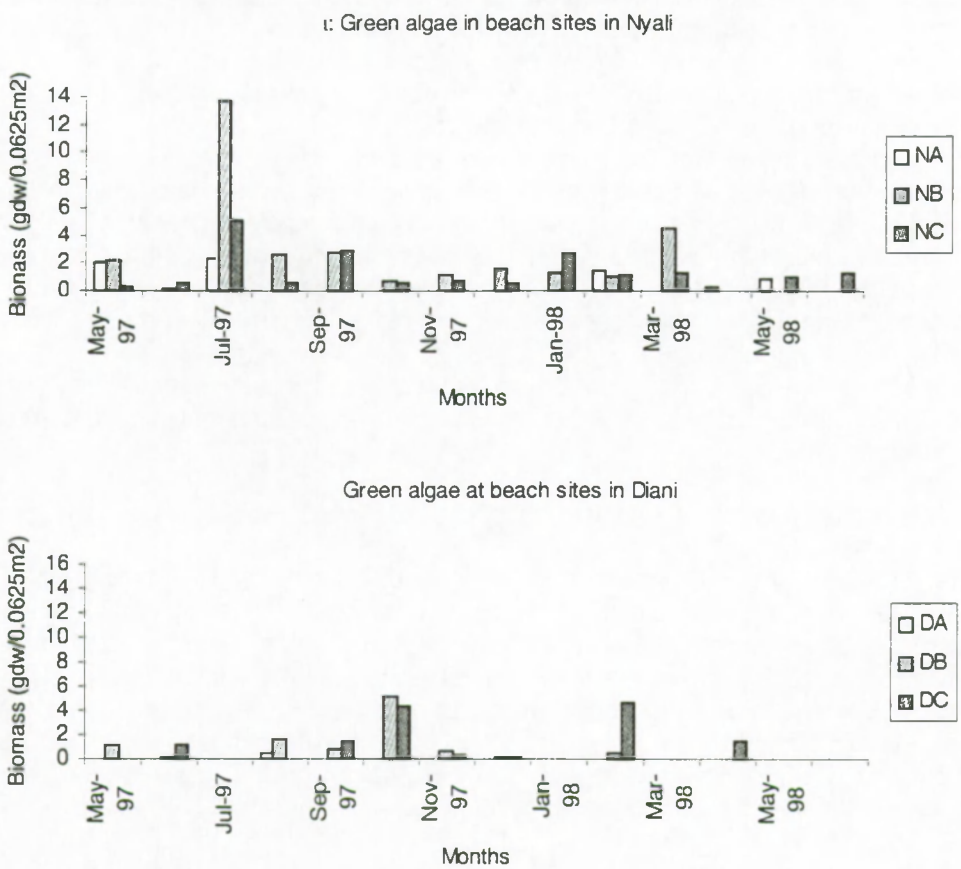


Fig. 5. Green algae at beach sites in Kenyan study lagoons.

<u>Phytoplankton:</u>

In Kenya, phytoplankton species composition, cell abundance and diversity were affected by different levels of anthropogenic input into the lagoons. The species *Oscillatoria* was associated with high nutrients and was abundant in nearshore stations receiving higher nutrients. Though phytoplankton cell abundance was more or less similar in the lagoons during wet and dry seasons, a gradient in abundance was observed from the beach to reef stations with higher values being obtained from the beach and middle stations as compared to the reef which were located away from the beach. Diversity of phytoplankton was higher in the wet months due to increased nutrients enabling more species to thrive. Chlorophyll-a and B.O.D values were directly influenced by groundwater seepage into the lagoon (Fig. 6). Higher values were obtained at nearshore beach stations as compared to the reef stations due higher amounts of nutrients at the beach sites. One lagoon had higher values of Chlorophyll-a possibly linked to slightly higher nutrient input. Increased nutrients through groundwater and runoff during the wet season were responsible for higher Chlorophyll-a and B.O.D levels as compared to the dry season.

Zooplankton:

The effects of groundwater into the studied lagoons in Kenya was reflected in zooplankton species composition. The presence of "indicator species", more specifically mysids,

