RUNNELLING TO CONTROL SALTMARSH MOSQUITOES: LONG-TERM EFFICACY AND ENVIRONMENTAL IMPACTS

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ABSTRACT. *Aedes vigilax* is a problem mosquito species prevalent in subtropical Australian coastal wetlands. We evaluate the long-term impacts of runnelling, an environmentally benign habitat modification method, on mosquitoes and the wetland environment. Runnelling uses shallow channels to enhance flushing of the marsh. The method successfully reduced larval numbers to below nuisance levels for the 6.5 year study period. We did not detect any significant difference in the wetland environment between runnelled and unmodified parts of the study area. However, the spatial extent of the effects may have extended beyond the modified area.

INTRODUCTION

Aedes vigilax (Skuse) is the main salt marsh mosquito species inhabiting the intertidal wetlands along the Australian coast, particularly in subtropical areas. It is a vector of Ross River virus, arguably the most important Australian arbovirus. With over 75% of Australians living within 25 miles (40 km) of the coast, management of the wetlands for vector control is important.

Most mosquito control in Australia is accomplished by applying larvicides to larval habitats (Dale 1992). Temephos 5% sand granules are commonly used for aerial application (Kay et al. 1973). So far there have been no major resistance problems from either the target species or the public. However, insect resistance is a potential problem and public opposition to pesticides is growing because of environmental concerns. This has intensified efforts to find biorational alternatives to organophosphates.

In conjunction with mosquito control authorities, we developed "runnelling" as a mosquito management tool (Hulsman et al. 1989). Our aim was to do as little as possible to the environment, thereby retaining wetland integrity, yet still reduce mosquito numbers to an acceptable level. Runnelling consists of a network of very shallow spoon-shaped channels or runnels that connect otherwise isolated pools to each other and to the tidal source. Wherever possible, the runnels follow natural patterns of water movement. Such modifications involve relatively minor changes to wetland hydrology. In essence, runnelling is a very simple form of Open Marsh Water Management (OMWM), which minimizes interference in the system and uses only one structure, that is, the runnel. The effects of ditching and OMWM as reported in the literature, were reviewed in Dale and Hulsman (1991) and compared with those of runnelling, as known at that time. Runnels appeared to have less impact than either ditching (e.g., Kuenzler and Marshall 1973, Collins et al. 1986) or OMWM (e.g., in Whigham et al. 1982).

The method appears to work by 3 mechanisms: it flushes larvae out of the marshes into estuaries where they drown or are eaten; it allows predators (mainly fish) access to the marsh and its larval food source; and it appears to affect oviposition site characteristics making them less attractive to gravid adults. There is evidence to support all 3 mechanisms (Dale et al. 1989, Hulsman et al. 1989, K. Hulsman, unpublished data and S. A. Ritchie, unpublished data).

During the first 15 months following modification, analyses indicated that the runnelled sites were behaving in much the same way as unmodified water bodies in the adjacent marsh (Dale and Hulsman 1988). Here we evaluate both runnelling as a long-term method of mosquito control and also the longer-term (6.5 year period) impacts of runnelling aspects of the environment (water table, substrate and vegetation characteristics).

METHODS

Study area: The study area is on Coomera Island (27° 52′S, 153° 23′E) which is situated between the heavily populated areas of Brisbane, 70 km to the north, and the Gold Coast to the south (Fig. 1). The area is one of the most rapidly developing parts of Australia and settlement is spreading along the mainland adjacent to the island (Resource Assessment Commission, 1992). The study site covers about 8 ha of tidal salt marsh, of which a small part (0.5 ha) has been runnelled. Tides are semi-diurnal with an annual range of around 2 m. Flooding is especially frequent during the summer months, when high tides are augmented by heavy rain-

