EFFECTS OF TOPOGRAPHY ON WIND FLOW AND SAND TRANSPORT & DEVELOPMENT OPTIONS - OCEAN BEACH DOMAIN

A Report for the Dunedin City Council

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1. INTRODUCTION

The current study examines the potential for aeolian (wind-forced) sedimentation in the Ocean Beach Domain. This work is of importance for two reasons. Firstly, the landscape of the Domain, although somewhat modified by historic development, is fundamentally the result of aeolian sedimentation. The component landforms comprise a range of dune forms and environments (Hilton, 2010). The Domain was developed over a complex dune system that comprised a continuous foredune that ran parallel to Victoria Road, an extensive deflation surface (and lagoon) and a transgressive (moving) dune field to the east of the St Kilda Surf Life-Saving Club. Future development options must be consistent with the processes that shaped the coast and gave rise to these landforms, including aeolian processes.

Secondly, the report examines the vulnerability of the current Domain and a range of development options to further sedimentation. At present there is little sign of active sedimentation in the Domain, since the surface is generally armored with clay, soil and vegetation. Sedimentation does occur, however, during south or southwest conditions. During strong winds sand is transported onshore by winds that accelerate across the seaward edge of Kettle Park (the seaward or stoss face of the back beach/foredune) and is deposited on the playing fields. We examine the potential for sedimentation under future development options, including minor and major modifications to the seaward margins of the western margins of the Domain. In particular, we predict the aeolian sedimentation that might result from re-establishing elements of the pre-European landscape, namely a gently-sloping back-beach; by lowering and re-contouring the current margins of the Domain in the vicinity of Kettle Park. Such a landscape might provide opportunities to reduce the impact of storm surge and wave-forced erosion.

2. WIND DATA VALIDATON

The wind data used in this study were recorded at two weather stations; Lawyers Head (Dunedin City Council) and Taiaroa Head (NIWA). The wind data at Lawyers Head directly represents wind conditions in the South Dunedin area. However, the data are available only for the period 2005 to 2008. The historical wind data at Taiaroa Head are available from 1971 to 2006.

The onshore (73 to 253 degree) wind data at Lawyers Head were compared to the data at Taiaroa Head (Figure 1). The hourly wind speed and direction from 2005 to 2008, from Lawyers Head weather station were tested with the wind data recorded at the Taiaroa Head weather station over the same period. Instrumental errors in the data sets were removed, yielding the total data points employed in the correlation analysis of 18,102 points.

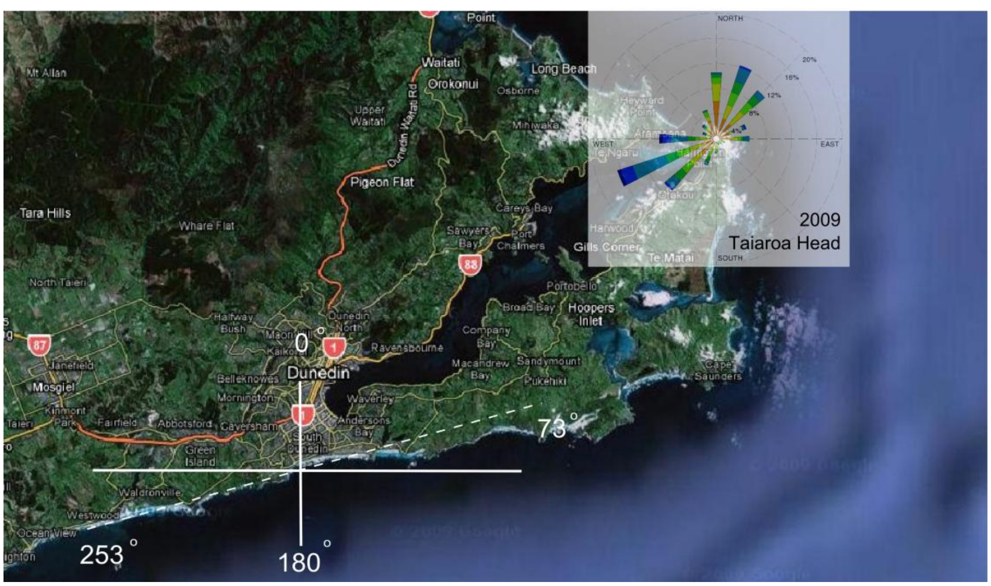

Figure 1: The analysis of wind speed and direction for ‘onshore’ winds between 073 and 253^{o}.

3. NUMERICAL SIMULATIONS

Computational Fluid Dynamics (CFD) is employed to investigate wind flow patterns, and sand transport at St. Clair and St. Kilda. In these areas, wind flow patterns are disturbed by the headland above and to the south of the Esplanade. These areas are sheltered from the prevailing southwest winds; however, the degree of shelter has not been investigated.

The pattern of landforms that existed prior to the introduction of marram grass and tree lupin and development of Ocean Beach Domain, described by Hilton (2010), strongly suggests that the western half of the Domain, west of Hancock Park, experiences significant shelter from the headland. The dune system west of and including Hancock Park comprised a large deflation surface, at or close to sea-level, and a transgressive dune field climbing up and over Lawyer's Head. If so, depending on the extent of this shelter, the risk of sedimentation following re-development may be minimal.

Two different spatial scales were used in this study. A large spatial scale domain was used to investigate the effects of the Peninsula headland on the wind patterns in the St. Clair and St. Kilda areas. The topologic details were derived from LIDAR data (obtained from the Otago Regional Council (ORC)). Smaller spatial scale domains were employed to investigate wind flow over the dune profiles (both pre-European and modified) over smaller areas.

A comparison of the pattern of sand transport between three-dimensional CFD simulations (Figure 2) and observations (Figure 3) was completed. A simplified three-dimensional foredune was employed in a simulation to investigate the pattern of sand transport under southwest winds. The approaching wind speed was modeled using the power law wind profile with a reference wind speed of 6 m/s at 5m above the surface. The direction of sand transport is in the same direction as the wind flow, towards the northeast, with a sand/air volume ratio of 10%. The sand cloud is seen to extend toward the northeast. The wind approaches the dune at the west end first where the velocity is then sped up. This velocity is higher than the velocity of the adjacent geometry to the east. The higher velocity results in higher dynamic pressure therefore the wind flow tends to be pushed toward the northeast, and so does the sand cloud.

The results of the CFD analysis are presented in Figure 3 for initial wind speeds of 6m/s and 15 m/s. Winds of 15m/s would be capable of transporting large quantities of sand along the beach and across the seaward edge of Kettle Park. The actual wind speeds would be very much higher at the crest of the stoss face of the foredune (where one is present) due to acceleration. The ridge and headland to the south of the Esplanade provides significant shelter to the Ocean Beach Domain between the Esplanade and the western edge of Hancock Park. The ice-skating rink is visible in Figure 3 (for reference).