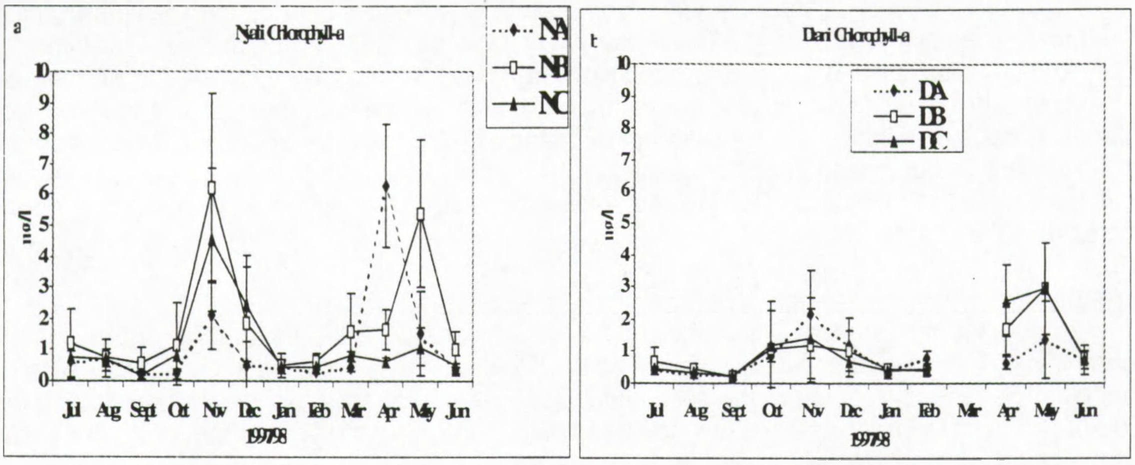


Fig. 6. Temporal changes in chlorophyll-a levels in Kenyan lagoons.

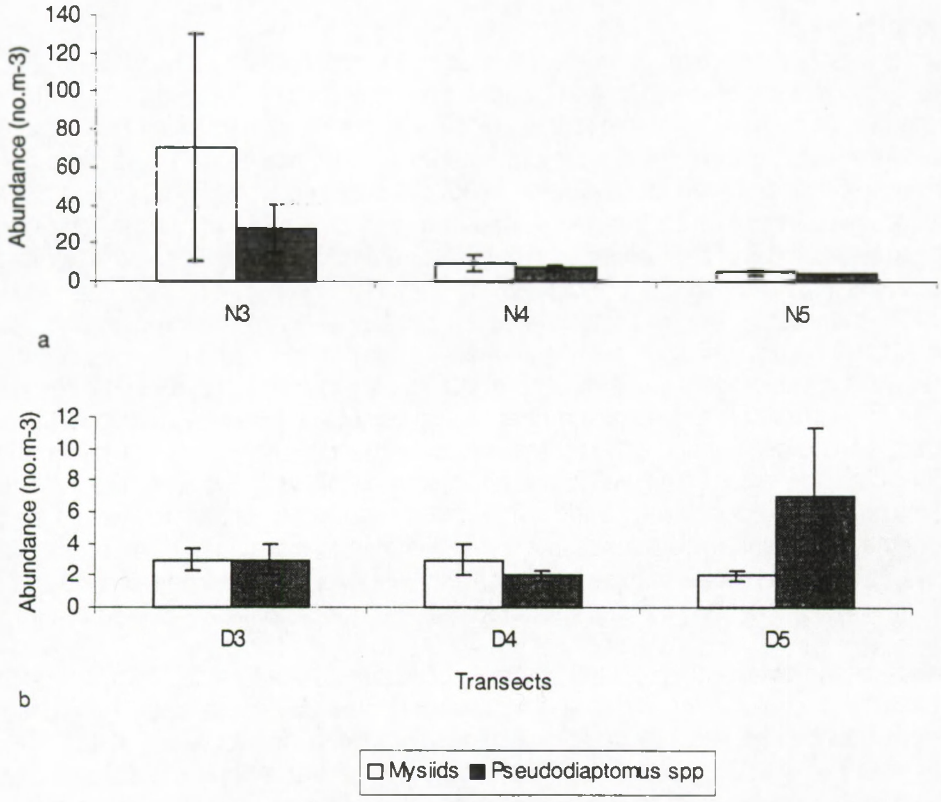


Fig. 7. Mean abundance of Mysids and Pseudodiaptomus spp in Kenya at Nyali (top) and Diani beach (bottom).

at particular spots (such as N3 at Nyali, the site closest to the beach) and throughout the year, was indicative of groundwater discharge (Fig. 7). The higher numbers of indicator species observed near the beach was a reflection of the slightly more nutritious waters with lower salinity at the beach than next to the reefs. Relatively higher density of fish eggs and larvae occurring at the mid-stations of the two lagoons also reflected the importance of these lagoons as nursery grounds. These areas, which also had seagrass cover, provided good habitat for meroplankters like: amphipods, isopods, squid larvae and juvenile fish.