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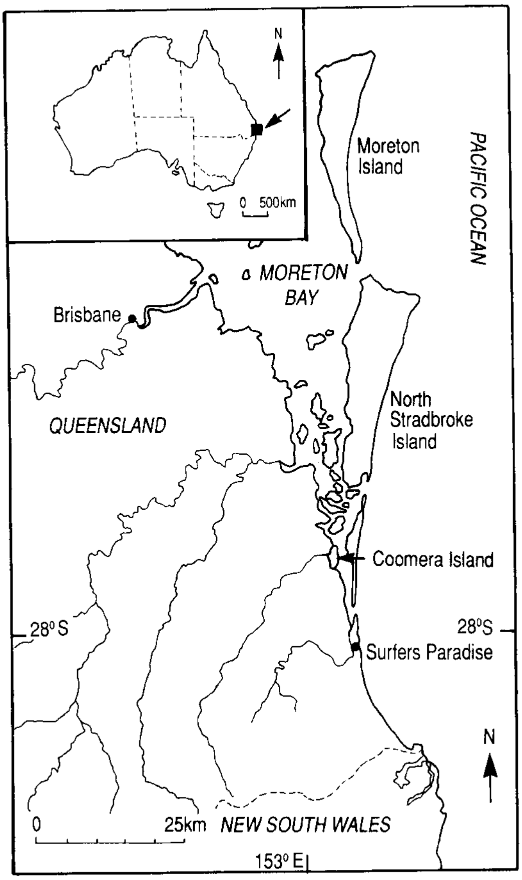

Fig. 1. Location of the study site in southeastern Queensland, Australia.

fall. *Aedes vigilax* breeds prolifically in salt marsh pools in the area and would require chemical treatment between 6 and 12 times a year, were no other form of control in place.

Field data

Mosquito control aspects. Larval numbers and runnel morphology were measured every 3 months. Larval numbers were recorded at 21 sites within the runnelled area and randomly in the surrounding marsh. At each site, three 240 ml scoops were taken with a dipper and larvae counted and age graded by stage. To increase the frequency of observations, we also used data provided by the local mosquito control agencies, collected at times of known breeding in southeastern Queensland. Runnel morphology was monitored to assess erosion or deposition. We measured the maximum depth and width of the runnels at 4 sites and took photographs from fixed points. Three of the sites (#1–3) were along a runnel which is approx. 45 m long; the fourth (#4) was at the outlet end of a runnel in a highly interconnected system of runnels.

Environmental variables: The following environmental variables were measured: water table level and salinity; substrate moisture content, its salinity and pH and density and size of the 2 dominant plant species, *Sporobolus virginicus* (Marine couch) and *Sarcocornia quinqueflora* (Samphire). The water table was observed in fixed plastic standpipes using a meter ruler (for level) and a standard meter (for salinity). Substrate samples were taken from the surface 5 cm, transported in sealed plastic bags and then analyzed in the laboratory. Moisture content was measured by drying a 50 g sample; salinity and reaction were measured by diluting a 20 g sample in a 5:1 ratio with distilled water, following the method of Bruce and Rayment (1972). Plant density was measured by counting the number of live tillers for *Sp. virginicus*, and the number of live succulent shoots for *S. quinqueflora* in 10 × 10 cm fixed quadrats. In each quadrat, size was measured as follows: the average height of 10 *Sp. virginicus* tillers (measured from ground level to the top of the youngest node) and the average length of 10 succulent shoots for *S. quinqueflora*.

Observations were made at distances of 0, 1, 2 and 4 m from the edges of 5 runnels and 2 unrunnelled pools (Fig. 2). Sites next to the 2 pools that were not connected to runnels were contrasted with sites next to runnels. This was because we wanted to determine whether modified water bodies (runnels) behaved differently from natural ones (pools). The 2 unrunnelled pools are near to the edge of the runnelled site and were as close to being "controls" as was considered possible, given marsh variability (Dale and Hulsman 1988). Data were collected 3 months prior to runnelling, monthly for the initial 15 months, and quarterly thereafter. Field observations were made at or near the new moon to standardize the stage of the tidal cycle. Analysis of the detailed 15 months data is described in Dale and Hulsman (1988). Here we use data at 3 monthly intervals, dating back to runnel construction. Seasons are spring (November), summer (February), autumn (May) and winter (August). This monitoring continues.

