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# Comparisons between topographically surveyed debris lines and modelled inundation levels from severe tropical cyclones *Vance* and *Chris*, and their geomorphic impact on the sand coast

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**Comparisons of topographically surveyed debris lines and modelled inundation levels from two very intense cyclones in Western Australia (WA) show close agreement. The largest differences between model predictions and surveyed debris occurred where wave run-up did not overtop the frontal sand dunes and was registered in the coastal landscape. Excellent agreement was found where dune overtopping occurred, as the debris largely represented the height of the storm tide.**

**The post-event field surveys also showed a clear relationship between the height of the inundation (about 7m in one instance), the height of the coastal sand dunes, and the extent of erosion of those dunes. Dunes were eroded vertically, and completely removed, where they were overtopped by the marine inundation (including wave run-up). Horizontal erosion or scarping and landward retreat of the dune occurred where the inundation was well below the dune crest. These observations are significant for policies on set-back distances and minimum habitable floor levels of coastal developments. The results show that these standards need to be above the level of the marine inundation, not the storm tide or storm 'still water' level, otherwise buildings erected on filled land behind frontal dunes could be undermined through wave attack and experience structural failure.**

**The field observations and model comparisons of the components of these marine inundations in Western Australia provide confidence in estimates previously used to ascertain the intensity of prehistoric tropical cyclones. The proportion of wave run-up on much less permeable and smoother surfaces (sand versus gravel and coral shingle) was considerably less than that used for estimates of prehistoric cyclone intensities, suggesting that wave run-up may play a less important role in constructing long-term sedimentary records of tropical cyclones.**

## Introduction

Surveys of the physical aspects of landfalling tropical cyclones are important for at least three reasons:

(a) to test the veracity of numerical surge models by comparison with topographically surveyed debris lines that mark the level of marine inundation, along with records from tide gauges;
(b) to determine the relative contributions of surge, tide, wave action and wave run-up to the total marine inundation; and
(c) to elucidate the nature and impact of marine inundations on sandy coasts.

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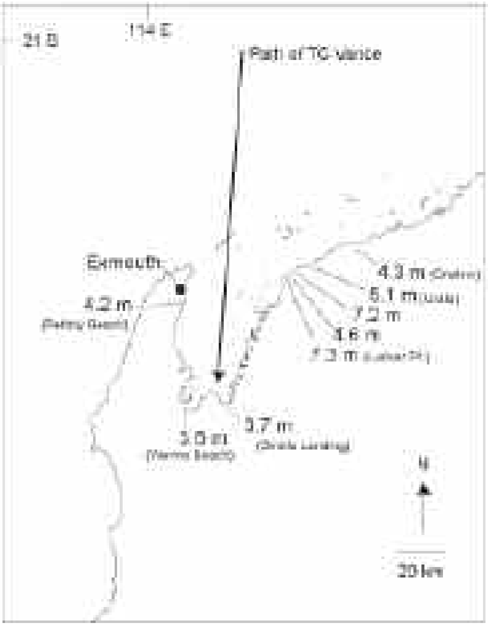
Post-cyclone surveys are common in the United States, where much emphasis is placed on examining the impacts of tropical cyclones (hurricanes) on coasts. This is because the US Flood Disaster Protection Act of 1973 requires the Federal Emergency Management Authority (FEMA) to map areas of coastal land susceptible to wave attack during hurricanes. This is not the case in Australia. With the exception of Hopley (1974) few, if any, detailed studies of the nature and impact on the coast of cyclone-induced marine inundations have occurred in this country. As a consequence, little is known of the nature and extent of erosion along Australian sandy coasts during intense tropical cyclones, and the relative contributions of the various components of the total marine inundation. This paper aims to partly redress this situation by presenting the results of topographic surveys of the heights, and descriptions of the impacts, of marine inundations on the sandy coast of Western Australia during landfall of tropical cyclones (TC) *Vance* in March 1999 and *Chris* in February 2002. The relationships between the field evidence of marine inundation heights, numerical storm-surge simulations, the extent and nature of erosion, and the implications of these results for assessing risks associated with coastal development in tropical cyclone prone areas are discussed.