On Inhaca Island (Mozambique), hydrographic conditions (water temperature and salinity) are homogeneous throughout the studied bay, which indicates good mixing and very low impact of groundwater discharge in the bay. Zooplankton abundance was generally similar all the year round, except for brachyura and some gastropod larvae. There was no relation between water temperature and salinity with zooplankton abundance. A groundwater effect was not detected in the zooplankton abundance and composition in the studied bay, which may be due to the small catchment area of the island. This implies small differences in groundwater outflow rates as can be seen in the model.

Meiofauna:

Studies on Zanzibar Island showed that nematodes were the most abundant meiofaunal organisms. Second in abundance were the harpacticoida. Results obtained at fresh water sites did not clearly separate from the saline sites and lack any clear pattern. This is considered to be due to the nature of the freshwater input in the intertidal areas where the tidal waters dilute the impact of the incoming groundwater for a large part of the day.

(d) Socio-economic studies

Water usage patterns:

On Zanzibar Island, problems attributed to water are mainly the continuity of supply and the salinity. Basically, piped water has a good quality, but due to breakdowns or repairs, even villages connected to the pipe system have to use wells up to one month per year. The situation of the wells is different in each village, even though the number of freshwater-wells has decreased in almost all of them. Cholera cases due to well pollution occurred in several villages. Water shortages occur at low tide, and in dry season (December, January, and February). Today, some villages have become very dependent on piped water. The majority of water in the villages is used for sanitary purposes (53% for children and 68 % for adults), cooking, and drinking (18% for children and 14 % for adults) and washing dishes or clothes (20% for children and 12 % for adults), only little is used for cleaning or feeding animals (9% for children and 6 % for adults). The amount of water used on average was calculated at 33 l d^{-1} for children and 55 l d^{-1} for adults. The overall weighted average water use of a tourist on the East Coast was calculated at 674 l d^{-1}. This is 15 times the average demand of local residents. A major proportion of the sewage from villages is leaking into the ground. As wells are often located close to houses, the amount of nutrients leaching into the groundwater and/or into the ocean could therefore be substantial. However, 40% of the hotels and guesthouses interviewed, stated that they had open tanks leaking into fissures and caves. One hotel pumped sewage into a cave, and another one directed its effluent into a former well. This way, a major proportion of sewage is possibly washed out into the sea.

On Inhaca Island (Mozambique), the majority of water is used for laundry, followed by showering, cooking and drinking, and washing dishes and others. Almost nothing is used for watering the plants, since the main type of agriculture practiced in the island relies only on rainwater. The amount of water used per person per day was similar among the studied villages and about half the amount consumed on Zanzibar Island. The water consumption at Hotel Inhaca was more than four times as much as in the villages (Table 1).

Table 1 Amount of water used per day per village

Village	Inhabitants	Amount of water used per person ($l\ d^{-1}$)
Nhaquene	1871	16.0
Ribjene	2480	16.2
Inguane	1153	16.2
Hotel Inhaca	97	72.2
Total	5601	17.1

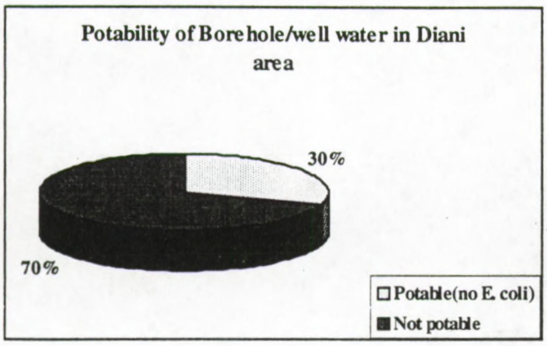
Water quality:

In Kenya, examination of the nutrient concentrations in the boreholes/wells neighbouring the two study plots indicated highly elevated levels (Table 2). Nitrate-Nitrogen formed the most dominant (ca. 95%) source of dissolved inorganic nitrogen in all the wells investigated. A relatively high nutrient concentration at one site as compared to boreholes at the other site could be a reflection of the different population pressures for the two places (one being urban and densely populated) and the usage of pit - latrines as main source of sewage disposal by coastal communities. In terms of microbiological contamination, boreholes/wells of the densily populated site had about four times more counts of contamination indicator species (faecal coliforms, *E. coli* and faecal streptococci) than the other sites boreholes. The majority of the groundwater from the boreholes and wells in the studied areas is not potable as the levels of faecal coliforms, *E. coli* and faecal streptococci exceed those recommended by the Kenya Bureau of Standards and EEC guide (Fig. 8). Groundwater can be made potable by simple physical treatment and disinfection like boiling, or rapid filtration and disinfection, while that in some wells/boreholes may require physical and chemical treatment and disinfection including chlorination.