Data analyses

Mosquito control aspects. For larval numbers and runnel morphology simple descriptive methods such as averages have been used to describe the outcome of the modification. As well, regression of runnel depth on time was done to assess accretion (positive slope) or erosion (negative slope).

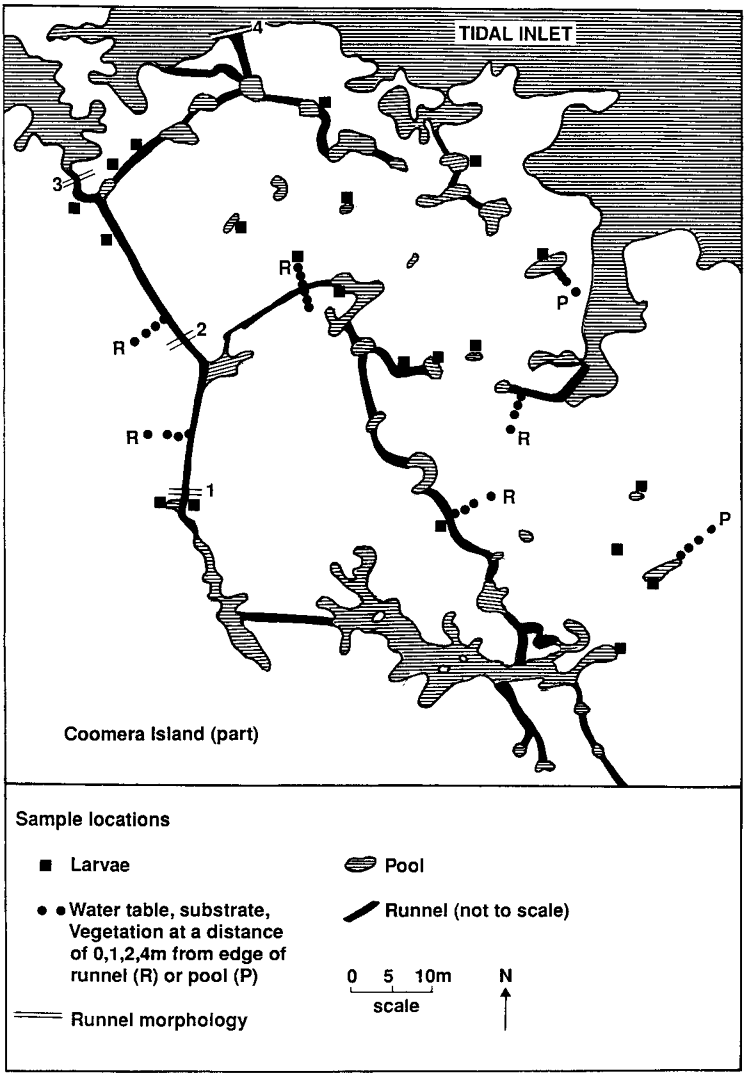

Fig. 2. Experimental design, showing sample points with respect to the modification layout.

Environmental variables: To evaluate the impacts of runnelling on the environment an ANOVA was calculated using the 5% significance level. To explore the macro-relationships, the ANOVA was done for each of the 9 environmental variables, on Type (pool or runnel), Distance, Year, Season and all their interactions. This is inherently likely to undervalue some potentially significant effects because of the complex interactions. Nevertheless, it is a means of exploring robust effects. Where it appeared that there were some significant effects a more refined analysis was done using selected variables.

Remote sensing: To evaluate impacts of runnelling on a larger area, we analyzed large scale color infrared aerial photographs of several hectares of marsh. Numerical image analysis has been used to subtract images taken before and after runnelling. These produced new images showing the relative changes in reflectance over the marsh, and hence indicated areas of greatest change.