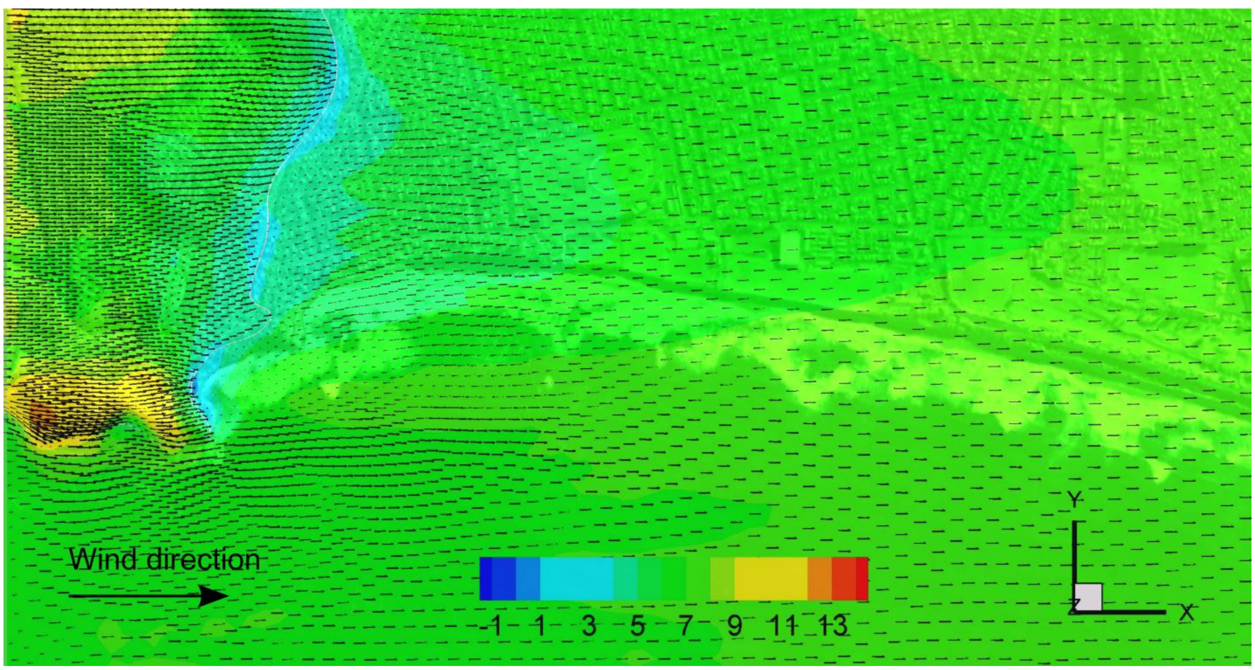

Figure 2(a): Velocity vector fields – 6m/s.

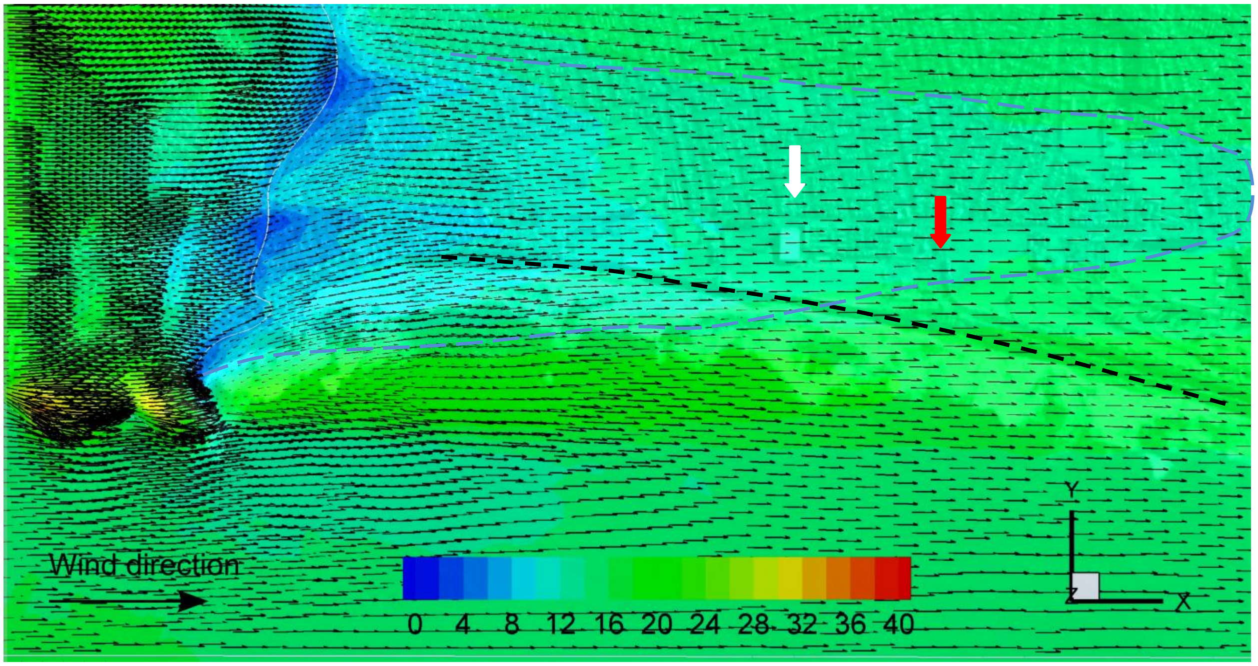

Figure 2(b): Velocity vector fields – 15 m/s. The areas shaded blue experience substantial shelter during southwest to westerly winds. The colour scale is in m/s. A white arrow marks the ice-skating facility. The red arrow marks John Wilson Drive. The line of high tides is shown as a dashed black line.

4. MODEL VERIFICATION

The model predicts that the section of the Ocean Beach Domain between the Esplanade and John Wilson Drive is sheltered from the prevailing southwest winds. We have undertaken limited field verification during a recent event (19 Jan) during which the winds at Musselburgh averaged 10m/s. We believe the open coast, unmodified winds, were in excess of 15 m/s. A hand-held anemometer was deployed at 25 locations between the Marae and Lawyer's Head over a 3-hour period. Multiple observations were made at each station over a period of 10 minutes and the results averaged. This is a simple experiment which cannot yield definitive results; nevertheless it provided some useful, indicative, data in support of the model.