The results of analysis of nutrients in wells on Zanzibar Island also show a predominance of nitrate and nitrite over ammonia and phosphate (Fig. 9). Nutrient concentrations showed considerable variation between wells and between villages. At Paje, the levels of nitrate/nitrite in the groundwater tended to vary a lot between subsequent low tides and also between different release points depending on time of measurement. This study was unable to determine a reason for this but considered it to be due to possible variations in the flow from the different contributing aquifer areas that are themselves probably connected to the different well and latrin areas with differing contamination levels.

Table 2. Mean Nitrate+Nitrite concentration levels in some boreholes/wells

AREA	BOREHOLE/WELL	CONCN. (μM N)
DIANI	Kitasa	59.37
	Bahati	117.00
	Mkwakwani	226.51
	Bondeni	148.41
	Solola	148.41
	Maweni	278.10
	Saidia	537.46
	Subira	234.87
	Bongweni	134.01
	Kibuyuni	148.41
	MEAN FOR DIANI	203.3±133.7
NYALI	FSH	643.00
	SBH	130.92
	NBH	420.77
	SOS	560.87
	FRT	184.06
	KSOKO	1451.70
	MWAND	219.81
	BERSH	606.28
	JER	2707.70
	KISIM	751.21
	KONG	1765.70
	MEAN FOR NYALI	858.4±799.3



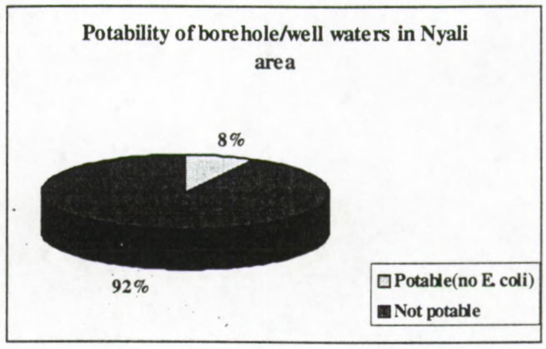


Fig. 8. Potability of water in Kenyan lagoons Nyali and Diani.

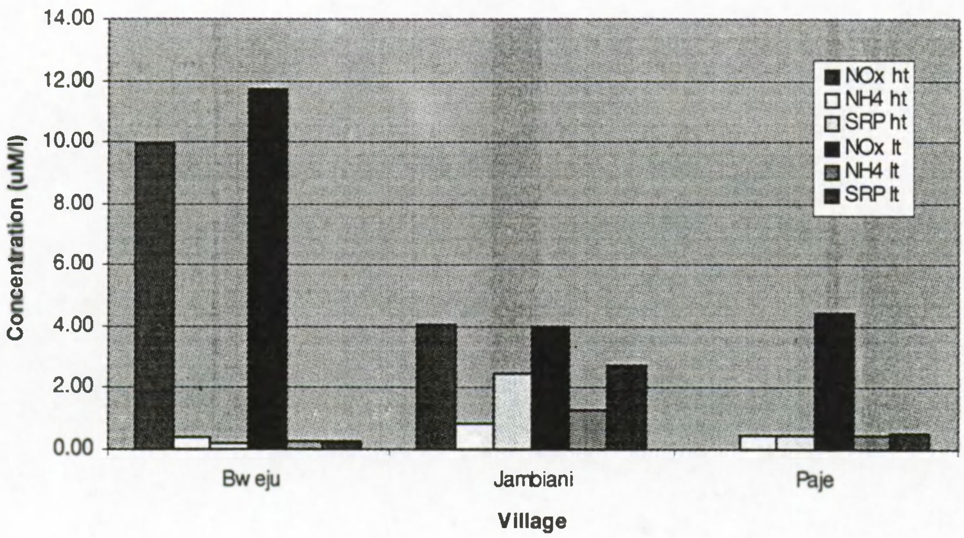


*Fig. 9. Graph of mean nutrient concentrations at high **(ht)** and low tide **(lt)** for each of the villages on Zanzibar Island showing clear tidal influence.*

On Inhaca Island (Mozambique), nutrient concentrations in well water were far below the acceptable limits for human consumption indicating that, regarding the chemical component, groundwater of Inhaca Island is still potable. There are no significant differences among the studied villages concerning the chemical composition of the water. This indicates that human impact in chemical terms is low. From all wells sampled in the villages, 84 % showed values of faecal coliforms that are higher than the maximum acceptable value. Thus, only 16 % of the wells have suitable water for human consumption. This result shows that one of the main human influences on the groundwater is bacterial contamination. Reasons for this can be that the majority of families in the island do not have toilets, and thus defecate in the bush and in the mangroves, or when toilets are available, the location of the wells can be inadequate in relation to the toilets. There are significant differences in contamination with faecal coliforms among the studied villages. The lowest contanimation was observed in the economic center of the island, which is the most urbanised village. The existence of latrines for every house significantly diminishes the faecal contamination of the water through runoff.