RESULTS

Mosquito control aspects

Effects on larvae. The number of larvae have been below nuisance levels in the runnelled area ever since the first 3 months after runnelling. These are shown in Fig. 3. In the field, treatment

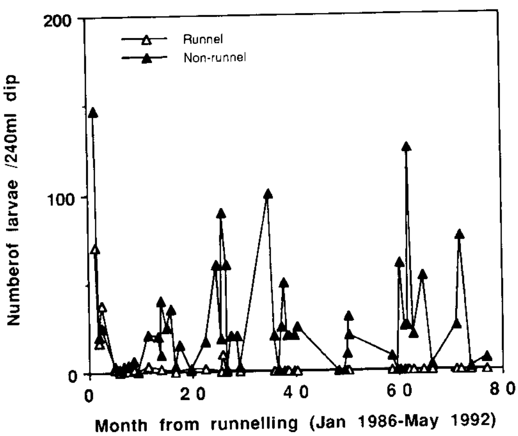

Fig. 3. Larval numbers in the modified and unmodified marsh before and for 6.5 years after runnelling.

by spraying is normally initiated after finding >5 larvae/240 ml dip in >20% of dips. Using this criterion, treatment would have been required some 38 times in the unmodified area compared with only 4 in the runnelled area.

Runnel morphology: Runnel depths varied during the 6.5 year period because of erosion and deposition (Fig. 4) as shown by the regression results. Sites 1–3 along the long runnel experienced erosion as indicated by a negative slope of the regression line. For site 4, in the denser network of runnels, the slope was positive indicating deposition. There was also an effect of distance from the tidal source on the variability of depth. Sites at some distance from the tidal source (#1 and 2) had a high correlation of depth on time (R = 0.84 and 0.83) whereas sites 3 and 4, closer to the tidal source, were more variable (R = 0.55 and 0.51).

Environmental variables

The ANOVA results are summarized in Table 1. Whether a site was near a pool or runnel and its distance from it was not significant for any of the environmental variables. Only Year, Season and their interactions were significant in accounting for variations in most of the environmental variables. The site Type (pool or runnel) by Year interaction was slightly significant only for salinity. Trends were clearly apparent for water table level and its salinity, substrate moisture salinity and *Sp. virginicus* density, at least for the first 4–5 years. More recently the trend is much less clear.

Water table level rose, especially during the first 15 months (Fig. 5). We found a significant effect of Year. After the first 15 months water levels have fluctuated but no clear long-term trend has emerged. This is probably because, once the water table is more or less at the ground surface, as it has been for many of our observations, the possible range of variation is severely limited.

Water table salinity declined during the period (Fig. 6). Again, time was the dominant influence. Year, Season and their interaction were all highly significant. As well as the overall decline in salinity, there has been a seasonal fluctuation. Salinity tends to be highest in spring and summer and declines into autumn, with a May minimum. As time progressed, this fluctuation appeared to be dampening. The Type by Year interaction was significant with pool sites slightly more saline than runnel ones although this difference also appeared to be diminishing.

Substrate moisture content: Year, Season and their interaction were all significant, showing that substrate moisture increased for around 5 years. Subsequently, it declined and thus needs further monitoring (Fig. 7a).

Substrate moisture salinity at both pool and runnel sites tended to decrease over time. After 6.5 years salinity levels were very similar (Fig. 7b). Year, Season and their interaction were all highly significant. The seasonal effect is of greater magnitude for substrate moisture salinity than for that of the water table. Substrate salinity peaked in winter, fell from spring through summer and was at a minimum in autumn. There was a slightly significant effect of the interaction between Type and Year with a greater reduction in salinity near runnels than

