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Effect of the 1997–1998 ENSO-Related Drought on Hydrology and Salinity in a Micronesian Wetland Complex

JUDY Z. DREXLER* and KATHERINE C. EWEL

Pacific Southwest Research Station, U.S. Department of Agriculture Forest Service, 1151 Punchbowl Street, Room 323, Honolulu, Hawaii 96813

ABSTRACT: The potential effects of global climate change on coastal ecosystems have attracted considerable attention, but the impacts of shorter-term climate perturbations such as ENSO (El Niño-Southern Oscillation) are lesser known. In this study, we determined the effects of the 1997–1998 ENSO-related drought on the hydrology and salinity of a Micronesian mangrove ecosystem and an adjacent freshwater swamp. A network of 9 piezometer clusters installed at the study site served as sampling points for continuous and manual measurements of salinity and water level. During the drought period from January through April 1998, mean water table levels in the mangroves and freshwater swamp were approximately 12 and 54 cm lower, respectively, than during May through December when precipitation returned to near normal levels. At the peak of the drought (February 1998), the most dramatic result was a reversal in groundwater flow that sent groundwater from the mangroves upstream toward the freshwater swamp. Flow nets constructed for this period and immediately after illustrate the strong hydrological linkage between the two systems. This linkage was also illustrated by measurements of groundwater salinity in the piezometer network. Ninety-six percent of the salinity measurements taken in the mangroves during the study were at least 10‰ less than the salinity of sea water, indicating that the mangroves were consistently receiving freshwater flows. An analysis of variance of groundwater salinity measurements during and after the drought showed that salinity levels in the 0.5 and 1.0 m depth piezometers were greater during than after the drought. In a comparison of salinity values in 0.5-m wells during low tide, mean salinity was approximately twice as high during the drought than after (14.7‰ versus 6.2‰, respectively). This study demonstrates that short-term climate perturbations such as ENSO can disrupt important coastal processes. Over repeated drought cycles, such perturbations have the potential to affect the structure and function of mangrove forests and upstream ecosystems.

Introduction

The growth and primary production of mangroves are strongly influenced by climatic variables such as solar radiation, temperature, rainfall, and evapotranspiration (Clough 1992; Alongi 1998). Changes in any or all of these factors could have major impacts on the sustainability of mangrove ecosystems. For this reason, many researchers have become concerned about the impact of global climate change on mangrove ecosystems (Ellison and Stoddart 1991; Semeniuk 1994; Field 1995; Ellison and Farnsworth 1996). Among the many predicted impacts, the clearest threat to mangroves is sea level rise. Current estimates for sea level rise are between 0.3 to 1.0 m for the next 100 years (International Panel on Climate Change 1992). How particular stands of mangroves will react to this predicted sea level rise strongly depends on local factors such as geomorphology, tectonics, tidal setting, and climate regime (Ellison and Stoddart 1991; Semeniuk 1994; Blasco et al. 1996). Mangroves on low-lying shorelines such as tidal flats will probably be most affected. Such stands will likely be inundated and therefore will retreat landward (Ellison and Stoddart 1991; Semeniuk 1994; Fujimoto et al. 1996). Freshwater marshes and swamps, which are often associated with mangroves (Pool et al. 1977; Tomlinson 1986; Myers 1990; Bonadie 1998), are also expected to shift landward (Jelgersma et al. 1993).

In addition to global climate change, there are also shorter-term climate perturbations that may affect coastal ecosystems. The El Niño-Southern Oscillation (ENSO) is one such climate phenomenon that occurs every few years and involves changes in atmospheric pressure and sea surface temperature in the Pacific Ocean. The implications of these changes include weakened trade winds and an associated eastward movement of water along equatorial regions (Philander 1990). ENSO conditions have been shown to teleconnect to other parts of the world creating major disruptions in climate (Rasmussen 1985; Glantz et al. 1991).

In areas such as the western Pacific, ENSO conditions have led to severe drought (Goldammer and Seibert 1990; Philander 1990). Such was the case during the 1982–1983 and 1997–1998 ENSO

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* Corresponding author; present address: U.S. Geological Survey, WRD, 6000 J Street, Placer Hall, Sacramento, California 95819-6129; tele: 916/278-3057; fax: 916/278-3011; e-mail: jdrexler@usgs.gov.

events, the strongest of this century (Garrison 1999; Wilkinson et al. 1999). The effects of drought on coastal vegetation can range from increased incidence of fire to more subtle impacts such as saline intrusion into freshwater ecosystems (Goldammer and Seibert 1990; Savenije and Pagès 1992; Diop et al. 1997; Alongi 1998; Goldammer 1999). Recent research suggests that ENSO events have become more frequent and intense since the mid-1970s (Trenberth and Hoar 1996; Timmerman et al. 1999). How this will affect coastal wetlands such as mangroves is unclear and depends strongly on the particular climate, geomorphology, and hydrogeology of an area.

The purpose of this study was to determine whether an individual ENSO event could have measurable impacts on mangroves and associated freshwater ecosystems. We studied the influence of the 1997–1998 ENSO-related drought on hydrology and salinity in a Micronesian wetland complex consisting of mangroves and an adjacent freshwater swamp, an assemblage common to many tropical settings around the world. By studying the wetland complex, we sought to assess possible impacts on both wetlands as well as to characterize the linkage between them.