**Fig. 1** **Location map of TC *Vance* coastal crossing and surveyed debris heights (above event tide) near and within Exmouth Gulf.**



## Characteristics of TCs *Vance* and *Chris*

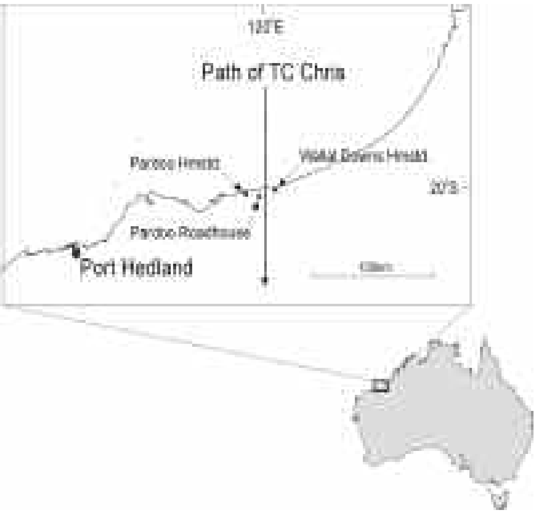
TC *Vance* had an estimated central pressure of 910 hPa as it approached and entered Exmouth Gulf on 22 March 1999 (Fig. 1), crossing the coast with a translational velocity of approximately 25 km/h and radius of maximum winds of 30 km. It was the most intense cyclone, historically, to cross the Australian coast, generating winds in excess of 300 km/h around its eye and producing the strongest ever recorded wind gust in Australia of 267 km/h (Bureau of Meteorology 2000). A storm surge 3.6 m above the Australian Height Datum (AHD) was recorded at Exmouth and a surge of 3.3 m was recorded at Onslow during the cyclone (Bureau of Meteorology 2000). The waves during this event were not measured, but they must have been of considerable size inside Exmouth marina as they hurled large boats over 2 m high jetties to impale and sink other moored boats. Five metre high rock walls surround the marina on its ocean side. At Onslow a large fishing boat was lifted onto the levy surrounding the Onslow salt ponds.

Tropical cyclone *Chris*, with central pressure 915 hPa, crossed the coast of Western Australia 160 km northeast of Port Hedland between Pardoo and Wallal station homesteads on 6 February 2002 (Fig. 2). TC *Chris* had a radius of maximum winds of 30 km and translational velocity of 20 km/h as it crossed the coast. The zone of maximum winds came within approximately 10 km of the Pardoo Roadhouse which incurred significant damage. All persons sheltering within the roadhouse were physically unharmed.

## TC *Vance* – comparisons between survey and model data

A field survey of the impact of TC *Vance* on the coastal landscape was undertaken within a few days of the cyclone making landfall. Topographic surveys of debris lines were undertaken using an electronic theodolite and electronic distance measurer and the heights of total marine inundation relative to the tide at the time of landfall of TC *Vance* were determined. The height of the marine inundation was determined from the position of debris lines which were composed of grasses eroded from the back of the beach and foredunes, seaweed, shells and coral clasts, and marine fauna such as juvenile sea turtles and fish. These debris lines normally occur at a consistent height along a stretch of coast following a storm-

**Fig. 2 Location map of TC *Chris* coastal crossing.**



induced marine inundation. They usually, but not always, represent the total extent of the marine inundation including wave run-up. Where the marine inundation breaches or overtops dunes, however, the surging seawater can often flow within the confines of a dune swale. Here, debris lines provide a more accurate reflection of the height of the storm tide or storm 'still water' level because the dune swales are more protected from the wave energy.

Surveys were undertaken at seven locations including Onslow, Locker Point near Tubridgi Point on the eastern side of the entrance to Exmouth Gulf, Giralia Landing and Wanns Beach at the head of Exmouth Gulf, Pebbly Beach near Exmouth and within Exmouth Marina. The total inundation heights during TC *Vance*, relative to the event tide, are presented in Table 1 and Fig. 1.

The surveyed data and records of the surge from tide gauges at Onslow and Exmouth show close agreement. The surveyed inundation level at Onslow was 4.3 m above the event tide (8.30 am 22 March 1999) and the surge level was measured at 4 m (3.3 m AHD) on the tide gauge. The surveyed inundation level at Pebbly Beach, close to Exmouth Marina, was 4.2 m above the event tide and the tide gauge registered a 3.6 m surge at Exmouth. The differences of 0.3 m at Onslow and 0.6 m at Exmouth between surveyed and tide gauge data are very likely to be due to wave action and wave run-up, respectively. The surveyed level at Onslow probably did not incorporate wave run-up as the area is fronted by a low gradient foreshore and the survey level was taken against a toilet block in the Onslow caravan park where water stains, fresh chip marks on the bricks and interview