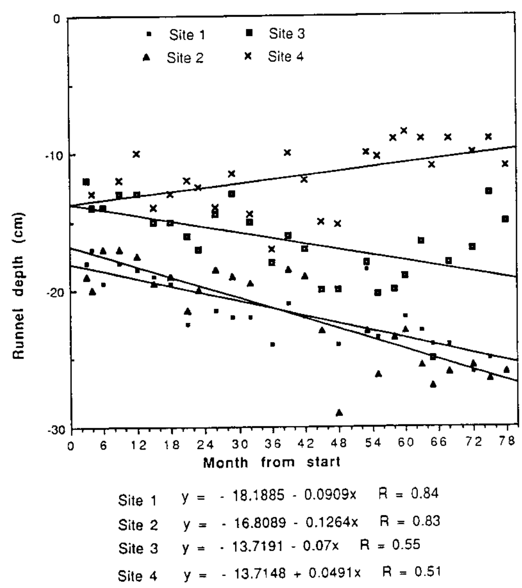

Fig. 4. Runnel depths from time of construction to 6.5 years later.

Table 1. Summary of ANOVA results for the environmental variables

Environmental variable	Treatment						General nature of the effect
	Pool or runnel (type)	Distance	Year × Type	Year	Season	Year × Season	
Water table	n.s.	n.s.	n.s.	$P < 0.001$ F = 41.72 df 1,712	n.s.	n.s.	Rise
Water table salinity	n.s.	n.s.	$P < 0.05$ F = 6.19 df 1,723	$P < 0.001$ F = 76.20 df 1,723	$P < 0.001$ F = 11.58 df 3,723	$P < 0.001$ F = 11.84 df 3,723	Decrease
Substrate moisture	n.s.	n.s.	n.s.	$P < 0.001$ F = 40.63 df 1,765	$P < 0.05$ F = 3.55 df 3,765	$P < 0.01$ F = 3.92 df 3,765	Increase
Substrate salinity	n.s.	n.s.	$P < 0.05$ F = 4.07 df 1,765	$P < 0.001$ F = 20.72 df 1,765	$P < 0.001$ F = 18.07 df 3,765	$P < 0.001$ F = 19.38 df 3,765	Decrease
Substrate pH	n.s.	n.s.	n.s.	$P < 0.001$ F = 64.63 df 1,765	$P < 0.001$ F = 57.91 df 3,765	$P < 0.001$ F = 61.25 df 3,765	Slight increase
Sp. virginicus density	n.s.	n.s.	n.s.	$P < 0.001$ F = 26.89 df 1,777	n.s.	n.s.	Decrease
Sp. virginicus height	n.s.	n.s.	n.s.	$P < 0.001$ F = 11.50 df 1,764	$P < 0.05$ F = 2.95 df 3,764	$P < 0.05$ F = 2.95 df 3,764	Decrease
Sa. quinqueflora density	n.s.	n.s.	n.s.	$P < 0.001$ F = 16.79 df 1,765	n.s.	n.s.	Decrease
Sa. quinqueflora size	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	No obvious pattern

n.s., not significant; $P > 0.05$.

near pools. However, the effect of modification alone was not statistically significant.

Substrate moisture pH results were only significant for Year, Season and their interaction. There was a slight increase in pH over the time period. Seasonally pH peaked in autumn and fell during winter, reaching its lowest in summer (Fig. 7c).

Plant characteristics varied considerably (Fig. 8a–c). Significant effects were related to time. *Sporobolus virginicus* density changed yearly, but not seasonally. The density declined irrespective of whether a site was near a runnel or pool. The height of *Sp. virginicus* was related to Year, Season and their interaction. Overall height decreased with time. Maximum heights were reached in spring, declined during summer and grew during autumn and winter. The decline in height during summer may be related to the increased frequency of tidal flooding.

For *Sa. quinqueflora* the only significant effect was of Year on density. Size was not significant in any analysis. As for *Sp. virginicus*, *Sa. quinqueflora* density declined over time.