Materials and Methods

Study Site

This study was conducted during January–December 1998 on the western Pacific island of Kosrae, Federated States of Micronesia (5°16′ to 22′N, 162°54′ to 163°02′E; Fig. 1). Kosrae is a high island, 112 km² in size, that was formed between 1.2 to 2.6 million years ago as a result of an alkalic-basalt oceanic volcano (Keating et al. 1984). Along the narrow coastal fringe, Kosrae contains approximately 1,562 ha of mangroves dominated by *Sonneratia alba* J. Smith, *Bruguiera gymnorrhiza* (L.) Lamk., *Rhizophora mucronata* Lamk., *Rhizophora apiculata* Bl., and *Rhizophora stylosa* Griff. Additional mangrove species found on Kosrae include *Heretiera littoralis* Dryand., *Lumnitzera littorea* (Jack) Voigt., and *Xylocarpus granatum* König. (Whitesell et al. 1986; Mueller-Dombois and Fosberg 1998; Duke personal communication). Average air temperature on Kosrae is approximately 27.4°C (Mueller-Dombois and Fosberg 1998). Annual precipitation is usually between 5,000–6,000 mm (Merlin et al. 1993). Precipitation is evenly distributed throughout the year, due to the high elevation of the island (highest point at 630 m) and its location within the trade wind belt (Mueller-Dombois and Fosberg 1998). Tides are mixed semidiurnal. Mean tidal amplitude is approximately 1 m (Nautical Software, Inc. 1997).

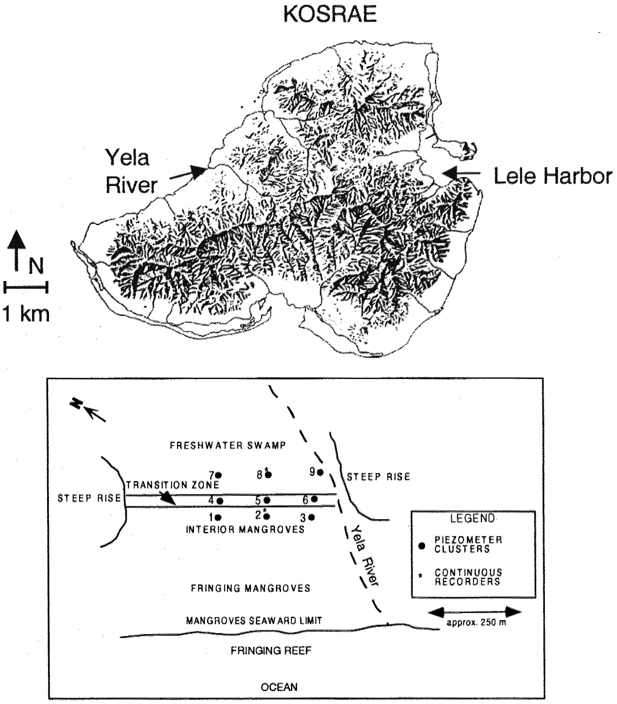

Fig. 1. Detail map of the island of Kosrae, Federated States of Micronesia (5°16′ to 22′N, 162°54′ to 163°02′E). Location of piezometer clusters 1–9 in the mangroves, transition zone, and freshwater swamp of the Yela watershed are shown in the bottom panel.

Research was focused in the Yela watershed, a relatively pristine, 659-ha area on the northwestern side of the island that has no human settlements and sustains only limited disturbance from logging (Fig. 1). The Yela watershed contains a largely intact mangrove swamp (105 ha) that is situated on a tidal flat and lies adjacent to a freshwater swamp (77 ha) dominated by *Terminalia carolinensis* Kaneh., a tree endemic to the eastern Caroline Islands. Between these two wetlands lies a narrow transition zone dominated by the trees *Hibiscus tiliaceus* L. and *Barringtonia racemosa* L. Spreng. The study was conducted along an area of the wetland complex comprising the downstream edge of the freshwater *Terminalia* swamp, the transition zone, and the upstream edge or interior of the mangrove swamp (Fig. 1). The soil consists of the Naniak series (fine-loamy, very poorly drained, mixed, nonacid, isohyperthermic Typic Sulfaquents) in the mangroves and the Inkosr series (fine, somewhat poorly and poorly drained, mixed, nonacid, isohyperthermic Typic Tropaquepts) in the freshwater swamp (Laird 1983). The soil ranges in depth from approximately 2.0 to 4.0 m and overlies a matrix of coral rubble and sand (Fujimoto et al. 1996; Cahoon unpublished data).

FIELD MEASUREMENTS

In January 1998, 3 piezometer clusters were inserted into each of the three zones: freshwater swamp, transition zone, and mangroves (Fig. 1). Each piezometer cluster consisted of 2.54 cm ID schedule 80 PVC pipes drilled with 2–3 mm holes along the bottom 10 cm and covered with screen, and a water table well (1.5 m in depth) with holes and screen along the entire length. Piezometers were inserted to 0.5, 1.0, 1.5, 2.5, and 3.5 m below-ground surface. The depth of the soil determined the number of piezometers inserted. Upon reaching the bottom of the soil layer during installation of cluster 1, we inserted the deepest piezometer (1.83 m) approximately 5 cm into the coral rubble. In order to install piezometers, a hole was first augered to the appropriate depth. A small amount of gravel and sand was then placed into the hole, the piezometer was inserted, and the rest of the hole was filled with the soil removed with the auger. Bentonite clay was used to seal the top of the soil column, and a small amount of soil was placed over the bentonite. The top of each piezometer was surveyed relative to a mean sea level (MSL) datum, which was established by the United States Geological Survey (Van der Brug 1972).