**Table 1. Modelled and surveyed debris line heights between Onslow and Exmouth for TC *Vance*.**

| *Location* | *Estimated time of inundation* | *Surveyed inundation height (m AET)* | *Surveyed inundation height (m AHD)* | *Tide gauge residual (m AHD)* | *Surge model plus set-up (m AHD)* | *Comments* |
|---|---|---|---|---|---|---|
| Onslow | 8.30 am | 4.3 | 3.6 | 3.3 | 3.3 | Likely storm 'still water' level |
| Urala | 9.00 am | 5.1 | 4.4 | N/A | N/A | Debris line |
| 2 km east Locker Pt | 9.00 am | 7.3 | 6.6 | N/A | N/A | Debris line – dunes knocked out |
| 500 m east of Locker Pt | 9.00 am | 4.6 | 3.9 | N/A | N/A | Debris line 3rd row dunes – 1st and 2nd rows removed |
| Locker Pt | 9.00 am | 7.3 | 6.6 | N/A | 6.6 | 3 dune rows removed |
| Giralia Landing | Midday | 3.7 | 4.3 | N/A | N/A | Debris line |
| Wanns Beach | Midday | 3.6 | 4.2 | N/A | N/A | Debris line |
| Pebbly Beach | 10 am | 4.2 | 3.9 | 3.6 | 3.6 | Debris line |

AET = above event tide, AHD = Australian height datum with an eyewitness confirmed the level of inundation here with an accuracy of better than 10 cm. The difference between survey and tide gauge data at Pebbly Beach was likely due to wave run-up as the surveyed debris line was at the rear of a moderately sloping (about 5°) beach where the inundation did not overtop the foredune.

The storm surge and offshore significant wave height during both TCs *Vance* and *Chris* were modelled using the GEMS Coastal Ocean Model (GCOM2D) (Hubbert et al. 1990; Hubbert and McInnes 1999). In the case of TC *Vance* they were undertaken for comparison with the survey data at both Onslow and near Tubridgi Point. The GCOM2D model solves a set of mathematical equations over an equally spaced grid to determine water depths and currents over varying bathymetry and inundated topography and incorporates wind stresses and atmospheric pressure gradients acting on the ocean surface, and friction on the ocean floor. The GCOM2D modelled surge at Onslow was 4 m (3.3 m AHD), which corresponds exactly with the tide gauge measured surge and differs by only 0.3 m from the survey data. The modelled surge for Tubridgi Point was 7.3 m (6.6 m AHD), which also corresponds precisely with the survey data. The zone of maximum winds during TC *Vance* struck the coast near Tubridgi Point. Here, debris trapped in a small tree on the crest of the foredune was 7.3 m above the event tide. Wave run-up does not appear to have played a role in the elevation of the debris at this site because the debris was above the dune crest; if wave run-up had played a role, then the debris would be most likely on the dune itself. The position of debris, lodged in the tree, suggests it was emplaced by either the storm tide and / or wave action on top of the storm tide. Hence, the storm tide appears to have been able to overtop the 6-7 m high dunes.

It is unusual for the results of the topographic survey heights of the debris and the height of the modelled inundation to be so close (both 7.3 m above event tide). The survey data was undertaken by J. Nott and the modelling was undertaken by G. Hubbert and each set of results was unknown to the other party until much later so there was no possibility of bias.

## TC *Vance* – geomorphic impacts of the storm tide

Tropical cyclone *Vance* had a dramatic impact on the sandy coast near Tubridgi Point. In most locations along this section of coast, the first two rows of dunes were completely eroded and the sand transported away, presumably offshore, and the third or most inland dune row was eroded to form a steep scarp.

**Fig. 3** **Cross-section of remnants of three parallel rows of dunes near Tubridgi Point where the zone of maximum winds struck the coast during TC *Vance*.**

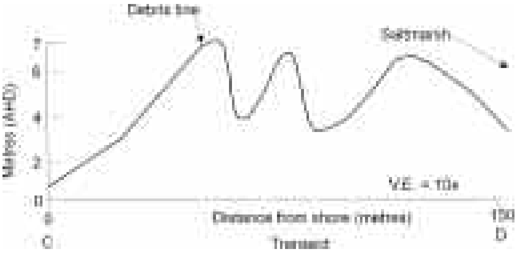


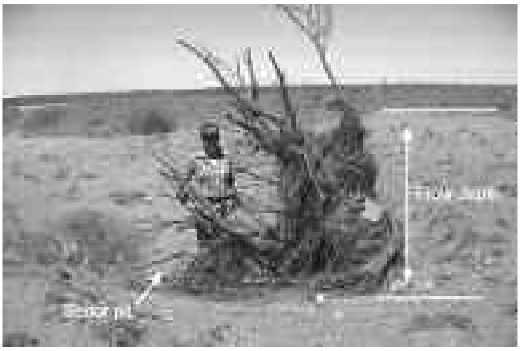
**Fig. 4** **Oblique aerial photo of area shown in Fig. 3 near Tubridgi Point. Note the virtual complete removal of all three rows of dunes and the extent inland of sand splay and the complete removal of dune and hind dune vegetation.**