Technology Implementation Plan

Table 1: Overview of results

No	Title of exploitable result	Category	Partners of the project involved	Dissemination intention	Type of IPR
1	Groundwater model for East Africa	A	VUB	CD-ROM with interactive groundwater flow maps of the regions studied	copyrights

Table 2: Timetable for exploitation and dissemination activities

Activity	Partners involved	start date	end date
delivery of data on groundwater flow rates to partners of GROFLO project	VUB	1 March 1997	31 July 1999
delivery of data on groundwater flow rates to other interested parties upon request	VUB	September 1999	no end date

Publications and papers

Publications in peer reviewed scientific journals and books

Gössling S. and Ron W. Johnstone, R.W. Causes and Consequences of Groundwater Use on a Tropical Island: Zanzibar, Tanzania. Submitted to Ambio.

Johnstone, R.W. and Gössling, S. Sustainable management of groundwater resources on a tropical island: issues and dilemmas. Submitted to Coastal Management.

Johnstone, R.W. The role of groundwater as a vector for nutrient enrichment in a tropical coastal ecosystem; Zanzibar, Tanzania. To be submitted Marine Ecology Progress Series.

Kamermans, P., M.A. Hemminga, J.F. Tack, M. A. Mateo, N. Marbà, M. Mtolera, J. Stapel and A. Verheyden. Groundwater effects on diversity and abundance of lagoonal seagrasses in Kenya and on Zanzibar Island (East Africa). To be submitted to Limnology and Oceanography.

Kamermans, P., M.A. Hemminga, N. Marbà, M. A. Mateo, M. Mtolera and J. Stapel. Leaf production, shoot demography, and flowering frequency of the seagrass *Thalassodendron ciliatum* (Cymodoceaceae) along the East African coast. Submitted to Aquatic Botany.

Tack, J. and Polk, P. (1999) The Influence of Tropical Catchments upon the Coastal Zone: Modelling the Links between Groundwater and Mangrove Losses in Kenya, India/Bangladesh and Florida. In The Sustainable Management of Tropical Catchments, Harper D and Brown T (Eds), Wiley, Chichester pp 359-371.

More papers are in preparation.

Papers to conferences

Apart from the presentations given at the three GROFLO workshops, which are listed in the Meeting Reports (Annex I), the following papers were presented:

Kamermans, P., M.A. Hemminga, N. Marbà, M. A. Mateo, M. Mtolera and J. Stapel. Tracing groundwater effects on lagoonal seagrasses in East Africa. Paper presented at the *3rd International Seagrass Biology Workshop*, Quezon City, Philippines, 19-26 April 1998.

Paula, J., P. Fidalgo, A. Martins and D. Gove. Standing crop of seagrasses associated infaunal communities at Inhaca island, Mozambique. Paper presented at the *Conference on Advances in Marine Sciences in Tanzania*, Zanzibar, Tanzania, 28 June to 1st July 1999.

Paula, J, A. Almeida, P. Fidalgo, D. Gove, J. Guerreiro, A. Macia, A. Martins and L. Saldanha. Eight years of European projects in marine sciences in Mozambique: joint research by University of Lisbon and University Eduardo Mondlane. Paper presented at the *Conference on Advances in Marine Sciences in Tanzania*, Zanzibar, Tanzania, 28 June to 1st July 1999.

Conclusions

The general conclusion of the GROFLO project is that the East African nearshore coastal ecosystem is affected by by the amount of groundwater outflow and by its 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", which means that they constitute an important component of the system. Changes in seagrass vegetation can affect the whole ecosystem. Results also indicate that anthropogenically induced 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 groundwater 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 rates and groundwater quality. 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, futher 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 agricultural areas and may be a result of fumigation of houses. The results on micro-organisms, nutrients and pesticides will be coveyed to the local administrators.