In piezometer clusters 2 and 8, water table wells of 7.65 cm ID were used. These wells were inserted as described above. A continuous water level and specific conductance recorder (600 XLM series, YSI, Inc., Yellows Springs, Ohio) was suspended at 1.35-m depth in each of these water table wells. Error free readings were recorded from January 17 to December 3, 1998 for the recorder at piezometer cluster 2 and from March 1 to December 31, 1998 for the recorder at piezometer cluster 8.

Manual measurements of water level and salinity were made during neap tides and at high and low spring tides between January and December 1998. The water level in each piezometer and water table well was measured with an electronic beeper device. Care was taken to stand downstream and at least 1 m from each piezometer and water table well during sampling in order to prevent compression of the soil. No measurable differences in water levels were observed as personnel moved around individual piezometer clusters. Water level elevations (z) in piezometers and water table wells were recorded relative to MSL. These values were converted to equivalent freshwater hydraulic head measurements (h) by correcting for water density changes throughout the piezometer network ($h = z \times \rho_{sample}/\rho_{freshwater}$). Groundwater was pumped out of each piezometer and water table well into a clean sampling flask. Salinity was immediately determined using a YSI Model 30 Conductivity Meter (YSI, Inc. Yellow Springs, Ohio).

Precipitation data were provided by the National Climatic Data Center (unpublished data). The collection station on Kosrae is situated at 5°21′N, 162°57′E and 2.1 m in elevation relative to MSL. The distance from the collection station to the study area is < 3 km. The station on the neighboring island of Pohnpei, Federated States of Micronesia, is situated at 6°58′N, 158°13′E, 36.6 m above MSL. Tidal data were obtained from Tides and Currents Pro, Version 2.5 b (Nautical Software, Inc., Beaverton, Oregon), a program based on raw data collected by the National Oceanic and Atmospheric Administration (NOAA) for Lele Harbor, Kosrae. Tidal data are relative to current mean lower low water (MLLW).

STATISTICAL ANALYSIS

In order to ascertain whether salinity measurements from the piezometer network were different during and after the ENSO-related drought, we carried out analysis of variance using the general linear model with repeated measures design (PROC MIXED, SAS release 6.12.) Raw data used in the model were the differences in mean salinity values during the drought (January–April) and after the drought (May–December) in each piezometer. We specifically used the low tide data during spring tide for the analysis so that any differences would not be obscured by daily tidal fluctuations or sampling time within the lunar tidal cycle. We also carried out the analysis on the entire data set and found the same general results. Zone, depth, and the interaction term (zone × depth) were the factors tested. Autocorrelation of errors for the different depths of wells in each cluster was incorporated into the model. Residual plots of the data indicated that there was more variability in salinity values at the 0.5 m depth than at the other well depths. Therefore, we structured the model to allow for more variance for the 0.5 m wells and equal variance for the other wells. Tukey-Kramer tests were used to analyze pairwise comparisons between components within each of the factors.

Results

HYDROLOGY

The severity of the ENSO-related drought is illustrated by the reduced rainfall in the early part of 1998 (Fig. 2a). The drought began in October 1997 and reached its peak in January and February, when rainfall was approximately 10% of normal levels (Pacific ENSO Applications Center 1998). Only after May did rainfall return to near normal levels (Pacific ENSO Applications Center 1998). A long-term data set of precipitation from

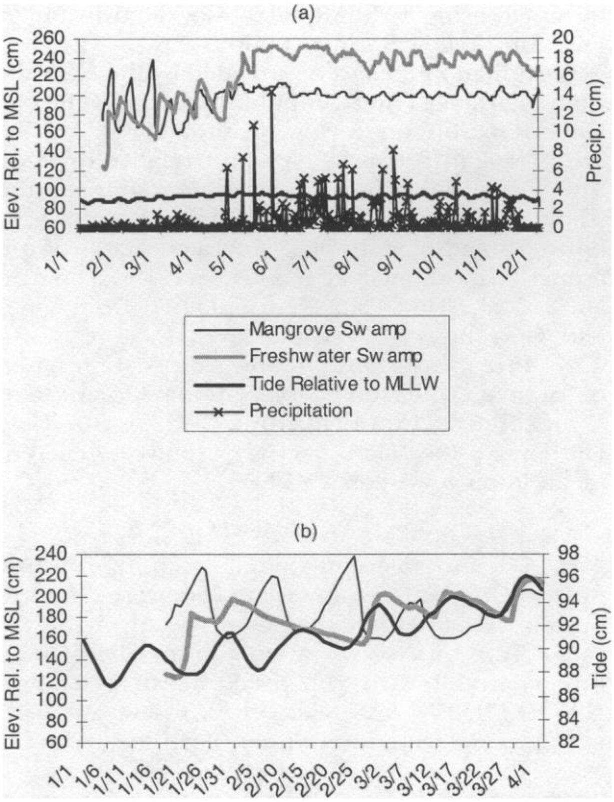

Fig. 2. Daily mean water table elevation in the mangroves and freshwater swamp, daily mean tidal elevation, and daily precipitation during January to December 1998 (a). A focus on the daily mean water table level elevation in each wetland and the daily mean tidal elevation during the ENSO-related drought (b). Tidal data are from the eastern part of the island (Lele Harbor) and are relative to current MLLW.

