FUNWAVE MODELLING OF BEACH INUNDATION IN RESPONSE TO MASS SAND NOURISHMENT: A STUDY USING SOME PROFILES FROM STOCKTON BEACH NSW.

Ian Taggart, University of Newcastle NSW, ian.taggart@newcastle.edu.au

ABSTRACT
Mass sand nourishment is recognized as a means of restoring beach amenity and one that possibly offers long-term protection from further shoreline loss and inundation of adjacent urban areas. While large scale beach nourishment has been used elsewhere, examples in NSW are extremely limited. Model inundation results, based on an actual beach profile, suggest that nourishment alone provides little reduction to inundation rates and therefore inundation risks.

MASS SAND NOURISHMENT (MSN)
MSN is considered attractive inasmuch as it is considered a softer approach to alternatives based on hard shoreline structures. As argued by Stuadt (2021) the design principles for nourishment are reasonably well established (Pilarczyk, 1986) but the long term environmental impacts and success metrics are less well understood.

KEY FOCUS AREA & CONTRIBUTION
The placement of large sand volumes on a previously eroded beach has several objectives. Above current MSL there is an opportunity to build sand dunes and reshape scarps, while another objective is to increase beach width (beach amenity). Sand placed in deeper water has the ability to alter wave breaking characteristics and to change the nature and location of wave energy dissipation. Implicit in the wave dynamics and beach profile alteration are the related issues of wave setup, wave run-up and inundation. The contribution this work seeks to make is using the Boussinesq phase resolving model FUNWAVE, to assess inundation risks.

CAVEAT
This work uses some beach profiles from Stockton Beach because it is a beach of current interest in the state of NSW for MSN. The area of interest is shown in Figure 2 along with some historical changes in (Taggart, 2022). We also impose an arbitrary 5m high overtopping hurdle to allow calculation of inundation rates under idealized wave conditions. The profile and this hurdle are simple abstractions to better understand the process at play, and to gain some insight into how nourishment strategies may impact inundation risk. We do not claim that these models therefore represent true estimates for inundation at this location.

THIS WORK
This study focusses on how beach profile alteration via MSN impacts the inundation risks of adjacent areas. At Stockton Beach in NSW, urban areas are (now) in close proximity to the beach (per Figure 1 and Figure 2). Even with growth in beach width, the distances available to absorb wave run-up is relatively limited.

Use is made of the Boussinesq wave modelling abilities provided by the FUNWAVE software package (Shi, 2012) to both visualize and quantity wave dynamics and overtopping in response to beach profile alteration. Our methodology is to take known beach profiles and examine how MSN could provide both wider beach amenity and also provide a means of altering wave dynamics. Wave overtopping, via 1-D modelling of transient wave propagation over a changing bathymetry is able to be quantified in response to profile changes. The wave set-up and run-up is tracked along with volumes of water overtopping defined structures.

CURRENT KNOWELDGE
Some current works describing MSN along with efforts to define success metrics associated with lookback studies are discussed in a NSW context by AECOM (2010) and Carley (2017).

METHODS
The steps followed here can be described as follows:

- Select a representative 1-D Profile from 5m above MSL to 20m water depths
- Setup FUNWAVE 1-D model to generate waves offshore heading shoreward
- Specify necessary Amplitude and Period (*Ts*) for the model wave generator
- Simulate 2000s of transient waves movement to shore. A snapshot of generated waves is shown in Figure 3.
- Shoaling and Wave-wave interactions implicitly captured by generated wave profiles
- Specify 80+ recording stations (for post processing later)
- Validate FUNWAVE results against special cases from accepted Eurotop formulas (try to bracket overtopping rates with simple Eurotop formulas)

For estimation of inundation rates we added an extra 1000m of sump (to collect fluid) was added after an initial (nominal) 5m height barrier. Water volumes in the sump calculated at times of 1000s and 2000s (allowing calculation of inundation rates over two time periods). The FUNWAVE keyword “Waterlevel” was used to adjust initial levels relative to MSL. (This required specification if an initial ETA profiles to ensure the sump was dry at *t=0*). Initial elevated water levels above MSL allowed for a combined effect of tide, wind and atmospheric setup, in addition to model based estimation of wave run-up and wave set-up.