Benefits and future actions

Benefits arising from the research activities developed within the scope of the GROFLO project were numerous and at different levels. The main benefit of the GROFLO project is the generation of baseline data on the relation between groundwater outflow and the functioning of Eastern African nearshore ecosystems. The underground water systems of East Africa are very important because a large percentage of the human population depends on it for supplying drinking water and other domestic purposes. Groundwater is also important in agriculture and industries. In addition, many important vegetation types such as mangroves and the associated plants and animals depend on it. The demand for groundwater in East Africa is increasing with the rising number of users - local populations and tourists and related activities e.g. hotels, swimming pools & factories. In urban areas, rapidly increasing demand for freshwater is necessitating increased exploitation. When exploitation increases above a safe-yield value, it can lead to increased seawater intrusion and reduced outflow into the ocean. This will not only interfere with the present patterns of water-use, but it will also impose negative repercussions since increased salinity will preclude the use of groundwater in agricultural, touristic, domestic and industrial sectors. Reduced discharge into the lagoons will reduce the salinity moderation and presumed nutrient boosting functions with negative impacts on fisheries, recreation and biodiversity conservation. As a result of data collected in Kenya in the framework of the GROFLO project, KMFRI identified a need for a comprehensive programme on groundwater management in the coastal zone of Kenya, perhaps, in the framework of integrated coastal zone management. The following examples illustrate how data collected in the framework of the GROFLO project can be beneficial to other groups of the society:

(i) The groundwater models that were developed by VUB during the GROFLO project, and that cover the southern half of the Kenyan coast, Zanzibar Island in Tanzania, and Inhaca Island in Mozambique, are now available on CD-ROM, and can be obtained from VUB upon request. The models can be a valuable aid to coastal managers. For example, the models can be used in Environmental Impact Studies to predict effects of changes in groundwater use on the outflow rates into the coastal zone.

(ii) Groundwater in Zanzibar, and particularly on the East coast where tourism is developing, has approached an over-exploitation level and alternative means to conserve need to be developed. The IMS is seeking to influence the Tourism development policy (Ministry of Tourism) with the view to make hotel developers present groundwater conservation strategies, such as water re-use and rain water harvesting systems, as one of the conditions for acceptance of their requests for Hotel investment. The Government should also start planning for seawater desalination plants.

(iii) Groundwater out-flowing into the near-shore ecosystems that originates from agricultural areas and townships is a potential vector of nutrient and pesticide pollution to such ecosystems on Zanzibar Island. Species diversity of macrophytes, benthic microphytes, macrobenthos and meiobenthos are threatened by polluted groundwater. For example, the results of the project have shown that seaweed mariculture on Zanzibar Island may be affected by the groundwater pesticide pollution. Efforts are underway to produce video programs to be shown to school children (by IMS staff) and the general public (by state TV station). Publication of the results so far obtained will help in termination of the use of disastrous pesticides such as DDT. The results of the GROFLO project are also expected to be communicated to the Ministry of Agriculture, with the view to influence policies promoting the use of organic fertilisers.

(iv) The information generated by the GROFLO project yield baseline data for the status of groundwater on Zanzibar Island. The IMS is planning a monitoring programme. As direct benefits to Tanzania, the GROFLO project has facilitated the establishment of a pesticide sampling and analysis protocol to suit our local situation.

(v) The results of water quality study of UEM at Inhaca Island (Mozambique) will be used by the Ministry of Health, through the National Laboratory for Hygiene of Water and Food, to take action in order to reduce the fecal contaminion, which is very high.

(vi) The results of sea-cucumber study of UEM at Inhaca Island (Mozambique) will be used by the Maritime Office at Inhaca Island and Maputo to manage the exploitation of sea-cucumbers at Inhaca Island.

Collaboration and training is another benefit of the project. The GROFLO project has been a multi-disciplinary study which has facilitated collaboration between scientists within and outside the Eastern African Region. The project has also demonstrated how North-South scientific collaboration should develop with the view to transfer expertise and facilite on-the-job-training. A higher degree of interchange and synergy between involved research teams was achieved. In Kenya, collaboration between KMFRI, VUB and NIOO-CEMO was continued. In Mozambique, where the activities of UEM/GML were focused, building capacity for research and advanced formation in marine sciences was incremented, through the involvement of students and technicians at different levels. As a collaborative project, both the IMS, and the personnel from SU have gained by developing stronger collaboration with each other and the other organizations directly (e.g. NIOO-CEMO) and indirectly involved in this program. The value of this is difficult to define at this stage but it is likely to enhance the future performance of all concerned.

All teams involved in GROFLO aim for a continuing interchange and joint collaborative actions, through the development of the existing links, and creating new approaches for research proposals in coastal ecology and ecosystem sustainability. In this context two actions can be mentioned:

(i) A proposal has been submitted to a Dutch foundation for the adavancement of tropical research (WOTRO). The subject of the proposal is a continuation of the study on the relation between groundwater and lagoonal seagrass vegetation in Kenya. The GROFLO study identified an effect of groundwater outflow on seagrass diversity an abundance. In the new study, the use of remote sensing techniques is proposed. This will allow verification of the seagrass distribution patterns on large scales. Experiments will be carried out to explain the observed patterns in terms of ecophysiological impacts on the seagrassses. Three GROFLO partners (NIOO-CEMO, VUB and KMFRI) are involved in this research proposal.