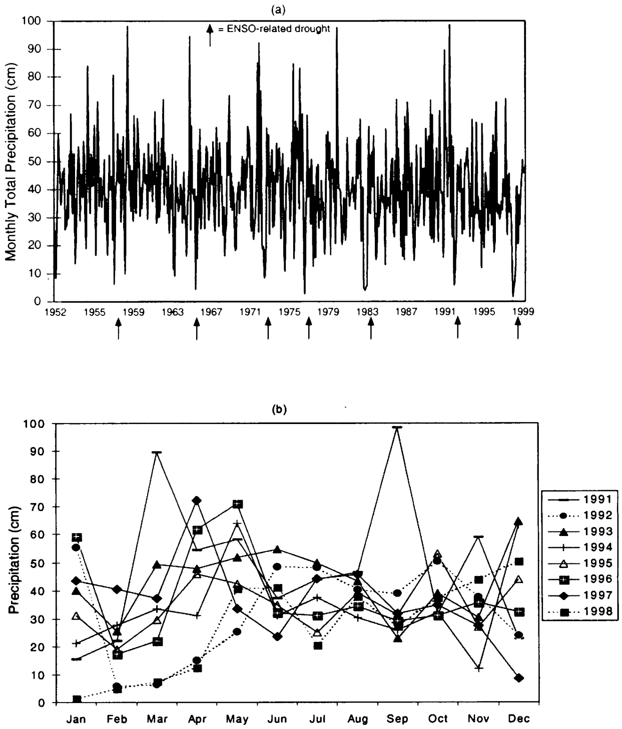

Fig. 3. Total monthly precipitation on the island of Pohnpei, Federated States of Micronesia, from 1952 to 1999 (a). Variability in total monthly precipitation from 1991–1998 (b). ENSO-related droughts occurred during 1957–1958, 1965–1966, 1972–1973, 1976–1977, 1982–1983, 1991–1992, and 1997–1998.

the neighboring island of Pohnpei, Federated States of Micronesia indicates that droughts have accompanied seven ENSO events from 1952 to 1999 (Fig. 3a). Droughts have occurred at other times as well, yet ENSO-related droughts, such as those during 1982–1983 and 1997–1998, are among the most severe on record. Although there is no defined seasonality for rainfall in this part of the Pacific (Mueller-Dombois and Fosberg 1998), monthly precipitation can vary across several tens of centimeters within any given year (Fig. 3b). During ENSO conditions reductions in rainfall are well below normal fluctuations (Fig. 3b).

The ENSO-related drought affected wetland hydrology by causing a decline in the mean elevation of the water table in both the mangroves and the freshwater swamp as well as causing dramatic fluctuations in water table level in both systems (Fig. 2a). During the drought period (January to late April 1998), mean water table levels in the freshwater swamp and mangroves were 54 and 12 cm lower, respectively, than for the remainder of the year. The elevation of the water table in the freshwater swamp dipped below that of the mangroves several times during the drought, even though the ground surface of the freshwater swamp is approximately 55 cm higher than in the mangroves. A few isolated rain storms during the peak of the drought had a major impact on the elevation of the water table in both wetlands. After the January 21 storm, which produced 0.79 cm of rain, there was a sharp rise (somewhat delayed in the mangroves) in water table level in both wetlands (Fig. 2b). In late January and early February there were several small storms as well as an especially high spring tide, which caused the water table level in the freshwater swamp to rise precipitously. A similar rise in the water table level of the mangroves was not seen until approximately one week later. After these initial storms, the freshwater swamp had a steady decrease in water table level while the water table level of the mangroves continued to fluctuate out of phase with the tide (Fig. 2b). Only after February 26, when a large rain event (1.52 cm) occurred together with a large spring tide (and several other precipitation events followed),