The area of Stockton Beach most utilized by the public extends some 2.5km from a northern breakwater (completed in 1913) (Taggart et. al 2022)

NOURISHMENT PROFILES

For any 1-D nourishment profile it is a straightforward book-keeping exercise to calculate the implied sand volumes V in units of m3/m. For a total length L then (assuming same profile) then the total volume is V2=V*L. Figure 4 shows three candidate profiles for beach nourishment as N1, N2 and N3. These profiles were prescribed in order to provide a degree of beach amenity (above MSL) while placing some volumes in deeper depths to replace past sand losses. While many sand nourishment projects place sand in water depths some 1-3 m below MSL (Carley 2017), the current eroded beach profiles here meant that deeper depth end up being chosen, with the idea to reduce initial beach slope from 1:20 to approach 1:40. Hence some nourishment volumes extended to the 8-10m (which is considered somewhat unusual). Refer to Figure 4 and Table *1* for details

Figure 1. Location of Stockton Beach on the NSW East Coast of Australia

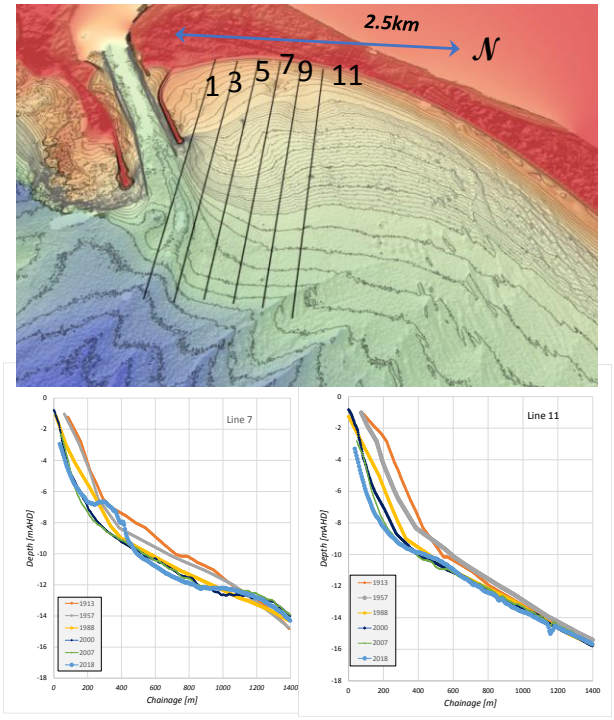

Figure 2. Area of Interest showing depth profiles along lines 7 & 11. The effect of long term erosion over a hundred years is noted to extend to depths below 14 metres.

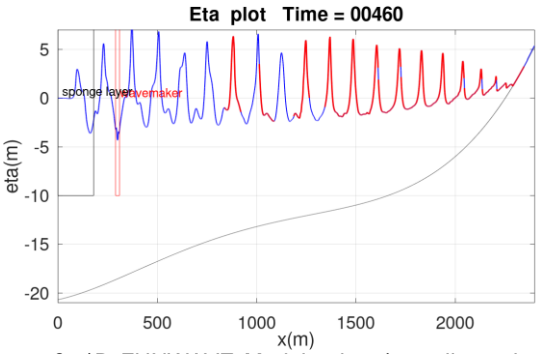

Figure 3. 1D FUNWAVE Model using 1m cell spacing and utilizing a wave generator (3m Amplitude waves) in a profile based on line 7&9 above. Breaking waves are coloured red. Wav setup and run-up are evident

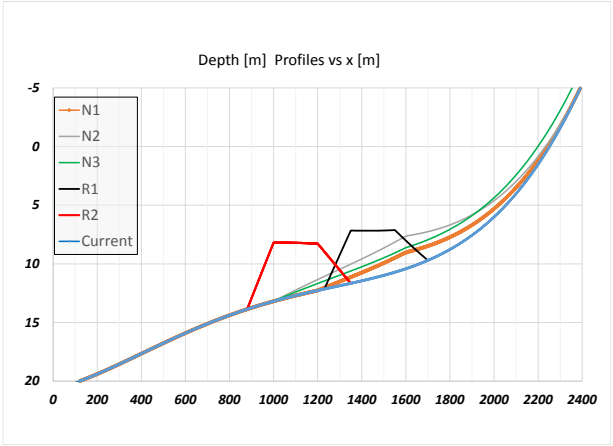

Figure 4. Beach Nourishment Profiles, N1, and N2 & N3 shown on a Current (2018) profile. Only N3 results in 50m increase in Beach width. R1 & R2 are offshore banks cases that were also considered (but are not discussed here)

Nourish. Profile	V [m3/m]	V2 (L =2.5km) [m3]	Comment
N1	839	2.1 E6	Nourishment in Depths to 12m
N2	1959	4.9 E6	Larger Volume
N3	1850	4.6 E6	50m extra Beach Width included

Table 1. Implied Sand Volumes in Nourishment Profiles

MODEL SETUP TO CALCULATE INUNDATION RATES

While initial studies focused on the wave setup and run-up characteristics to estimate overtopping and inundation rates the simulation grid was extended shore wise to incorporate a sump (Figure 5). Any overtopping volumes (to an initially dry sump) over a fixed period of elapsed time could be estimated an average inundation rate calculated.