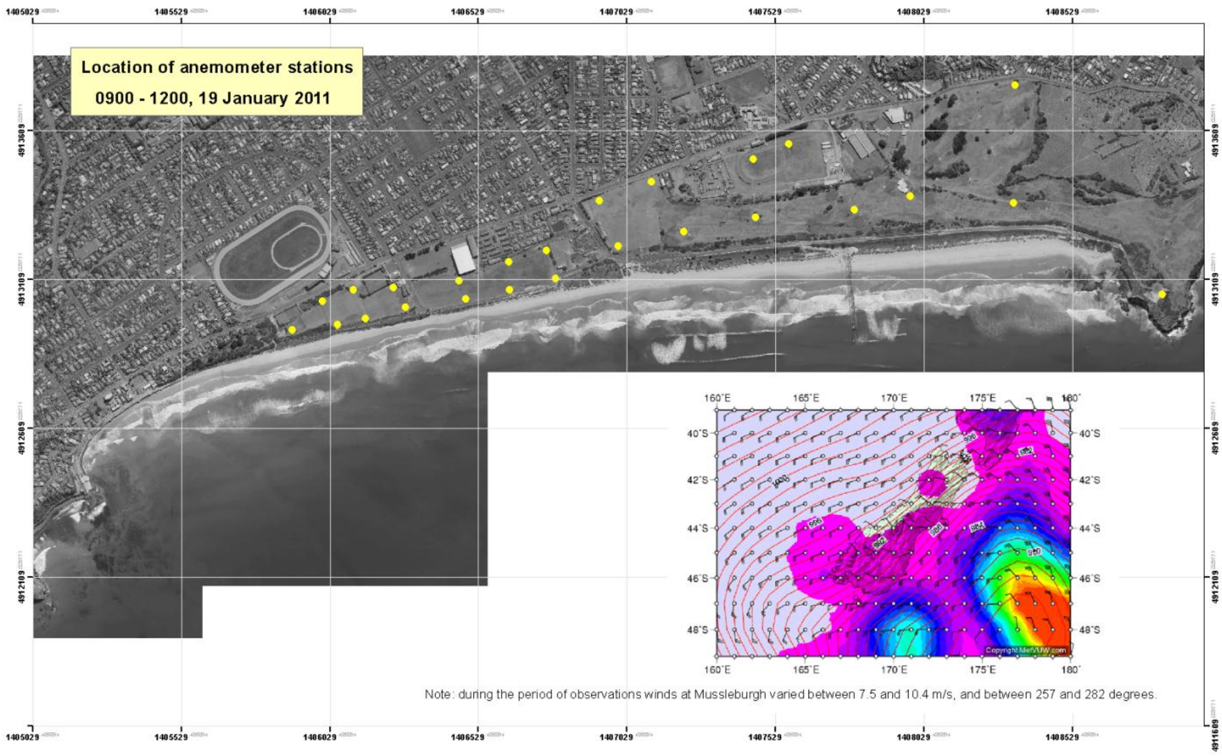

Figure 3: Location of anemometer stations – 19 January 2011.

Observations were sorted into three classes: (i) 0 to 5 m/s; (ii) 5.1 to 10 m/s; and (iii) 10.1 to 15 m/s, and mapped accordingly (Figure 4). The results are in broad agreement with the model. Wind speeds west of Moana Rua Road fell into class one and were generally close to zero; wind speeds east of Hancock Park exceeded 10 m/s; and winds between Moana Rua Rd and the Golf Course were of intermediate strength (Class 2). The anomalous reading near the ice stadium may have resulted from flow acceleration across the scarp.

This was a simple experiment that 'suggests' the efficacy of the modelling. Further verification will require a greater number of observations, observations referenced to ambient conditions, and observations made over a wider range of conditions.

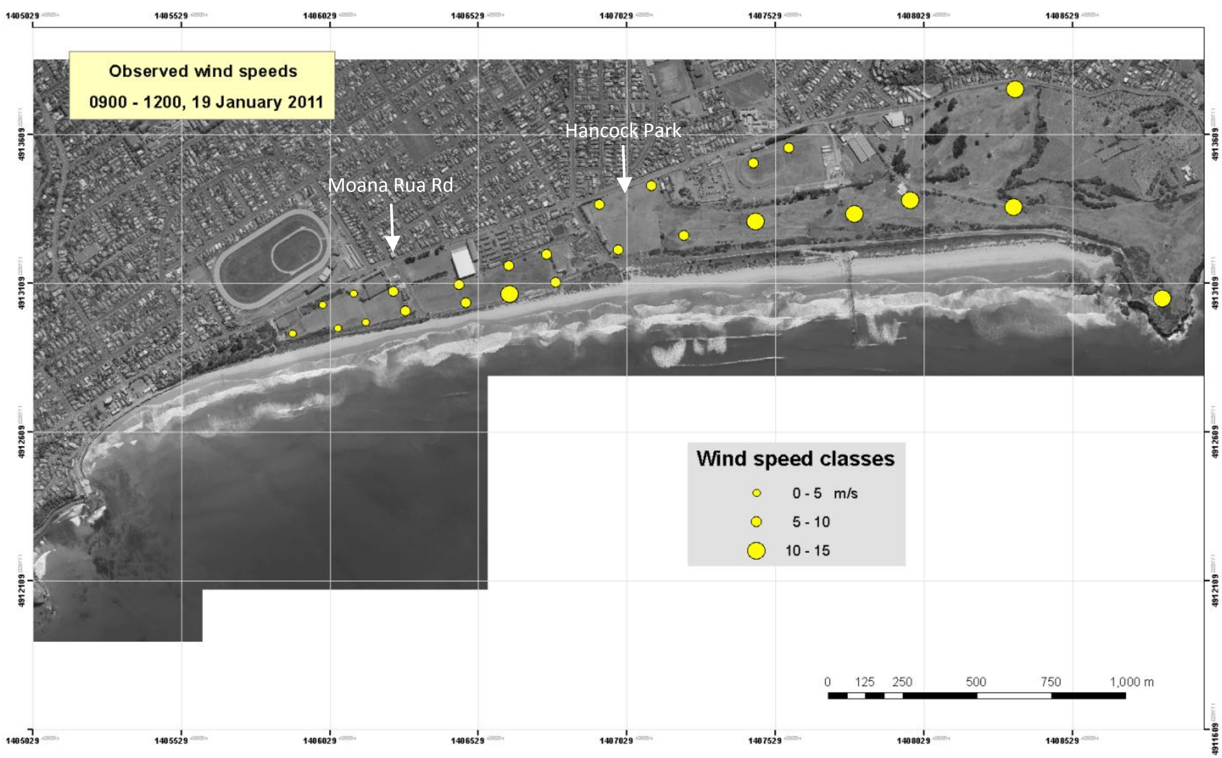

Figure 4: Wind speed classes, 19 January 2011, Ocean Beach Domain. During the experiment wind speeds were negligible west of Moana Rua Road; intermediate between Moana Rua Rd and Hancock Park; and strongest east of Hancock Park.

5. SEDIMENTATION

A simplified three-dimensional foredune was employed in a simulation to investigate the pattern of sand transport under southwest winds (Figure 5). Here the term ‘foredune’ is used to describe the steep slope between the playing fields and the back-beach. Some sand accumulates on this surface, or is dumped there, from time to time, however its character is essentially erosional.