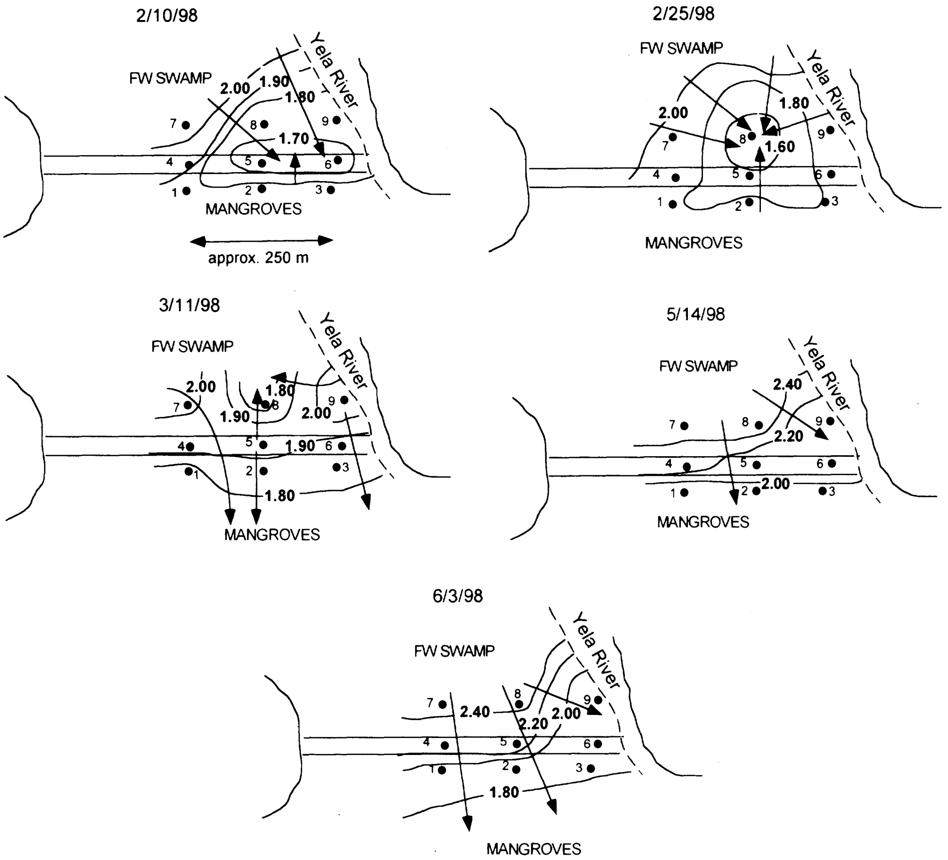

Fig. 4. Water table maps for the peak and shortly after the ENSO-related drought of 1998. Hydrological measurements were taken at low water or lower low water during spring tides on February 10, February 25, and May 14, 1998. Measurements for March 11, 1998 were taken at low water during spring tide, except for piezometer clusters 7, 8, and 9, which were measured during the initial onset of the rising tide. For June 3, 1998, measurements were taken during neap tide. Isolines upstream and downstream of the piezometer network are extrapolated. Arrows depict the general direction of groundwater flow. Water table elevations (m) are relative to the historical mean sea level datum described earlier.

did the water table level of the freshwater swamp finally transition into being steadily greater than that of the mangroves. Although the water table level in the freshwater swamp regained general synchronicity with the tides in early March, it wasn't until the end of March that the water table level in the mangroves did the same.

A closer examination of the period during the peak of the drought showed that there were reversals in the direction of groundwater flow (Fig. 4). Water table maps of the study area indicate that, on February 10, groundwater along the transect containing piezometer clusters 2, 5, and 8 (in the central area of the site) flowed from the mangroves into the transition zone. On February 25, groundwater flowed from the mangroves all the way to the freshwater swamp. In mid-March, groundwater flowed from the transition zone to the freshwater swamp. These reversals occurred during low tide and were confined to the central area of the site. Along the transect containing piezometer clusters 3, 6, and 9, there was considerable influence from the river. During February 25, river water flowed into the freshwater swamp due to the hydraulic head gradient created by the drought. During March 11, river water also flowed into the freshwater swamp, but this was mainly due to the rising tide and not drought conditions.

Flow nets constructed for the transect containing piezometer clusters 2, 5, and 8 show that at the peak of the drought (February 25) there was major recharge occurring at piezometer cluster 8. Piezometer cluster 5 was also a recharge site, but to a much smaller degree. There was predominantly reversed lateral flow (horizontal flow) at clusters 5 and 2. At clusters 2 and 8, there was also some discharge at depth. On March 11, flow conditions began to change in response to precipitation (Fig. 5b). There was slight discharge deep in the soil along the whole transect and lateral flow in both directions (upstream and downstream) from piezometer cluster 5. Groundwater mounding at clus-