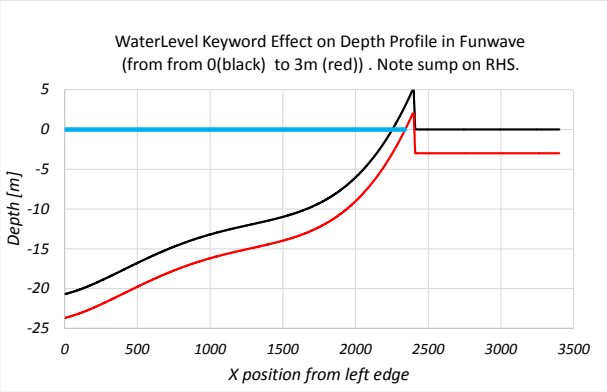

Figure 5. Beach profiles were augmented by an idealized shoreline height with a flat sump located behind. Collected water volumes were recorded as part of the simulation process and av. rates calculated by a post-processing step.

KEY RESULTS

Beach Profile alteration both above and below MSL is directly linked to available MSN sand volumes. Needed volumes are implied by the changed profiles relative to current state as shown in Table 1. The volumes are larger than those presented by AECOM (2010) but are similar magnitude to 10-year losses using the methods described by Carley (2017). One key finding is that MSN, in the absence of sufficient and long distances above MSL to cope with the run-up and set-up characteristics of the incident wave, provides a relatively modest level of inundation protection. Similar results have been reported in the literature (Suzuki 2012). The contribution made by this work is that it allows the direct visualization and quantification of placed sand volumes in relation to overtopping and inundation rates

WAVE SETUP and RUN-UP

By making use of wave station location to record the temporal history of wave height (eta(x, t)) at a given locations, a post processing step can find suitable averages. The averaging process need to first find zero crossings then take the averages over respective +ve and -ve section. This allows calculation of wave setup at each station location.

Figure 6 shows that nourishment case N1 leads to a reduction in average wave amplitude close to shore but the wave setup is predicted to actually increase. Other case N2 and N3 (along with attempts at placing offshore sandbanks/reefs) showed similar results. When we come to directly simulate inundation rates, the characteristics observed and noted here, strongly apply.

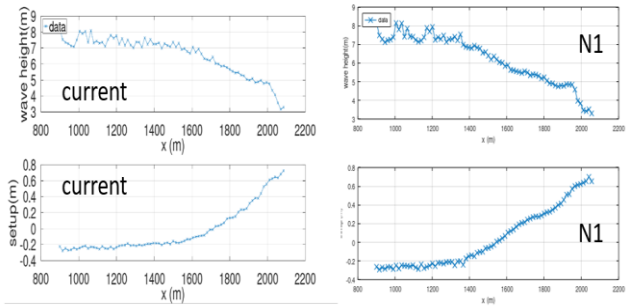

Figure 6. Before and after results for wave stations. Existing case (left) and after Nourishment (Case N1) right.

FUNWAVE (Shi, 2012) allows for wave overtopping to be tracked by placing a (negligibly) thin layer of water over nominally dry land and allowing for changes in this layer thickness as part of a solution update. This allows events like Tsunami ingress over (initially dry) land to be tracked. In a similar fashion, overtopped volumes in a sump were also tracked here and processed to provide a measure of the Inundation rate (expressed in units of L/m/s). We noticed our results for inundation were not smooth in time due reflected wave-wave interactions occurring. Sometimes the inundation results appeared stronger at the 1st transient. We made a calculation of inundation rates at 1000 and 2000s (over 1000s intervals) and took the maximum value as the result. This work used monochromatic waves. The results for inundation rates are presented for 3 separate amplitude cases and different nourishment strategies in Figure 7, Figure 8 and Figure 9. These figure are based on the same initial profile and the x-axis reflects the degree of tide and storm setup (over the initial MSL) prior to using FUNWAVE to calculate additional wave contributions. The base case appears as solid red markers. Future work should consider longer time and wider wave (frequency) spectrums.