**Fig. 5** **Remnant of dune near Tubridgi Point with debris in tree on crest of dune. Note depth of marine inundation. Dune is located at the rear of the beach, so the actual depth of marine inundation here is several metres greater than the height of debris above immediate ground level.**

Precisely where the zone of maximum winds struck, however, all three rows of 6 - 7 m high dunes (Fig. 3) were removed and the sand transported inland as an extensive splay approximately 400 - 500 m wide and 200 - 250 m deep (extending inland from the position of the former first dune row) (Figs 4 and 5). This sand splay decreased in thickness from 1.5 m at the rear of the position of the former third row of dunes, to 0.75 m thick at its most inland extent. The splay terminates abruptly at a salt marsh where it is marked by a steep-fronted (about 30° angle) toe slope. Sediments within the splay were deposited as steep (about 30°) tabular cross-beds (Fig. 6). Medium to coarse-grained sand occurs at the base of the unit, along with clasts of coral and shells, and grades upwards into medium to fine-grained sand. Lithic gravel measuring up to 25 cm across, were deposited in an imbricated position within the sand sheet inland of the position of the former dunes. (Imbrication is the depositional alignment of gravel or clasts where the particles lie against each other in a shingle-like pattern.) These gravel dip towards the ocean, showing they were deposited by an onshore flow. The marine inundation also generated scour pits within the sand splay. These pits measure up to 3 m wide and 1 m deep and occur on the lee (inland) side of tree stumps. The onshore flow was also able to carve channels 1 m deep and several metres wide over distances of several tens of metres (Fig. 7). These channels were carved by the onshore flow of water rather than by water draining from the land as demonstrated by the imbricated gravels in the sand floor of these channels. All of the vegetation including clumps of spinifex grasses, which dominated the low-lying salt marsh plain behind the former dunes, small trees (up to 3 m high), and bushes, were stripped from the land surface up to 300 m inland by this flow. Only occasionally did the dead stumps of trees remain, such as on the crest of an eroded knoll of the former foredune, or inland of the former dunes. Debris in these dead stumps show that flow depths were still at least 2 m, 150-200 m inland, and flow velocities were also high as gravel clasts were embedded within the debris at an elevation of 1.5 m above the present ground surface (Fig. 7).

**Fig. 6** Tabular cross-beds in toe of sand splay/sheet 300 m inland. Cross-beds such as these indicate water laid deposits by a unidirectional flow of reasonably high velocity.

**Fig. 7** Scour pit on lee (inland) side of a tree remnant. Pit measures approximately 3 m long by 2 m wide and 1 m deep. Note also the lithic clast and debris in tree indicating depth velocity of flow here (180 m inland).



The extent of the sand splay, the tabular cross-beds, scour pits, and imbricated gravel suggest that the marine inundation generated by TC *Vance* near Tubridgi Point, struck the coast with considerable force and moved inland as a reasonably high-velocity bore. The presence of similar scour pits and erosional features in beach and dune sands have been determined empirically to occur when flow velocities exceed 4 – 5 m/s during the passage of tsunamis across sand barriers. Also, the fact that the flow was transporting lithic gravel clasts as suspended, or at least saltating (bouncing), load 1.5 m high over 200 m inland shows that the flow velocity must have been high. Hence, the flow depth was between 6 - 7 m high (above the event tide) across the beach here and at least 2 m high 200 m inland. Such flows and the impacts upon the coast are more reminiscent of tsunamis than those normally ascribed to storm surges.