Remote sensing: The image analysis showed that marsh reflectance in the green to near infrared wavelengths was greater before modification than after. However, the largest differences in reflectance were in the vicinity of the runnels. As well, reflectance was lower after runnelling than before in the treated area compared with more distant areas (Dale et al. 1991). In this area lower reflectance indicates a less dense *Sp. virginicus* cover and generally a lower position in the catchment (Dale et al. 1986a). This would be an expected effect of increased flushing.

DISCUSSION

Larval numbers: Runnelling has undoubtedly reduced larval numbers. Figure 3 shows that runnelling may not be immediately effective. It may take several months for larval numbers to reach their lowest levels. This delay in effectiveness may be related to the way the method works. For the flushing mechanism, the effects ought to be immediate; hence, an initial decline in larvae. We have observed that *Ae. vigilax* larvae avoid rapidly moving water (15–45 m/min) but will move with the flow in slower moving water (3–7 m/min). Since rate of water movement will vary with tide level and stage of tide, it is likely that larvae will not always be translocated by this means. For the predation mechanism, it may take some months for predators to discover and adapt to the more accessible larval food source. At both Coomera Island

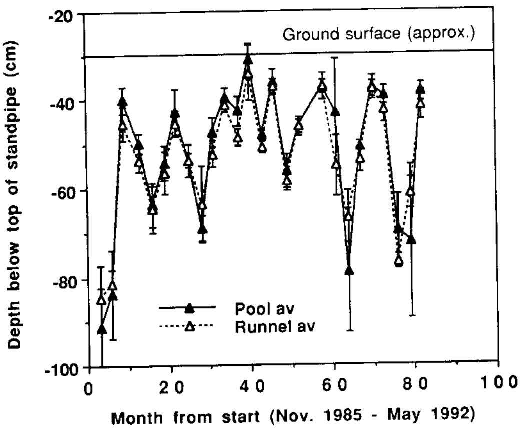

Fig. 5. Water table depth, below top of standpipe (±1SD).

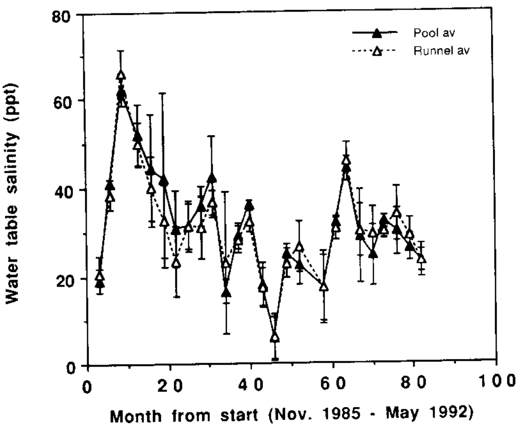

Fig. 6. Water table salinity (±1SD).

and Cobaki inlet, New South Wales, from January 1986 to November 1988, fish were found 14 times more often in runnelled compared with unmodified areas (Dale et al. 1989). However, there may be other local explanations, which are not globally applicable. For instance, it could be that other food sources became scarce in this area at this time, tempting the fish to consume a hitherto less desirable diet item (Morton et al. 1988). Finally, if oviposition sites are affected, the effect on larval numbers may not be apparent for some time, perhaps even a year later, particularly since *Ae. vigilax* has installment hatching and dessication resistant eggs.

Runnel morphology: The runnels required no maintenance over the 6.5 year period. Thus, the method is cost effective. In other areas in southeastern Queensland and northern New South Wales, maintenance costs range from \$0 to \$50/ha/year (Dale et al. 1989). There are design implications related to whether a runnel will erode or silt up. This appears to be closely related to runnel density, or the interconnecting of the local runnel system. The greater the interconnections (as at site 4) the more likely it is