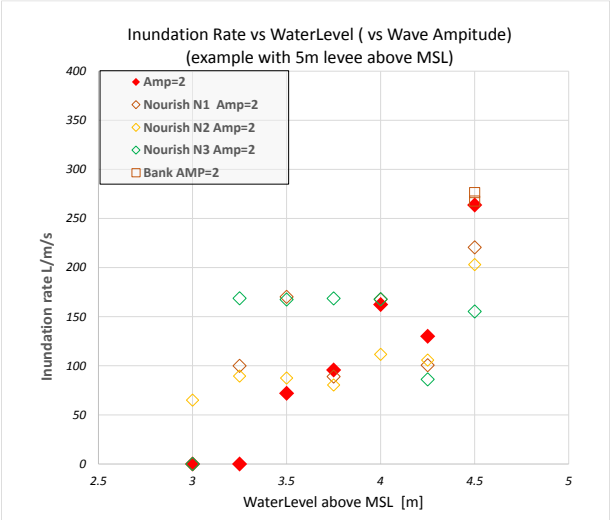

Figure 7. Inundation rate for 2m Amplitude waves (Ts=11sec)

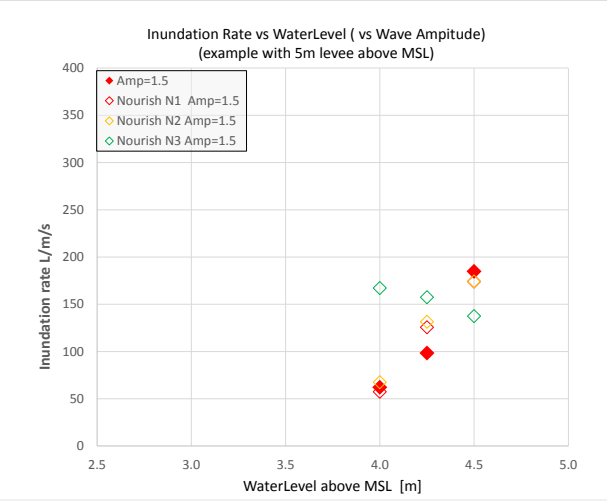

Figure 8. Inundation rates for lower (1.5m) amplitude case.

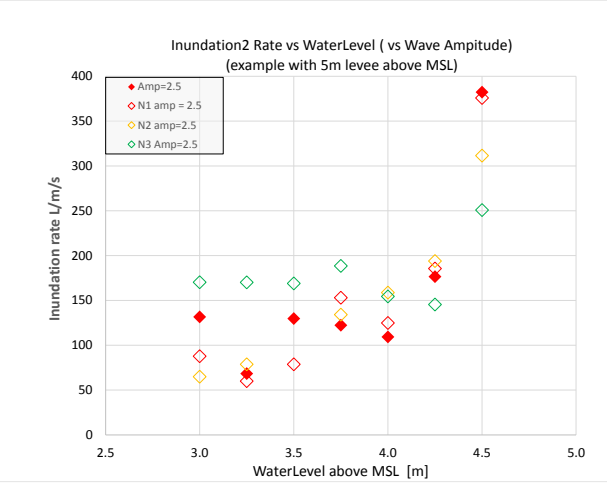

Figure 9. Inundation rates for 2.5m amplitude case

VALIDATION STEPS

In this section we will attempt an order-of-magnitude validation of inundation / overtopping rates by applying some Eurotop formulas in a simple manner. The term simple means that we are taking some liberties by applying them outside their defined cases. The intent is to see if the inundation rates obtained from FUNWAVE are reasonable for an order-of-magnitude perspective.

To our knowledge there a few studies that have attempted to document how beach nourishment impacts wave setup, run-up and overtopping in a situation where little accommodation space exists. The present beach profiles obtained from a numerical model therefore need to be validated against expected results (albeit in somewhat altered geometries). The most extensive and documented work on overtopping is that resulting from the Eurotop project and its various updates (Eurotop 2007 and 2018). This work is based on both scaled flume models and pilot studies, and invariably used the significant wave height parameter H_{mo} or H_s, close to the foot of a structure, in a variety of simple, well defined, geometries. The Eurotop geometries (Figure 10) themselves do not consider the subtle variations in subaqueous and sub areal sand profiles. Hence we have chosen two Eurotop formulas that are intended to provide, at best, for order-of-magnitude overtopping rates. The two Eurotop cases are also intended to represent "High" and "Low" case estimates. The Eurotop work often relates to unbroken waves, whereas in our situation, the waves have already broken. This further emphasizes the point that we seek order of magnitude validation only, and have chosen to use the Eurotop formulation based on convenience. We refer to figure 5.11 in Eurotop 2018 to highlight that breaking (plunging) waves result in less overtopping than surging ones.