## TC *Chris* field survey

An initial field reconnaissance of the area impacted by TC *Chris* was undertaken by helicopter with staff of the Bureau of Meteorology and the Fire and Emergency Services Authority (FESA) Western Australia. Detailed

**Table 2. Modelled and surveyed heights of marine inundation during TC *Chris*.**

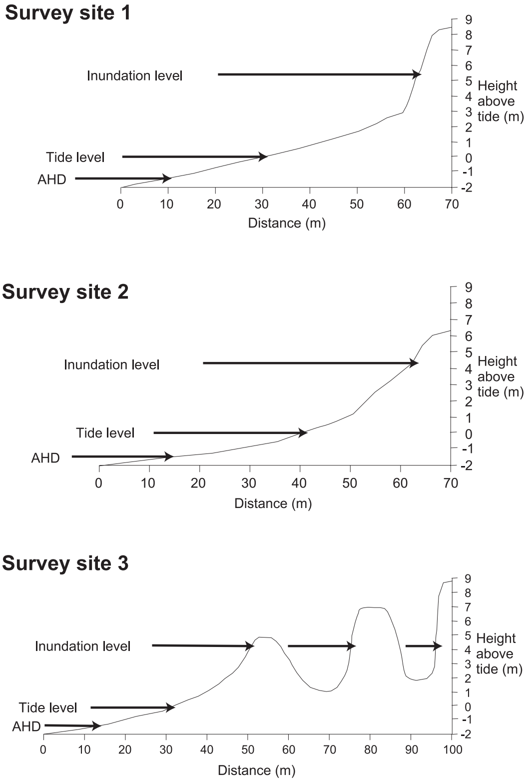
| Location | Approx. distance from crossing (km) | Lat. (degrees south) | Long. (degrees east) | Modelled surge and wave set-up (m AET) | Surveyed height of debris (m AET) | Diff. in height (m) |
|---|---|---|---|---|---|---|
| Survey site 1 | 10 | 19.92 | 120.178 | 3.88 | 5.4 | 1.52 |
| Survey site 2 | 20 | 19.9 | 120.236 | 3.18 | 4.1 | 0.92 |
| Survey site 3 | 27.5 | 19.89 | 120.273 | 3.38 | 4.2 | 0.82 |
| Predicted site of max. surge | 30 | 19.87 | 120.30 | 3.98 | N/A | N/A |

AET = above event tide

topographic surveys were then undertaken where the storm surge impact appeared to have been greatest. The results of these surveys are presented in Table 2 and Fig. 8. As with TC *Vance*, topographic surveys were undertaken using an electronic theodolite and electronic distance measurer. At only one location, site 3 was debris surveyed in a hind dune swale. This debris was emplaced following inundation of the foredune. It is this type of evidence that provides probably the most accurate representation of the height of the storm tide. Debris lines seaward of foredunes often reflect the extent of wave run-up. The surveyed height of the debris line at site 3 therefore, represents the most reliable indicator of the level of the storm tide or still water level during the event

The height of the debris lines varied between survey sites. In Fig. 8, these heights are presented relative to the tide level at the time of landfall of TC *Chris*. The debris at survey site 1 was 5.4 m above the level of the tide at the time of cyclone crossing, 4.1 m at site 2 and 4.2 m at site 3. It is likely that wave run-up has contributed to these heights at sites 1 and 2. The extent of the wave run-up contribution can be estimated by making comparisons between the height of the surveyed debris lines and the predicted surge heights from numerical models.

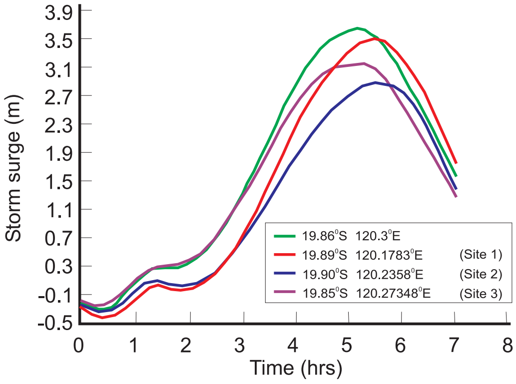
**Fig. 8 Cross-sections of beach and dunes impacted and surveyed debris heights generated by TC *Chris*.**



## TC *Chris* - comparisons between survey and model data

The highest storm surge predicted by the GCOM2D surge model for TC *Chris* was 3.7 m (Fig. 9). This figure refers only to storm surge and does not take into account the effect of the tide which is a non-linear addition to the surge. Wave set-up also adds to the height of the water column and is often found to be equivalent to approximately ten per cent of offshore significant wave height (average of highest one-third of waves). The SWAN shallow water wave model (Booij et al. 1996) estimated the highest offshore significant wave height at 2.8 m. Hence, the highest numerically modelled storm surge plus wave set-up level was less than 4 m.