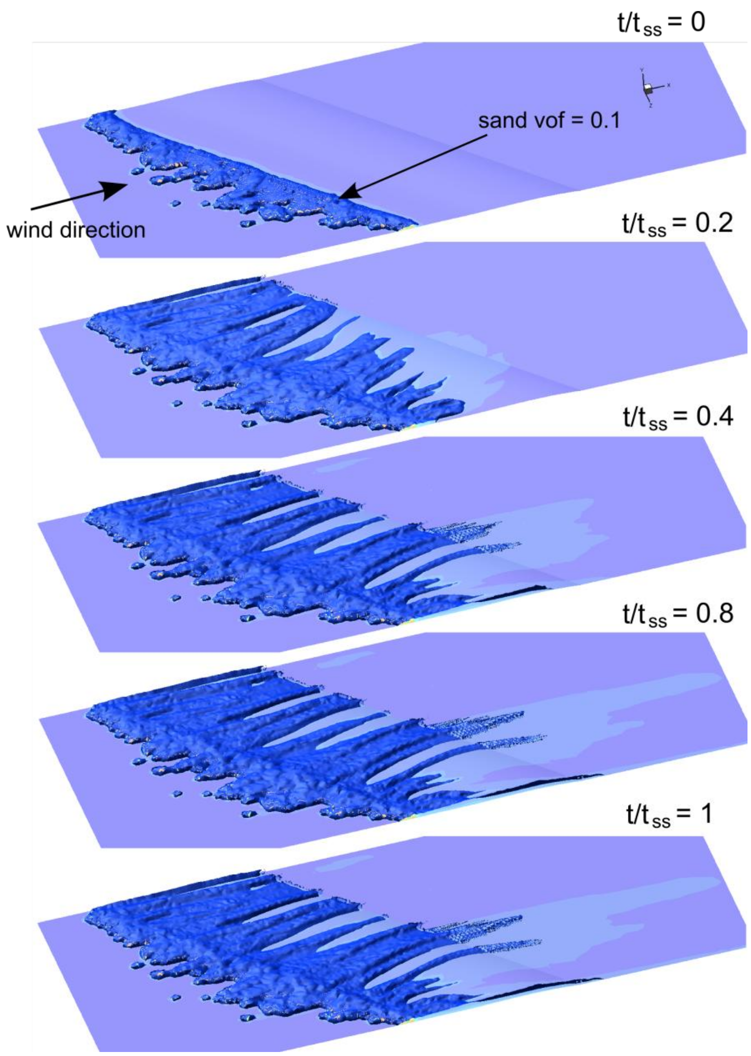

Figure 5: Sand plume represented by plotting an iso-surface of the low volume fraction sand over the simplified three-dimensional foredune topography over time intervals.

The approaching wind speed was modeled using the power law wind profile with a reference wind speed of 6 m/s at 5m above the surface. The direction of sand transport is in the same direction as the wind flow, towards the northeast, with a sand/air volume ratio of 10%. The sand cloud is seen to extend toward the northeast. Wind approaches the face of the foredune from the west. The flow accelerates so that wind speeds are higher than flows immediately to the east. The higher velocities result in higher dynamic pressure, so that the flow tends to be skewed towards the northeast. Hence, sedimentation is not normal to the shoreline, but towards the northeast.

These predictions accord with observations of sand that accumulates on Kettle Park during high westerly winds (Figure 6). Invariably the plumes of sand are skewed towards the northeast. We have observed that any significant accumulation of sand on the stoss face of the foredune is vulnerable to erosion during southwest winds, including sand dumped for beach nourishment.

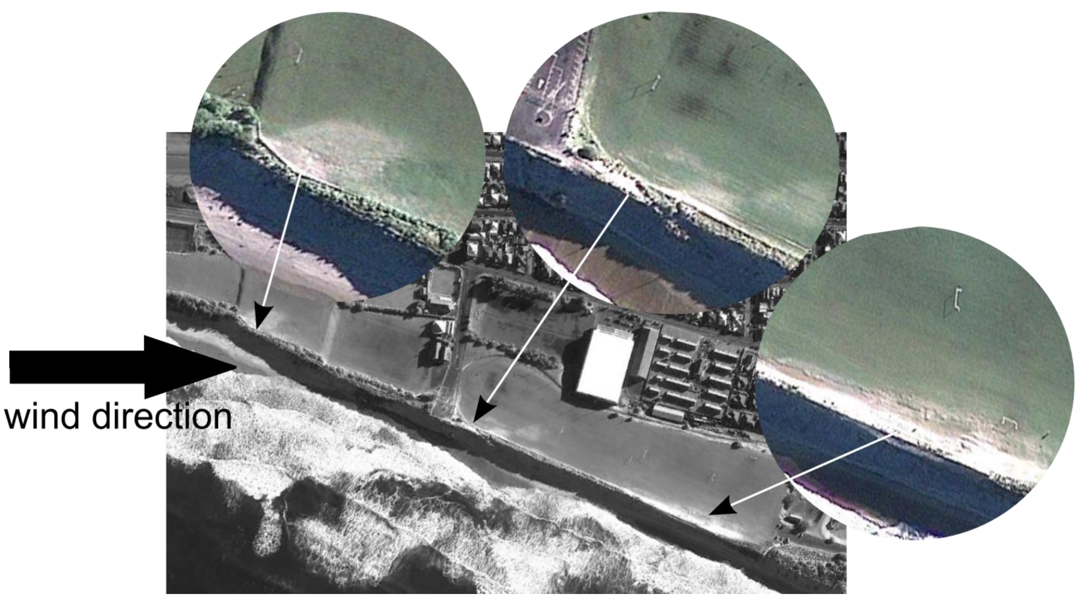

Figure 6: Google image, July 2009, showing sand plumes on Kettle Park.

Smaller spatial scale domains were also employed to investigate wind flow over the dune profiles (both original and modified). Figure 7 shows the positions of the surveyed profiles on the original 1890 map with the profile CD shown in Figure 8. Figure 9 compares the 'ice rink' profile of 2010, with the C-D profile of 1890.

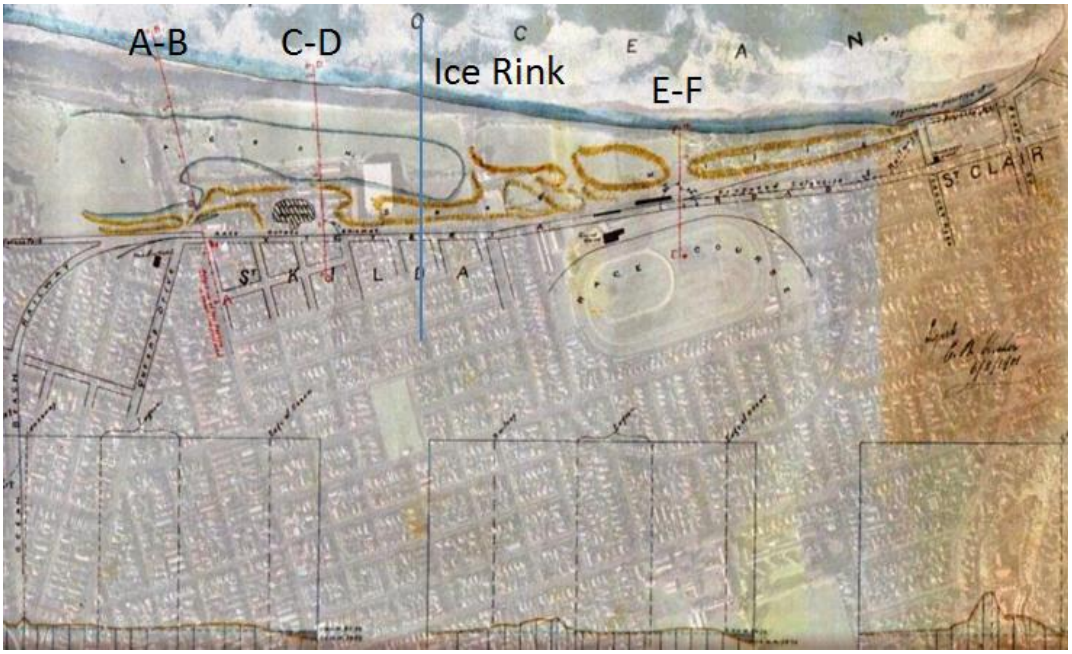

Figure 7: Location of 1890 surveyed profiles (AB, CD, EF) (discussed in Hilton, 2010).