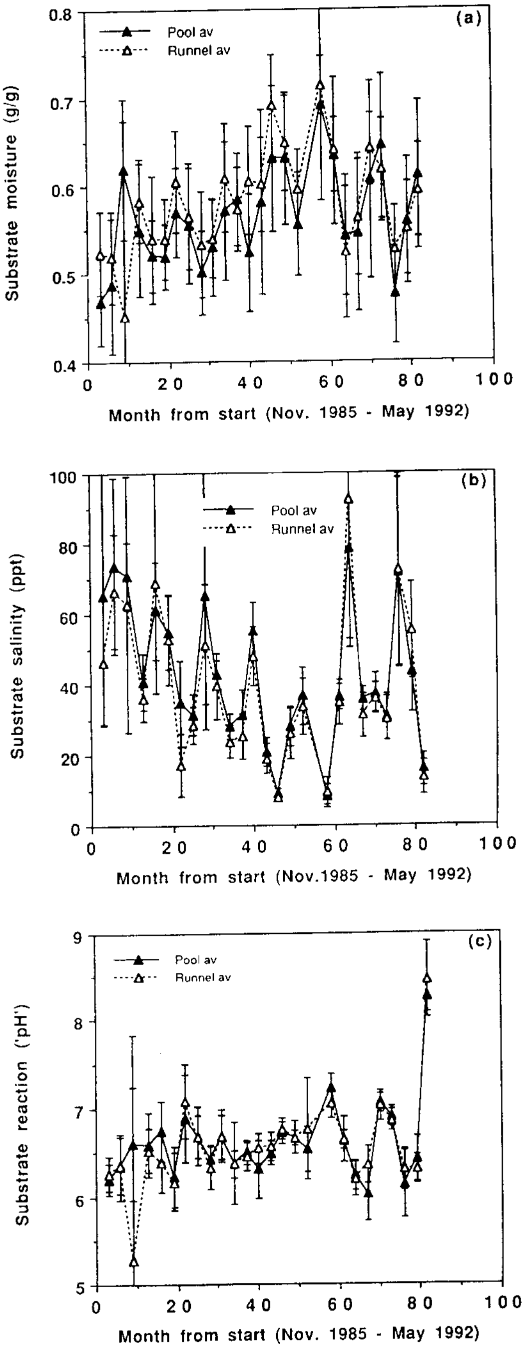

Fig. 7. Substrate characteristics: (a) moisture content; (b) salinity; and (c) reaction ("pH") (±1SD).