**Fig. 9** **Model surge heights generated by TC *Chris* for different locations along the affected coast.**



The modelled and surveyed heights of marine inundation agree well. The highest predicted (modelled) surge was 30 km east of the location of landfall by the cyclone eye. This was approximately 2 km east of survey site 3. No survey was undertaken here because of difficulties in gaining access. The location of the predicted maximum surge was approximately where the eastern or outer limit of the zone of maximum winds occurred as suggested by radar imagery; the radius of maximum winds was estimated at approximately 30 km (A. Burton, Bureau of Meteorology, personal communication). The next highest predicted surge was only 10 km east of the location of cyclone landfall and this site (site 1 in Table 2) corresponded to the highest surveyed debris height with sites 2 and 3 both showing lower predicted and surveyed surge heights. Interestingly, both surveyed debris lines and the modelled surge heights showed that the surge and marine inundation did not increase progressively from the point of cyclone crossing to the location of highest surge.

The surveyed debris lines lie at slightly higher elevations than the level of the predicted or numerically modelled estimates of surge height plus wave set-up. Table 2 shows that these differences vary from 1.52 m to 0.82 m. The lowest difference occurred at survey site 3 which is regarded, based upon the field setting, as the most reliable indicator of the actual storm surge plus wave set-up height. The most likely reasons for the differences between the modelled and surveyed heights are errors in the coastal bathymetry and the interpretation of the surveyed debris lines. Unlike the modelling of TC *Vance*, where very accurate coastal bathymetry was available, the bathymetry used in modelling TC *Chris* was quite coarse and may not have represented the coastal bathymetry very accurately. It is almost certainly the case that a substantial part of the difference in heights at sites 1 and 2 is because the debris lines here are also a function of wave run-up. Wave run-up is likely to be less significant at site 3 for the reasons stated earlier, but it is possible that it has contributed somewhat to the elevation of the debris line here. Another possible source of error is the lack of a precise datum to which the debris lines were surveyed. The datum was taken as the level of the tide at the time of surveying and requires a minor calculation to relate it to the Australian Height Datum (AHD). Normally, if surveying close to a standard tide port, this method should be accurate to less than 20 cm. However, the survey sites lie between standard tide gauge ports (Port Hedland and Broome) and the time difference in tides between the survey sites and Port Hedland has not been determined by the National Tidal Centre, Bureau of Meteorology (formerly the National Tidal Facility, Flinders University). Hence, it is reasonable to expect a possible error margin of several tens of centimetres (and possibly as high as 50 cm) in the estimation of the datum height.

## TC *Chris* - geomorphic impacts of the storm tide

Based upon the extent of erosion of foredunes, the maximum surge appears to have occurred along a 500 – 700 m stretch of coast located adjacent to survey site 3. As discussed, this section of coast lies close to the modelled estimate of the location of likely maximum surge, and also the likely location of maximum winds from interpretation of the cyclone crossing point as shown by Bureau of Meteorology radar imagery. Dune erosion appears to have been greater here than elsewhere along the coast. At each of the other survey locations (sites 1 and 2) dune erosion occurred in the form of scarping i.e. there was erosion of the seaward face of the dunes resulting in a more vertical profile and landward recession of the dune face. At survey site 3 the frontal dunes were overtopped by the storm tide and wave run-up, and there has been vertical erosion i.e. reduction in the height of the dune, and in some instances complete removal of the frontal dune (Fig. 10). Here also, dune swales behind the frontal dune have channelled the storm tide and this has probably exacerbated the erosion of the second and third rows of dunes (Figs 11 and 12). The dune swales here appear to have been colonised previously by mangroves, as dead mangrove stumps occur in the swale between the first and second rows of dunes. It is

**Fig. 10** **Eroded foredunes at survey site 3. Marine inundation overtopped foredunes with resultant vertical erosion and removal.**

**Fig. 11** **Erosion of second row of dunes by waters surging through interdune swale.**

**Fig. 12** **Erosion of third row of dunes. Note dead cow wedged in opening scoured by storm surge/tide.**

unlikely that these mangroves were killed during TC *Chris* as the dead stumps appear to have been in their present form for at least several years.

Dead cows littered the beach along this entire section of coast. At all locations, except survey site 3, these cows lay seaward of the first row of dunes. At survey site 3 some of the cows were deposited amongst both the second and third rows of dunes. In one instance a cow was deposited in a narrow opening through the third row of dunes (Fig. 12). This opening appears to have been scoured, or at least enlarged, during the cyclone storm tide event, for an oblate shaped depression has been eroded into the sand floor at the mouth of the opening. Mud was eroded and transported from the swale between the first and second rows of dunes and deposited at the head of this opening well inland of the third row of dunes. The storm tide in this instance penetrated approximately 150 m inland beyond the position of the first row of dunes.