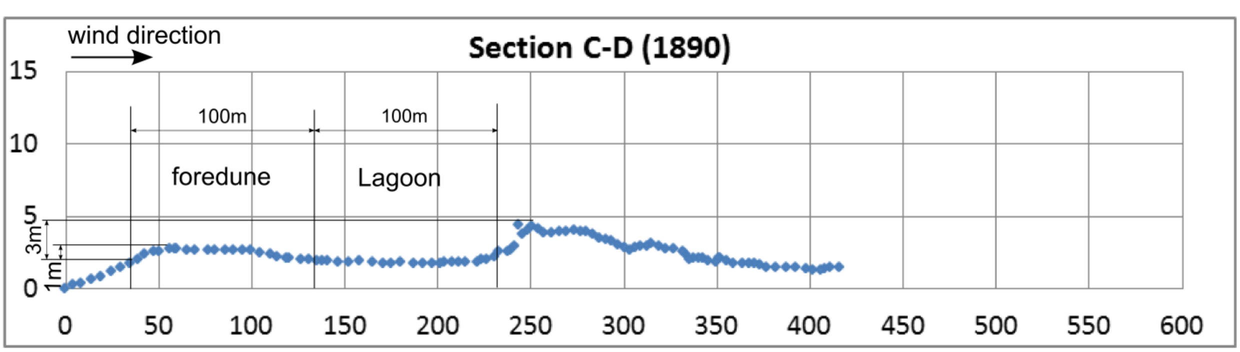

Figure 8: Profile C-D located in Figure 7. The "foredune" was probably an ephemeral feature comprised of over-wash (wave-deposited) and aeolian sediments.

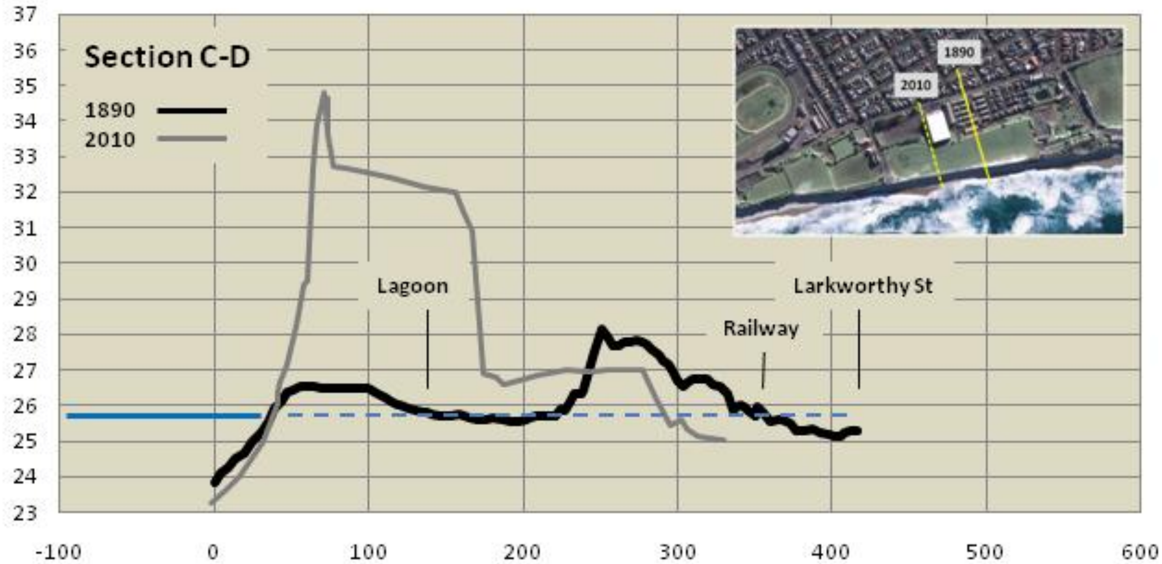

Figure 9: Comparison of the 1890 and 2010 profiles in the vicinity of the ice-skating rink.

The 1890 profile shows a low "foredune" next to the edge of ocean. The width of this shallow foredune is approximately 100m (Figure 8). We can't be certain this was ever a true foredune – formed in association with back-beach vegetation. It was, more likely, a deposit formed as a result of aeolian- or wave-forced sedimentation, in the absence of vegetation.

A foredune is unlikely to form in front of the current topography; that is, the seaward margins of Kettle Park. The wind speed-up along the front slope is too high for sand to accumulate. Any sand that accumulates on the surface of the scarp, during low wind conditions, is likely to be exported alongshore or onto the park during high wind conditions. The current conditions, therefore, favour aeolian (wind-forced) erosion of the beach sands.

6. AN EVALUATION OF ALTERNATIVE COASTAL TOPOGRAPHIES

The current topography of the coastal margins of the Ocean Beach Domain is entirely artificial – the result of works to raise the level of the land to prevent flooding. This was achieved by the construction of John Wilson Drive and the raised platform to the west (Kettle Park). Construction of Kettle Park appears to have involved reclamation of the former back-beach, so that this stretch of coast is vulnerable to erosion. In contrast a narrow foredune has formed along the base of the John Wilson Drive reclamation. What would be the effect of modifying the topography along the seaward margins of Kettle Park? Is it feasible to provide space for the formation of an incipient or permanent foredune, similar to the dune in front of John Wilson Drive. Is it feasible to provide for a much wider and lower back-beach to accommodate storm surge and so reduce the likelihood of severe erosion?

We examined the likely stability of three topographies using computational fluid dynamics, within the virtual space. The three scenarios represent significant modifications to the existing landscape (Figure 10). The M1 (red line) would result from a major redevelopment of Ocean Beach Domain, involving the excavation and deposition of large quantities of fill from a seaward to a landward location. A terrace would be formed to accommodate storm-surge run-up to reduce the likelihood of scarping. Scenarios M2 and M3 would entail relatively minor excavation of the existing margins of Kettle Park. M3 includes a marram-covered foredune.