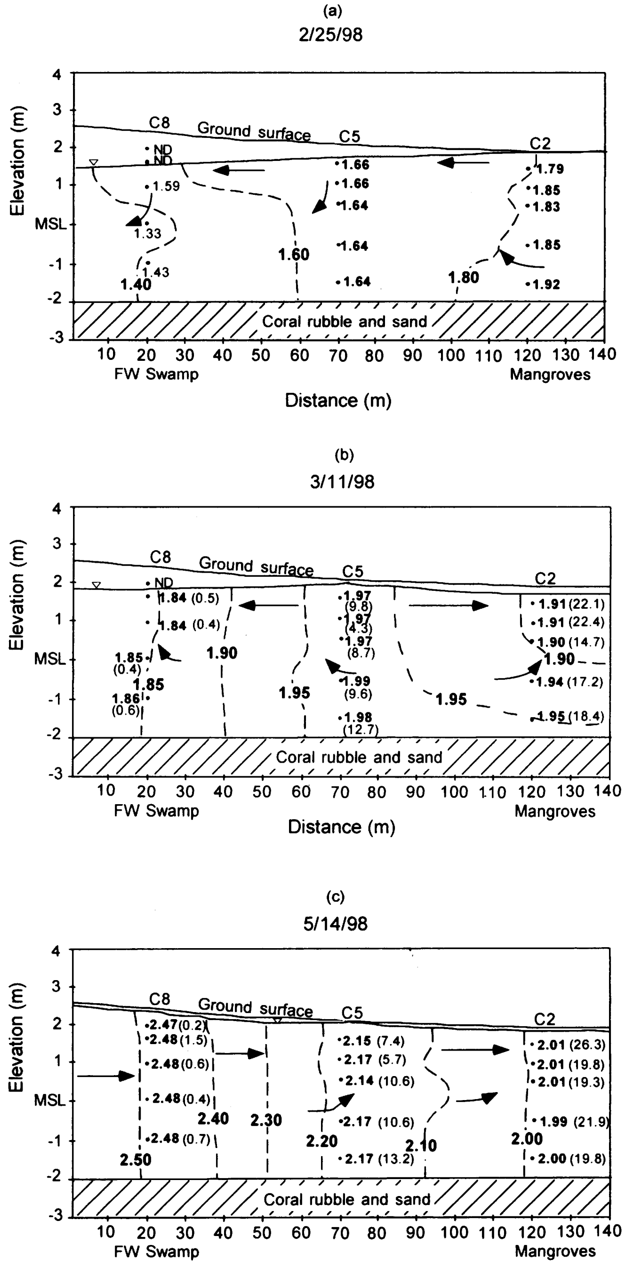

Fig. 5. Flow nets for the transect encompassing piezometer clusters 2, 5, and 8 during (a) the peak of the drought (February 25), (b) when the drought began to subside (March 11), and (c) shortly after the drought subsided (May 14). Hydraulic head values (in meters) are in bold print and salinity values (‰) are in parentheses. Dotted lines are equipotential lines of hydraulic head. Open triangles depict the elevation of the water table. Downward-pointing arrows represent groundwater recharge and upward-pointing arrows represent groundwater discharge. Arrows pointing horizontally represent lateral flow. ND = no data due to dry conditions.

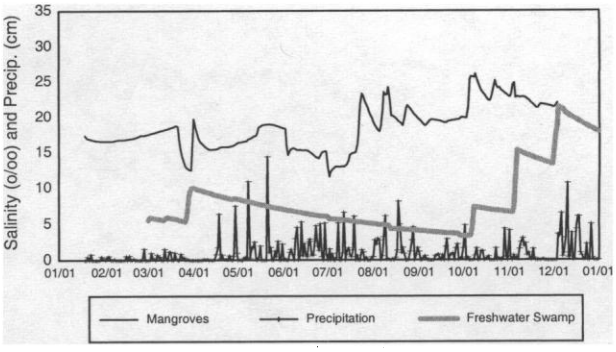

Fig. 6. Daily precipitation and mean daily salinity values for water table wells in the mangroves and freshwater swamp.

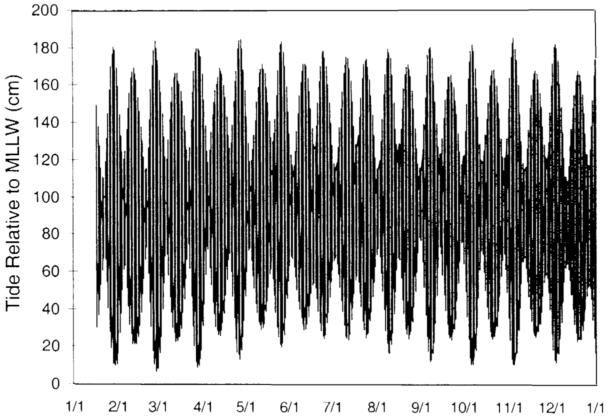

Fig. 7. Hourly tidal fluctuations during the study period.

ter 5 appears to be the result of recent tidal flooding. The influence of this flooding can be seen in the elevated salinity (9.8‰) near the ground surface (Fig. 5b). Shortly after the drought subsided (May 14), water table levels in the freshwater swamp were considerably higher resulting in groundwater flowing laterally from the freshwater swamp toward the mangroves (Fig. 5c). This occurred despite the tidal influence on the 0.5-m piezometers in clusters 2 and 5 (see salinities in Fig. 5c). Once rainfall resumed to near normal levels in late spring/early summer, soils in both the mangroves and freshwater swamp returned to near-saturated levels, and occasionally periods of overland flow were observed along the whole transect. Although piezometer clusters 1, 3, 4, 6, 7, and 9 did not exhibit reversals in groundwater flow during the drought, there was a major drawdown in the elevation of the water table at these clusters. Water table levels rose only after the rains resumed in mid-late spring (Fig. 4).

TABLE 1. Mean salinity in piezometers and water table wells (WT) during the study period.