## Discussion

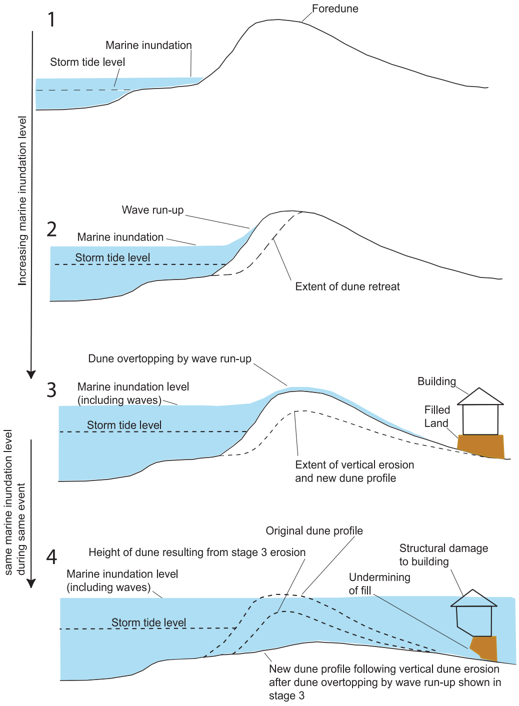
Tropical cyclones *Vance* and *Chris* displayed both differences and similarities in their respective impacts on the coast. The major difference between the two was the much greater extent of erosion caused by TC *Vance*, resulting in deposition of the sand splay and development of erosional features (scour pits). Presumably, this more extensive impact is related to the size of the surge (>6.5 m) generated by *Vance* which was almost double that generated by TC *Chris*. Local bathymetry and coastal configuration must have played a substantial role in producing such a dramatic difference in surge heights between the two cyclones for both systems were of similar intensity, spatial extent (radius of maximum winds) and had similar forward velocities.

The most striking similarity between the two inundations was the nature of erosion to the sandy coast. Both events showed a relationship between the extent and type of erosion, the height of inundation and height of coastal sand dunes. Extensive erosion occurred where the inundation was able to overtop the sand dunes. These dunes experienced vertical erosion resulting in virtually complete removal of the dunes. In the case of TC *Vance*, three rows of dunes near Tubridgi Point standing approximately 6-7 m high were overtopped by the 6.6 m AHD inundation and these dunes were removed. Elsewhere, along this coast, where the inundation did not overtop the dunes, those dunes were scarped and experienced horizontal erosion or retreat landwards. In these instances the dunes halted the inland penetration of the storm inundation. The same was true of TC *Chris*. The dunes along the impacted section of coast east of Port Hedland during TC *Chris*, were generally lower in height than those along the coast impacted by TC *Vance* and the marine inundation generated by TC *Chris* appears to have been lower than that produced by TC *Vance*. However, where the inundation from TC *Chris* was able to overtop the dunes, those dunes were largely removed and the inundation surged inland to erode the second and, to a lesser extent, the third row of dunes. Where the inundation from TC *Chris* was lower than the dunes, those dunes experienced horizontal or landward retreat.

The nature of erosion to the sandy coasts impacted by TCs *Vance* and *Chris* is very similar to the erosional impacts of hurricanes in the United States. Based upon observations and measurements of numerous hurricane impacts on US sandy coasts, FEMA has noted that where the dune reservoir (area of dune above the storm ‘still water’ level) is greater than 540 sq feet (about 50 cu m per metre length of beach) that dune is likely to experience horizontal erosion only (FEMA 2003). Where the dune reservoir is less than 540 sq feet that dune is likely to erode vertically and be largely removed. In the latter situation, FEMA note that the marine inundation will penetrate inland beyond the former dune position. The United States Geological Survey (USGS) has also made similar observations (USGS 2003). While dune reservoirs have not been calculated for the former dunes along the WA coast impacted by TCs *Vance* and *Chris*, the resulting styles of erosion and relationship to inundation height were essentially the same.