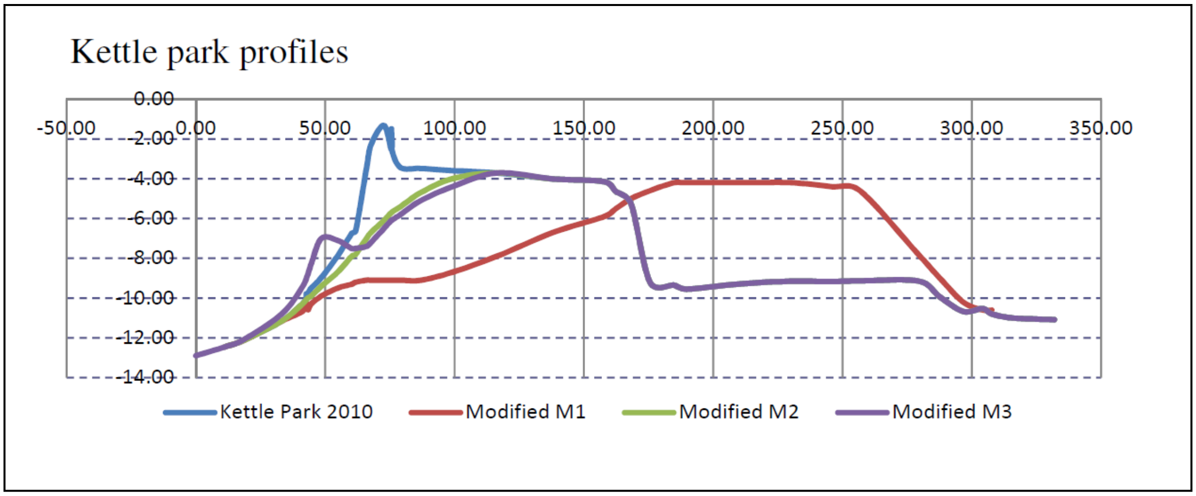

Figure 10: Re-development scenarios (M1, M2, M3) and the existing profile (Kettle Park).

Figure 11 shows velocity contours of wind velocity over the 1890 and contemporary St Kilda (John Wilson Drive) and Kettle Park (2009) profiles; with the input power law wind profile having a reference speed of 6m/s at 5m above the surface. It can be seen that lowering the profile results in a decrease in air-flow speeds. The small front dune in the existing St. Kilda profile helps establish a sheltered zone behind. The velocity in this sheltered zone is relatively low. As expected, the maximum wind speed was found at the top of the existing scarp bordering Kettle Park.

Figure 12 shows the wind velocity contours over the three modified topographies (Kettle Park). Interestingly, the differences between the wind fields over the three modified profiles are not significant. The M1 and M2 profiles have the same maximum height, but have different stoss face (seaward face) morphologies. The M2 topography requires less modification; while in M1, the dune needs to be shifted landward. The M3 profile offers the advantage of providing accommodation space for the formation of a small foredune. This feature is unlikely to be stable, rather it would need ongoing maintenance following scarping events. The purpose of this incipient foredune would be to protect the high-value amenities to landward. The sheltered area behind the incipient dune also prevent aeolian erosion and along the front-slope of the Kettle Park reclamation.

We must emphasize, however, that scenarios M2 and M3 will not provide for storm surge run-up, and scarping of the back-beach and margins of Kettle Park by waves during storm and low pressure conditions will continue. Only scenario M1 has the potential to mitigate both forms of erosion (wind and wave/pressure-forced).

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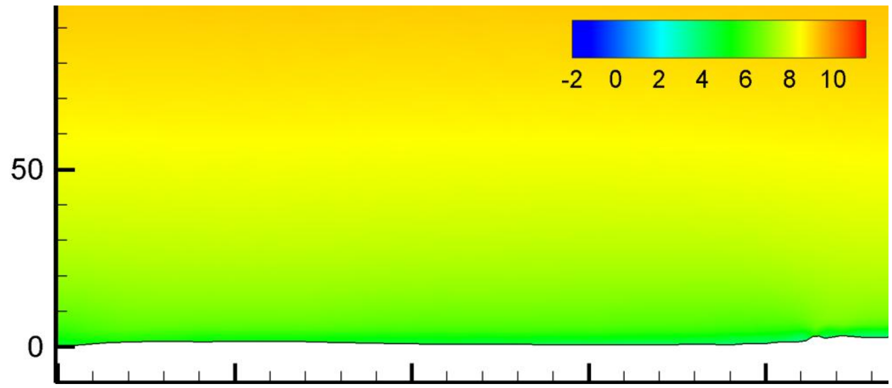

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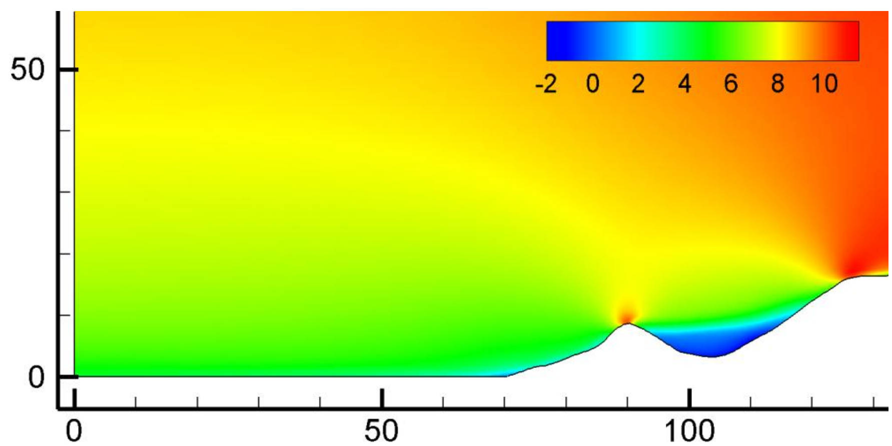

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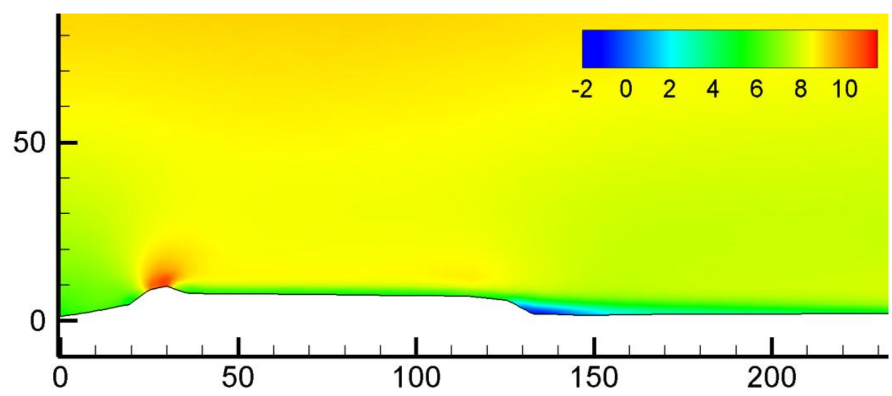


Figure 11: CFD wind velocity contours over (a) the 1890 (section C-D) landscape; (b) John Wilson Drive; and (c) Kettle Park topographies. The profile scales (in meters) vary. Red indicates areas of high wind energy and potential erosion. The velocity scale is in m/s.