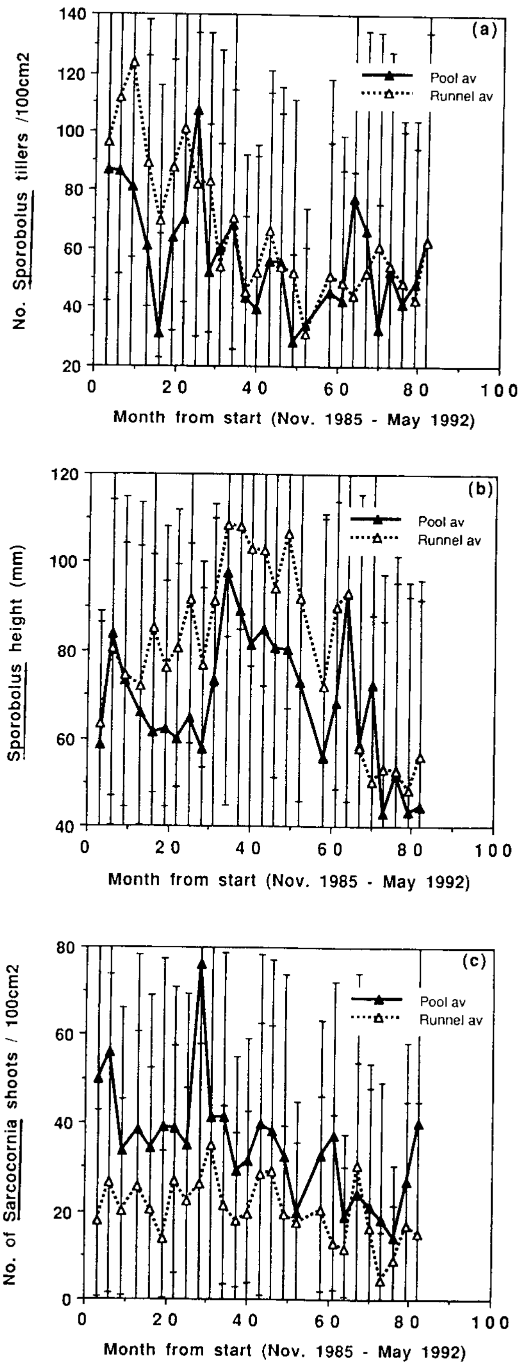

Fig. 8. Plant characteristics: (a) *Sp. virginicus* density; (b) *Sp. virginicus* tiller height; and (c) *Sa. quinqueflora* density (±1SD).

that accretion will dominate over erosion. There is as yet no precise formula for runnel network density. As well, other site specific factors, such as the erodibility of the substrate, need to be taken into account. However, the conservative approach is to keep density relatively high since deposition is more easily remedied than erosion.

Environmental variables: The marked variations in most of the environmental variables make it difficult to establish if changes were part of a general trend or were simply fluctuations. For the first 4–5 years it appeared that there were clear trends. For example, there was a rise in the water table and substrate moisture and a decrease in their salinity. However, it now seems that the system is fluctuating, sometimes wildly, but without an obvious direction. Large changes can occur over quite small time periods. For instance, we have data showing that substrate moisture salinity for 26 sites rose from 38 ± 7 ppt to 52 ± 13 ppt 3 days later in summer 1992; probably in response to evaporation from the substrate. Conversely, heavy, prolonged rainfall that occurs often during March–April could be expected to have the opposite effect. As substrate salinity changes so too will plant characteristics. This and waterlogging may account for the decrease in *Sp. virginicus* density. In some instances there are limits beyond which fluctuations cannot occur. An extreme example is if the water table was to reach the surface. Subsequent fluctuations above this level would then be related to flooding levels and would not strictly be changes to the water table at all. Another example is if all the plants were to disappear from a site (as has happened at a few sites in areas of decreasing density of *Sp. virginicus*).

The environmental variables were not independent of one another. Thus, a marked change in one affected others. It is likely that the water table was the single most important variable affecting substrate moisture, its salinity and plant species composition and growth. Thus, increased tidal flushing would make the area hydrologically similar to areas lower in the catchment and closer to the flooding source. Eventually, other characteristics such as vegetation and mosquito larval and egg distribution would come to resemble those of a lower catchment position. In such locations and in the runnelled area, we have found few eggs (Dale et al. 1986b, K. Hulsman, unpublished data; S. A. Ritchie, unpublished data). This supports the contention that the suitability of oviposition sites is affected by runnelling. A lower catchment position also accounts for the general rise in the water table. Increased flushing may account for the decrease in the salinity of the water table and of substrate moisture. Substrate salinity was lower near runnels than pool sites (albeit not significantly so) and this may reflect a greater flushing near runnels. Flushing would be less near pools because they are collection points rather than channels.

The field study and remote sensing approach uncovered slightly different aspects of the changes occurring. The major consistent change recorded by both suggested a change toward characteristics typical of a lower catchment position. Whether the effects were because of runnelling or some other perturbation is uncertain. However, the difference images from the image analysis do suggest that the largest differences were related to the runnelled area, even though there has been a general lowering of reflectance and hence increasing wetness of the whole marsh.

Whether the Coomera runnelling program is environmentally benign depends on the magnitude and extent of its effect on the natural system and on how much disturbance can be tolerated by the interconnected systems. Our results show relatively small differences between sites close to runnels or pools. Other extrinsic factors such as water level variations could account for the changes observed, but are independent of the mosquito control program. These include semi-natural processes related to tidal change as well as direct human interference from development. It is heartening that, despite external disturbances, the program remains effective in maintaining larval numbers below the nuisance threshold in the treated area.

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