These observations of the impacts of TCs *Vance* and *Chris* have important implications for coastal planning in cyclone-prone regions of Australia, particularly in Queensland. Legislation and policies relating to coastal management and protection in Queensland (Queensland EPA 1999) recommend that the elevation of the storm tide is the most appropriate level in setting safe set-back distances and minimum habitable floor levels for coastal developments in cyclone-prone regions (Fig. 13). No acknowledgment of the impact of erosion of dunes and inland penetration of the marine inundation, including high velocity currents and waves is made in these policies. As shown by the inundations during TCs *Vance* and *Chris*, once the frontal dune is eroded, substantial erosion of hind dune areas occurs. In Queensland, low-lying hind dunes areas are often filled with sediment to raise the elevation of the land to the level of the one per cent Annual Exceedence Probability (AEP) storm tide to allow construction of dwellings at the recommended minimum habitable floor level. In an inundation that overtops the frontal dunes it is very likely that any infilled land could be eroded, following removal of that foredune, causing potential serious structural impacts to buildings. Many of the frontal dunes in northern Queensland are low (2-3 m AHD), so it would not take a substantial inundation for them to be overtopped. But Queensland has not experienced a severe marine inundation since 1918 when a category 5 cyclone made landfall at Innisfail. Hence, there is a lack of experience with, and observations of, severe cyclones and their impact upon sandy coasts in Queensland. This has led to a certain level of naivety in formulating policies for coastal development. This does not appear to be the case in Western Australia where set-back distances for new developments consider the total ocean inundation occurring during a category 5 cyclone (Western Australian Planning Commission 2003).

**Fig. 13 Schematic model of the relationship between storm tide and marine inundation height and erosion of foredunes. Note that once marine inundation overtops foredune the dune erodes vertically resulting in its complete removal. This allows waves and high velocity currents to penetrate inland to areas of land often filled for urban and tourist developments.**



Comparisons between the surveyed and modelled inundation heights due to TCs *Vance* and *Chris* also provide useful data on the extent of wave run-up during these types of events. Registered wave run-up values in the coastal landscape were greater for TC *Chris* (0.8-1.5 m) because the inundation was not able to overtop the dunes in many locations. Because the inundation from TC *Vance* easily overtopped dunes, the debris lines in the landscape tended to record the storm tide height rather than wave run-up. Near Pebbly Beach, on the eastern side of Exmouth Gulf, the difference between the tide gauge measured storm tide and the surveyed debris was 0.6 m. This value gives a measure of wave run-up during TC *Vance* where the surge was smaller than that occurring near Tubridgi Point. Wave run-up therefore varied between approximately 23 – 43 per cent of storm surge height for TC *Chris* and by approximately ten per cent during TC *Vance*.

Determining wave run-up values relative to surge levels, and offshore wave heights, provides a calibration for models estimating the intensity of prehistoric tropical cyclones. Nott and Hayne (2001) and Nott (2003) used wave run-up values between 40-70 per cent of surge to determine prehistoric tropical cyclone intensities in Queensland. These values were determined for much rougher and more permeable surfaces (gravel and coral shingle beaches) than sandy beaches, where the latter would be expected to produce much larger run-up values compared to the former. Wave run-up values on the sandy beaches impacted by TCs *Vance* and *Chris* therefore are considerably smaller than those adopted by Nott and Hayne (2001) and Nott (2003). Hence, in comparison, it would appear that these authors have used conservative values of wave run-up in their studies. This suggests that their estimates of prehistoric cyclone intensities in Queensland are also probably conservative. Further post-cyclone surveys are needed, however, before such conclusions can be fully substantiated.

## Conclusion

Close agreement was found between the GCOM2D storm surge model and the heights of surveyed debris marking the level of marine inundation during tropical cyclones *Vance* and *Chris* in Western Australia. The largest differences between model estimates and survey debris occurred at those locations where the inundation (wave run-up) did not overtop the frontal sand dunes. Excellent agreement between the modelled and surveyed debris heights was found where dune overtopping did occur, and the debris largely represented the height of the storm tide.

The impact of the marine inundations from both cyclones on the sandy coasts of Western Australia is very similar to that observed in the United States following hurricane impacts. Dunes were eroded vertically and completely removed where those dunes were overtopped by the inundation. Where the inundation was well below the crest of the dune, horizontal erosion or scarping and landward retreat of the dune occurred. These observations are significant for policies governing set-back distances and minimum habitable floor levels for coastal developments. They show that aligning the minimum habitable floor level and set-back distance to the storm tide or storm 'still water' level is inappropriate, as substantial erosion to both fore and hind dune areas can occur when the foredune is overtopped by a marine inundation. The results of this study suggest that a much safer minimum habitable floor level is one that coincides with the level of total marine inundation where wave run-up and wave action are considered, along with the likely extent of erosion during these extreme events.

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