(ii) The trace element and isotope study of the VUB identified the usefulness of biogenic calcite substrates (mollusc shells) as potential archives of environmental parameters. Future research on this topic is planned: (1) further comparison between sites with different freshwater flow characteristics to confirm the conclusions from this exploratory research and (2) the comparison between "old" (historic) shell specimens and modern ones in order to assess temporal change of environmental conditions.

Summarizing, the GROFLO project can be rated as a success in that its results are relevant to solving management questions, and the project has a long term benefit to recipient countries/institutions in terms of expertise.

Management Report

Contents

Organisation of collaboration

A steering committee was established that consisted of senior scientists that were the local coordinators of the GROFLO research groups at each participating institute. This committee was chaired by the general coordinator of the project. The steering committee monitored the progress and coordination of the project and convened during each workshop. Co-operation between partners was achieved through joint field campaigns, such as the macrobenthic studies on Inhaca Island by IMS, UEM and GML and the socio-economic studies on Zanzibar Island by IMS, SU and UEM. In addition, short visits to others labs took place for analysis of samples (e.g. KMFRI and VUB), and information was exchanged during the workshops.

In general, the way in which coordination and cooperation was organised was effective. Only the case of one specific institute, there were problems in the interaction and in the proper embedding of the research in the framework of the project. This was wholly due to inadequate leadership of the local coordinator of the institute. Steps were taken by the institute's director, to avoid any such problems in future projects.

Meetings

Three meetings were held during the GROFLO project.

1. Mombasa, Kenya, 4 - 6 March 1997

The purpose of this first meeting was to select the research sites on the basis of the coarse groundwater models. In Kenya, two sites were selected (Nyali Beach and Diani Beach). On Zanzibar Island, four sites were selected (Paje, Fumba, Makoba and Chwaka). An on Inhaca Island a number of sites were selected within Saco Bay. In addition, specific decisions on research activities, such as type of samples and sampling frequency, were made. It was decided to collect samples on a seasonal basis that minimally included both dry and wet seasons. For the zoobenthic sampling it was realised that it was essential that all parties involved used the same techniques so that data sets would be directly comparable. To this end, it was agreed that Tanzanian researchers would travel to Mozambique and participate in the benthic samplung to be conducted by the Mozambiquan and Portuguese counterparts. Interaction and cooperation with the MEAM project (Macrobenthos of Eastern African Mangroves) was examined.

2. Yerseke, The Netherlands, 30 March - 1 April 1998

The second meeting was used to evaluate the progress made so far and to adjust the workplan where necessary. A special session was devoted to the refinement and validation of the groundwater outflow model. Based on new results of the groundwater models an extra study site was included in Kenya. The botanical research activities already showed promising results in that certain groups or species could be identified as indicators of groundwater outflow. The zoological work 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. As far as the research on Zanzibar Island was concerned, the are problems of scale and underground rivers were extensively discussed, but it was concluded that the sampling sites should be left unchanged. On Inhaca Island, the observation of no clear differences in the benthic fauna between the mangrove bay sites, made it imperative to include new study sites.

3. Inhaca Island, Mozambique, 12 - 15 April 1999

During this final meeting, all research groups gave an overview of their obtained results. General conclusions that can be drawn regarding the impact of groundwater on nearshore ecosystems were discussed. These can be found in the scientific parts of this final report. In addition, ideas for future cooperation were investigated. The results of the GROFLO project were considered very promising and possible research subjects in the framework in the framework the 5th Framework Programme (INCO-Dev A4 domain c, Ecosystem Management for Sustainability) were discussed. 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.

Participants

Attendance at the different workshops is given in brackets.

KMFRI
E. Okemwa (1)
J.M. Kazungu (1,2,3)
J. Mwaluma (1,3)
S. Mwangi (2)
B. Mwashote (1,3)
P. Wawiye (1)
J. Kitheka (1)

NIOO-CEMO
M.A. Hemminga (1,2,3)
P. Kamermans (1,2,3)
M. Mateo (1)
N. Marba (1)

VUB
J.F. Tack (1,2)
A. Verheyden (2,3)

IMS
M.S.P. Mtolera (1)
A.J. Mmochi (1,2,3)
O.U. Mwaipopo (1)
J. Shunula (1,2)
S. Ndaro (2)

SU
R. Johnstone (1,2)
E. Hansson (2)
J. Hast (2)

GML
L. Saldanha (1)
R. Costa (1)
J. Paula (2,3)
P. Fidalgo (2,3)

UEM
D. Gove (1,2,3)
R. Abdula (2,3)
H. Chavale (2)

Exchanges

In Sweden, two exchange students were involved in the project. Stefan Gössling is a PhD student visiting from Lund University. Stefan is a German student working on his PhD at Lund University where he is currently enrolled. Erik Hansson, Honours Student (4th year), is a visiting student from Gothenburg University and he gained all of his data for his thesis from his work with the GROFLO project.