Zone	Cluster	Well Depth (m)	Salinity (SD)
Mangroves:	1	0.5	11.97 (6.63)
		1.0	15.41 (3.85)
		1.5	7.47 (2.26)
		1.83	2.17 (2.22)
		WT	16.56 (6.77)
	2	0.5	15.58 (7.04)
		1.0	15.60 (5.99)
		1.5	17.13 (2.60)
		2.5	20.98 (2.43)
		3.5	21.64 (2.23)
		WT	17.99 (6.86)
	3	0.5	16.50 (5.06)
		1.0	19.97 (3.62)
		1.5	19.38 (2.02)
		2.0	20.18 (2.66)
		WT	21.64 (4.22)
Transition Zone:	4	0.5	1.36 (1.40)
		1.0	0.74 (0.03)
		1.5	0.63 (0.27)
		2.0	0.67 (0.25)
		WT	2.22 (5.04)
	5	0.5	7.01 (3.53)
		1.0	7.13 (1.93)
		1.5	10.59 (2.30)
		2.5	12.32 (1.55)
		3.5	14.88 (1.26)
		WT	8.54 (3.88)
	6	0.5	6.10 (3.88)
		1.0	5.81 (1.02)
		1.5	5.91 (1.46)
		2.22	5.06 (0.40)
		WT	6.50 (3.78)
Freshwater Swamp:	7	0.5	0.17 (0.18)
		1.0	0.15 (0.04)
		1.5	0.22 (0.03)
		2.5	0.38 (0.04)
		WT	0.41 (1.05)
	8	0.5	1.32 (2.49)
		1.0	1.13 (0.56)
		1.5	0.94 (0.36)
		2.5	0.98 (0.40)
		3.5	2.01 (3.49)
		WT	2.69 (3.51)
	9	0.5	1.86 (2.83)
		1.0	0.88 (0.27)
		1.5	0.61 (0.18)
		2.0	0.72 (0.12)
		2.5	0.82 (0.05)
		WT	2.11 (2.54)

SALINITY

Groundwater salinity in the water table wells equipped with continuous recorders ranged from 11.6‰ to 26.1‰ in the mangroves and 3.4‰ to 21.5‰ in the freshwater swamp (Fig. 6). Salinity patterns were quite different between the two wetlands. In the mangroves, groundwater salinity roughly mimicked major tidal fluctuations (Figs. 6 and 7). This pattern became increasingly more consistent after the drought subsided. In the freshwater swamp, only especially high spring tides caused peaks in groundwater salinity (Figs. 6 and 7). The impact of each of these spring tides on salinity varied during different times of the year, yet the pattern of slow dilution after inundation was consistent. The variability in dilution time and impact from tidal flooding appears to be a function of the extent of flooding and the relative influence of flushing by precipitation and groundwater inflow.

Groundwater salinity values ranged from < 0.1‰ to 31.2‰ throughout the piezometer network. Mean groundwater salinity values generally increased with depth in piezometer clusters 2, 3, and 5, and generally decreased with depth in piezometer clusters 1, 4, and 6 (Table 1). Within the mangrove zone, the 1.83-m piezometer in cluster 1 (which was inserted directly into the coral rubble) had the lowest salinity, indicating groundwater seepage from below the peat column. In piezometers 7, 8, and 9 the standard deviations of salinity measurements were either too high or the range of mean salinities too low to discern any particular pattern. Overall, salinity in these clusters was extremely low.

Analysis of variance carried out to determine significant differences in groundwater salinity between the ENSO and post-ENSO time periods showed that zone, depth, and the interaction term were all significant at $p < 0.005$ (Table 2). The significant effect for zones was due to the difference between salinities during and after the drought in the mangroves (Table 3). Further analysis of the depth component throughout the study site showed that mean salinity levels in the 0.5 and

TABLE 2. Two-way analysis of variance of the differences in salinity values in the piezometer network (low tide only) during and after the ENSO-related drought.

Source	Degrees of Freedom	F	p-value	Variance Component Estimate
Zone	2	22.04	0.0017	
Depth	5	176.08	0.0001	
Zone × Depth	10	42.05	0.0001	
0.5-m piezometers				13.677
All other piezometer depths				3.443

TABLE 3. Least square means for zones and depths (m) in the two-way ANOVA from Table 2.

Effect	Zone	Depth	Least Square Mean	Standard Error	Probability > |t|
Zone	Mangroves		−3.6948	0.4012	0.0001
Zone	Freshwater Swamp		−0.2412	0.4737	0.6272
Zone	Transition Zone		−0.4350	0.4012	0.3183
Depth		0.5	−7.9529	1.3320	0.0001
Depth		1.0	−2.8154	0.6190	0.0005
Depth		1.5	−1.0524	0.6190	0.1123
Depth		2.0	0.3147	0.6263	0.6242
Depth		2.5	0.9458	0.6239	0.1533
Depth		3.5	1.3180	0.6311	0.0568

1.0 m wells were greater during than after the drought (Table 3).

Discussion

The drought associated with the 1997–1998 ENSO event led to dramatic changes in hydrology in the Yela watershed of Kosrae. The mangroves and freshwater swamp experienced a mean decline of 12 and 54 cm, respectively, in the elevation of the water table. There were also large fluctuations in the water table of both wetlands during January and February of 1998. Such fluctuations during the drought period indicate, that under especially low rainfall conditions, spring tides and relatively small storms can exert a major impact on water table levels (Fig. 2).

Tidal inundation, river flooding, groundwater flow, and precipitation all strongly influenced water table levels in the wetland complex, but their relative influence changed during the study period (Figs. 2, 4, and 5). In the freshwater swamp, flooding from the river had a markedly greater influence during the drought than after (Fig. 4). In both wetlands, the water table levels during the drought were largely out of phase with tidal fluctuations, whereas once the rains returned water table levels were again in phase with the tides, except during especially large precipitation events (Fig. 2).