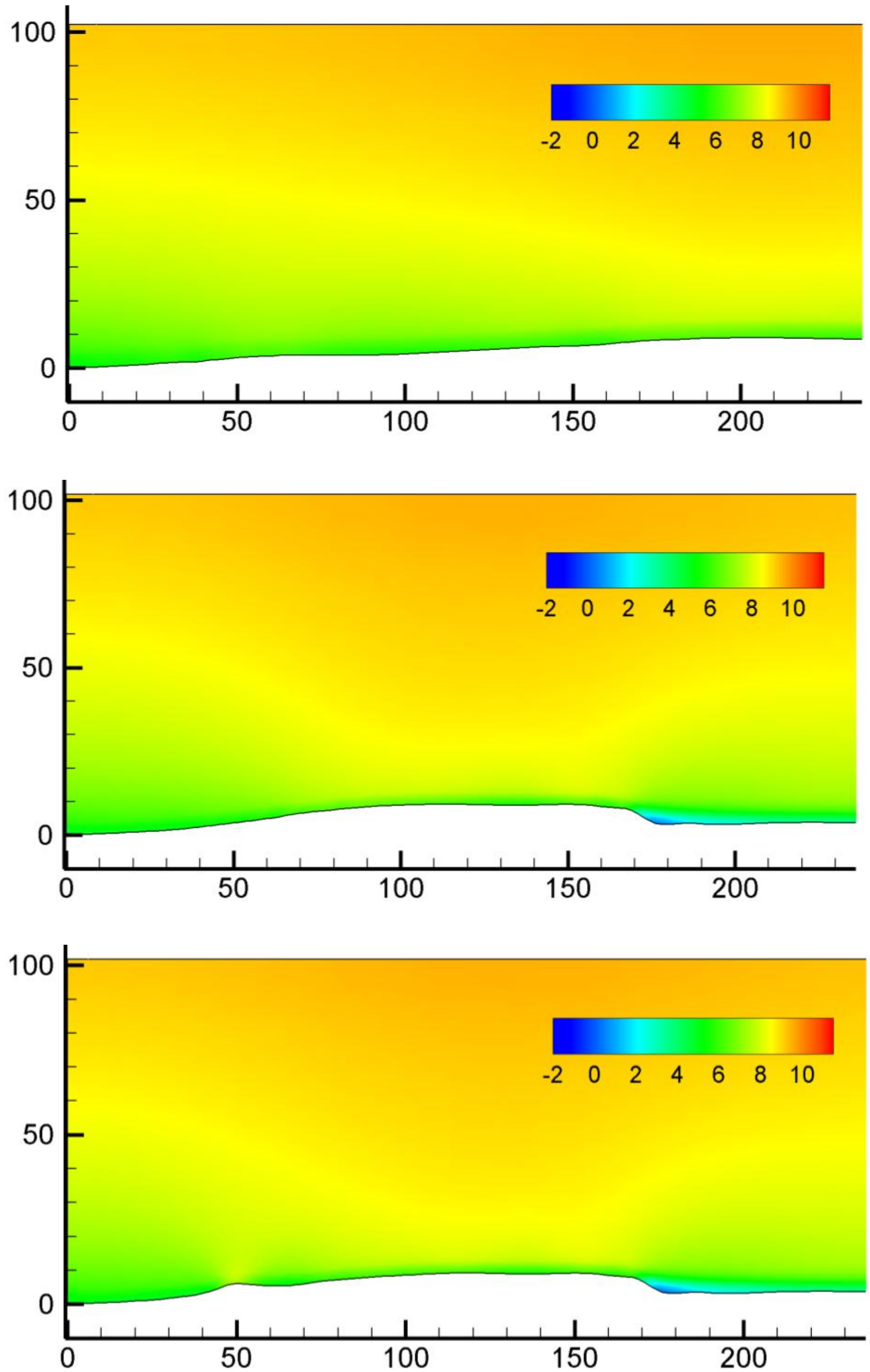


Figure 12: Wind velocity contours over the modified profiles – M1 (top), M2 and M3. The same horizontal and vertical scales are employed (in meters).

7. LONGTERM VARIATION IN THE WIND REGIME

We investigated the nature of the local wind regime as part of the current study. The objectives were to:

(i) describe the wind regime experienced in the study area;
(ii) identify any long-term trends in wind variation.

The first objective was a necessary prelude to the modeling reported above. The second was examined to identify evidence of long-term trends in wind energy. Specifically, have the number of extreme wind events, which are associated with aeolian sand erosion at Ocean Beach, increased in recent years. Most of the management problems experienced at Ocean Beach are related to the juxtaposition of re-claimed land and the sea. The 1890 topography clearly provided for the dissipation of storm surge across a broad deflation surface and lagoon system. Reclamation of this area to (and probably seaward of) a line commonly crossed by storm waves/surge has established a situation of periodic erosion. Elevation of the land (relative to the pre-reclamation levels) results in the acceleration of onshore winds and more frequent wind-forced sedimentation. We were interested in any evidence that this latter process has become more frequent or intense.

We did not have access to an ideal data set. Wind data is gathered at Lawyers Head by the DCC, however, the data set is relatively short and there are significant gaps in the record. We had access to a much longer (hourly wind speed and direction) data set from Taiaroa Head, from 1972 to 2010. However, this site is some kilometers from Ocean Beach and is somewhat sheltered from the southwest. There is also a gap in the record in 2002.

We undertook a range of analyses that compared the available data from Lawyers Head (2005 to 2008) with observations at Taiaroa Head, with a particular focus on 'onshore winds'-winds of geomorphic significance in the study area (from 73-253^{o}). We also examined the long-term Taiaroa Head record for evidence of trends in the frequency of high wind events. These analyses are included in a progress report submitted to the Dunedin City Council in August 2010.

This work concluded:

- southwest winds are the prevailing winds in the study area;
- wind speeds at Taiaroa Head can be used to represent wind in the study area;
- the study site is a windy location - strong winds, in excess of 10 m/s, occur approximately 38% of the time; and
- the period from 2004 to the present has been relatively calm compared with the long-term record at Taiaroa Head; particularly for winds above 15 m/s (Figure 13a, b).