Problems

The single major problem in the administrative/financial domain of the project was the terrible delay (more than 6 months) in the transfer of new funds from the European Commission, after submission of Progress Reports and Cost Statements. This hampered the progress of the research, particularly that of the African partners, because at some stages no money was available anymore for further research. The project coordinator contacted officers in Brussels at numerous occasions, and his impression was that transfer of money involved too many steps, with the particular problem that any small obstacle or question arising was not fed back to the relevant previous controller (or the project coordinator) resulting in frequent, but unnecessary, stops in the chain of steps. Big improvements should be made in the efficiency of the procedure!

Completed Catalogue Page

Project summary

Not only in riverine areas, but everywhere along the coast a dynamic balance exists between the seaward outflow of groundwater and salt water intrusion into coastal freshwater aquifers. Groundwater is a resource of enormous significance. In the Eastern African coastal zone, withdrawal of groundwater occurs in many places to supply an increasing number of beach hotels and settlements of the local population. Concomitant with a decrease in groundwater levels, due to withdrawal, it is also likely that these waters exhibit elevated nutrient and pollutant concentrations. This is largely due to poor soil conservation and agricultural practices as well as inappropriate disposal of effluents into pits or sink holes.

Despite this increasing anthropogenic pressure on groundwater reservoirs, little information exists regarding the importance of groundwater for ecological processes and structures in the nearshore environment. However, it can be expected that the diffuse groundwater outflow in non-riverine coastal areas will potentially affect nearshore marine ecosystems by (1) moderating saline conditions; (2) by delivering nutrients such as N,P, Si used by primary producers; (3) by delivering pollutants.

Objectives

To assess the significance of changing inputs of groundwater - and the anthropogenic substances it contains - for Eastern African nearshore ecosystems

To meet the general objective of the project, three more specific objectives were pursued:

(1) To construct a model of groundwater flow along the Eastern African coast.

(2) To elucidate differences in nearshore community structures and ecosystem functions in relation to groundwater outflow.

(3) To elucidate the importance of groundwater as a vector of anthropogenic inputs into the coastal zone.

Results achieved

The general conclusion of the GROFLO project is that the East African nearshore coastal ecosystem is affected by the amount of groundwater outflow and by its quality. The data collected showed a strong impact of groundwater outflow on a number of components of the back-reef lagoon ecosystem. Sites with high groundwater outflow displayed a lower seagrass species diversity than sites with low groundwater outflow. Seagrasses are “structuring species”, which means that they constitute an important component of the system. Changes in seagrass vegetation can affect the whole ecosystem. Results also indicate that anthropogenically induced 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 was indicative of groundwater discharge. And, a proliferation of green macroalgae was observed at the beach sites with groundwater influence. 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 rates and groundwater quality.

The socio-economic studies provided valuable baseline data on water usage patterns. Analysis of the water quality of the wells yielded results on levels of contamination with micro-oganisms, nutrients and pesticides that call for caution. The results will be coveyed to the local administrators.

The groundwater model that was developed during the GROFLO project, proved to be an an indispensable tool for the field studies. The model is now available on CD-ROM, and can be obtained from VUB. It can be a valuable aid to coastal managers, e.g. for use in Environmental Impact Studies to predict effects of changes in groundwater use on the outflow rates into the coastal zone.

Project Data Sheet

Annexe 2

Contract number : ERBIC18CT960065	Year :

Data sheet
for final report
(to be completed by the co-ordinator for the whole project)

1. Dissemination activities

	Published	Submitted
Number of communications in conferences	7	0
Number of communications in other media (internet, video, ...)	0	0
Number of publications in refereed journals	0	6
Number of articles/books	3	0
Number of other publications	0	0

2. Training

Number of PhDs	5
Number of MScs	4
Number of visiting scientists	1
Number of exchanges of scientists (stay longer than 3 months)	0

3. Achieved results

Number of patent applications	0
Number of patents granted	0
Number of companies created	0
Number of new prototypes/products developed	0
Number of new tests/methods developed	0
Number of new norms/standards developed	0
Number of new softwares/codes developed	0
Number of production processes	0
Number of new services	0
Number of licenses issued	0

4. Industrial aspects

	yes	no
Industrial contacts	☐	☒
Financial contribution by industry	☐	☒
Industrial partners : - Large	☐	☒
- SME[1]	☐	☒

[1] Less than 500 employees.