At the peak of the drought, the most dramatic result was a reversal in groundwater flow in the central part of the study area that sent groundwater from the mangroves upstream toward the freshwater swamp (Figs. 4 and 5). This occurred because the hydraulic head plummeted in the freshwater swamp, and although the hydraulic head in the mangroves also fell, tidal forcing maintained the hydraulic head at a higher elevation than in the freshwater swamp (Fig. 5a). This situation led to the reversal of flow (groundwater flows from high head to low head). After precipitation returned to near normal levels, the water table in the freshwater swamp rose and groundwater resumed flowing from the freshwater swamp to the mangroves (Fig. 5c).

These hydrological changes not only demonstrate the sensitivity of the wetland complex to small changes in hydraulic head, but they also illustrate the strong linkage between mangroves and an adjacent ecosystem. In Japan, a similar linkage was demonstrated at a site where groundwater moved across a shore bank between a mangrove-dominated lagoon and the open sea (Mazda et al. 1990). In our study this linkage between ecosystems was also illustrated by groundwater salinity within the mangroves, which was substantially fresher than the salinity of sea water (35‰) (Fig. 6 and Table 1). In fact, 96% of all salinity measurements in the mangroves were at least 10‰ less than 35‰, suggesting that freshwater flow from upstream diluted saline groundwater. Clear evidence was found at piezometer cluster 1 of groundwater inflow from the coral rubble (Table 1). Within the piezometer network, the patterns of change in mean salinity with depth indicate that freshwater entered the mangroves through a combination of infiltration from rainfall/overland flow and from groundwater discharge at depth. Piezometer clusters situated in areas with high infiltration of freshwater had increased salinity with depth (e.g., piezometers 2, 3, and 5, which were occasionally areas of major overland flow), whereas clusters situated in areas receiving groundwater seepage had decreased salinity with depth (e.g., piezometer clusters 1, 4, and to a lesser extent 6, which apparently received groundwater discharge from the river; Table 1). The importance of groundwater in reducing salinity (and thereby facilitating mangrove growth) was also noted by Semeniuk (1983) in his work on mangroves near the margins of arid hinterlands in northwestern Australia.

The ENSO-related drought led to increased salinity in the 0.5-m and 1.0-m wells of the piezometer network (see Results and Table 3). This suggests that lack of rain led to desiccation, which, in turn, increased salinity values more near the surface than deeper in the soil. Because the continuous recorders measured salinity at 1.35 m in depth, they were not able to capture the extent of this concentration effect. Continuous salinity measurements from the mangroves only showed a slight increase during the drought and no such increase was found for the continuous salinity measurements from the freshwater swamp (Fig. 6).

The long-term implications of the above-mentioned changes in hydrology and salinity have yet to be investigated. Nevertheless, it is of interest to speculate on how such ENSO-related droughts may affect mangroves and associated ecosystems in the future. Reduction in freshwater flows, associated drawdown in the water table, and increased salinity near the surface may reduce productivity in these and other mangroves accustomed to flushing and nutrient/sediment inputs from freshwater flows (Clough 1992; Mitsch and Gosselink 1993; Alongi 1998; Ewel et al. 1998a). Preliminary data on tree-band measurements used to assess growth rates suggest that mangroves in the Yela watershed grew little if at all during the ENSO-related drought (Allen personal communication). Drought-related impacts may also reduce recruitment and development of seedlings in both wetlands. Failure in recruitment would probably be higher in the *Terminalia*-dominated freshwater swamp where drawdown was much more pronounced. Drawdown and the accompanying increase in groundwater salinity near the surface could impose stressful conditions on shallow-rooted *Terminalia* seedlings. Such new recruits are unlikely to be as tenacious as mangrove propagules (e.g., *Rhizophora* or *Bruguiera* spp.). Mangrove propagules are viviparous and once independent of the mother tree can withstand dry, saline conditions and can remain unrooted for long periods (Davis 1940; Larue and Muzik 1954; Tomlinson 1986). Over several drought cycles, reduced recruitment in both systems could lead to a number of changes in the structure and function of both wetlands, including an expansion landward of the mangroves and a concomitant shift upstream by the freshwater swamp (cf., Jelgersma et al. 1993).

This study demonstrates that mangroves and associated ecosystems are vulnerable to impacts from short-term perturbations in climate. If the greater frequency of ENSO events is indeed the result of anthropogenic activities (Timmermann et al. 1999), this example represents a powerful yet indirect way in which humans are affecting the coastal ecosystems on which they depend for many ecosystem services (Ewel et al. 1998b). As a case in point, Kosrae is probably on the lower end of impacts from drought (caused by ENSO or other factors) because of its usually high rainfall, large groundwater storage capacity, and relatively pristine ecosystems (Mink 1986; Merlin et al. 1993; Ewel et al. 1998a). Islands or coastal areas in drier climates and under greater development pressure are more likely to suffer larger impacts such as the fires that devastated Indonesia during the 1982–1983 and 1997–1998 ENSO events (Goldammer and Seibert 1990; Goldammer 1999). Results from this study suggest that, although a large proportion of climate research is focused on the ecological outfall of global climate change, the ramifications of short-term climate perturbations such as ENSO should not be overlooked.

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