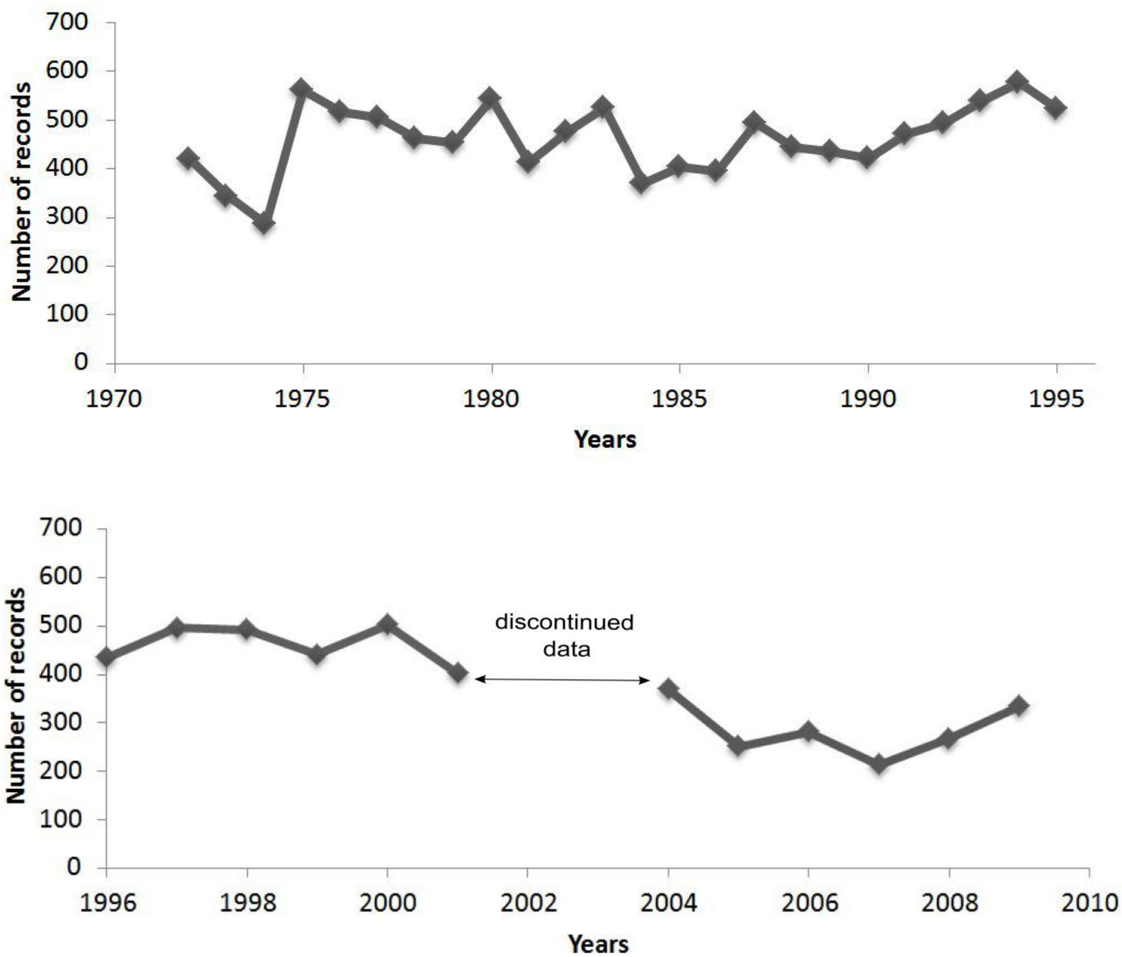
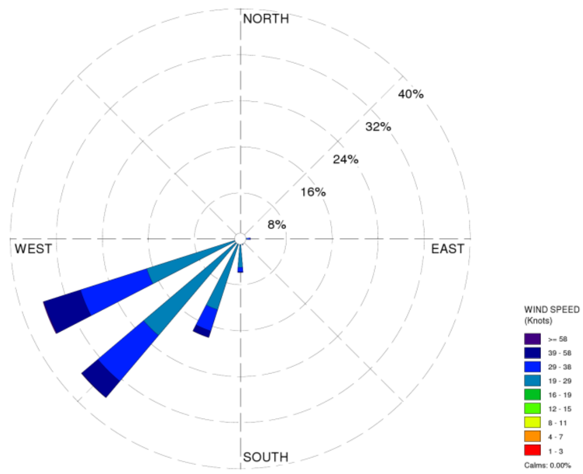


Figure 13a: The number of onshore wind events exceeding 10m/s, Taiaroa Head, 1970-2010.

a.



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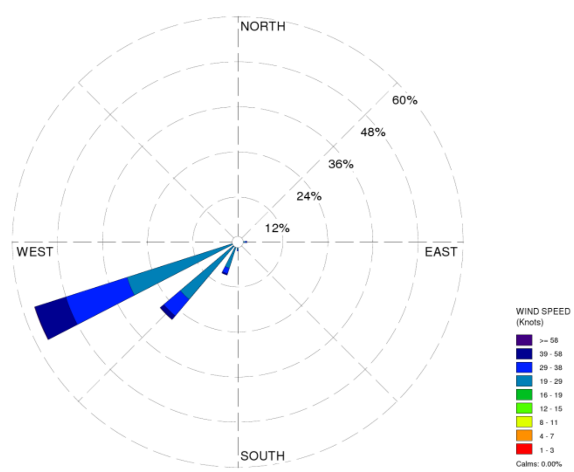

Figure 13b: Wind roses for the periods 1972-1995 and 1996 to 2008 for onshore winds, Taiaroa Head.

8. CONCLUSIONS

The Ocean Beach Domain is an exposed coast that is subject to moderate to high wind energy. Southwest winds are the prevailing winds. The Domain is relatively sheltered from northwest winds.

Reclamation of the deflation surfaces and lagoon, from the late 1880s, has raised the level of the land relative to the beach. Consequently, wind flows across the back-beach during southwest conditions are accelerated, creating a sand transport system that effectively exports beach sand during high wind events. This sand is deposited downwind, on Kettle Park and other facilities, involving some loss of amenity and ongoing maintenance costs. There is currently insufficient space between the playng fields of Kettle Park and the high tide line to accommodate a foredune.

We modeled wind speed and direction across the South Dunedin landscape during southwest wind conditions. The results indicate that the section of Ocean Beach Domain between John Wilson Drive and the Esplanade is relatively sheltered by the hill country above St Clair. The Domain between the Esplanade and Moana Rua Road is particularly sheltered. A limited set of anemometer observations were in accord with this modeling. The modeling and observations also accord with interpretations of the geomorphology of the St Clair – St Kilda sand system prior to development (Hilton, 2010). This work recognized three major subdivisions of the dune system – a strip of dunes bordering Victoria Road, separated from a transgressive dunefield (St Kilda) by a deflation surface containing a lagoon.

The implication of this work is that the Dunedin City Council has some flexibility in how it manages the western section of the Domain. The goal of protecting the St Clair urban area from flooding associated with storm surge and tsunami must remain paramount. However, the Council might modify the existing landscape to establish a range of recreational and hazard management landscapes, with areas that have a sandy surface, with little fear of significant aeolian sedimentation. That is, the new landscape is unlikely to be eroded by the wind. Dune formation and migration in this area should not occur.

We modelled wind flows across the existing landscape at Kettle Park and John Wilson Drive and across three alternative coastal topographies. These alternative topographies included minor and large-scale modifications to the existing landscape. We sought to reduce back-beach acceleration of flow by lowering the topography along the edge of Kettle Park. We identified topographies (M3) that would provide for the establishment of an incipient foredune, that might be maintained for hazard management purposes. Scenario M1, the most radical, also provides for the establishment of a surface that would accommodate some storm surge run-up. This scenario would require excavation of the fill underlying Kettle Park, development of parking facilities and amenities across the rear of the new topography, and re-establishment of a low-lying sandy surface/beach. It is likely this lower surface could be partially vegetated with native sand-binding species.