The "Low" Eurotop case is provided by unbroken waves incident on a vertical wall structure with no foreshore effect (eq. 7.1 Eurotop 2018) and is listed as equation (1). While the "High" case resents a limiting formula for that of sloped wall seaward of a small vertical barrier or promenade (eq. 5.44 Eurotop 2018 with influence factor of 0.8, as shown by equation 2.). In this work we will assume that that spectral significant wave height is equivalent to the zero-crossing significant wave height ($H_{1/3}$) or H_s.

$$\frac{q}{\sqrt{g.H_s^3}} = 0.047 * exp\left[-\left(2.35\ \frac{R_c}{H_s}\right)^{1.3}\right] \quad \ldots . (1)$$

$$\frac{q}{\sqrt{g.H_s^3}} = 0.09 * exp\left[-\left(1.5\ \frac{R_c}{H_s * 0.8}\right)^{1.3}\right] \quad \ldots . (2)$$

The geometry for equations is shown below. The angle (α) does not appear because equation (2) represents a limiting form. R_c represents the height of a barrier to be overcome (and in the case of a wall or embankment is positive).

We also need to account for the use Monochromatic waves (typical of simplest wave makers in a flume) and the relationship between monochromatic wave height and Hs as used according to Kudale and Bhalerao (2015) who suggested that for the same damage H_m should be larger than the equivalent H_s (variable or random wave case) by a factor of 1.27. Hence for a H_s of 2m, the equivalent H_m will be taken to 2.54m, and for a H_m of 4m the equivalent Hs would be 3.15m.

We have chosen to use the factor of 1.27 to convert monochromatic wave heights to equivalent Hs and also to increase the value of R_c (from 5m) by an extra 1.5m as an ad-hoc way of trying to account for the breaking waves in our modelled situation and the use of a Hs far from the foot of the structure (and any extra dissipation inherent in the numerical model). We again emphasize that we are only seeking order of magnitude validation in modelled inundation rates only. Without the increase

in R_c equation 1) and 2) would predict higher inundation rates.

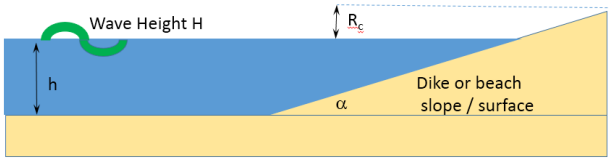

Figure 10 Geometry for Eurotop cases/equations.

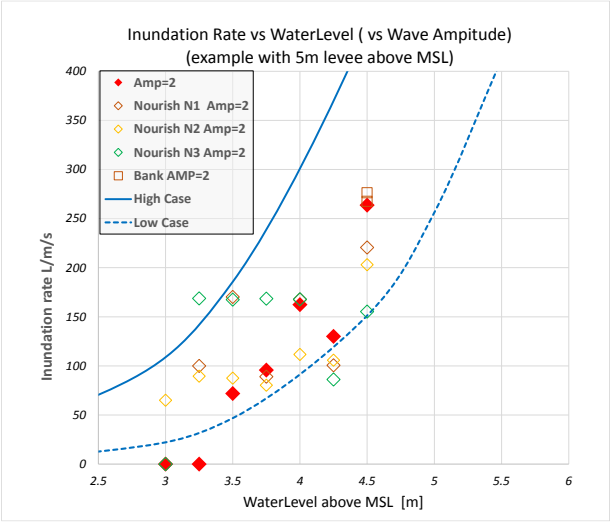

Figure 11 Superimposing the results of Eurotop equations (1) and (2), on previously modelled results for the case of Monochromic waves generated with an Amplitude of 2m.

The takeaway from Figure 11 is that, with the ad-hoc adjustment to Rc for use in formulas, the simulated inundation rates are magnitude comparable to those provided by equations 1) and 2). This means that the modelled inundation rates are reasonable from an order of magnitude perspective. This also providers a measure of confidence that the modelled differences with sand nourishment are therefore also reasonable.

INSIGHTS

Given that the beach profile used as a starting point displayed strong erosion features out to water depths of 14-18m, the three modelled nourishment options considered did not significantly reduce inundation risks. Often, the resulting wave setup and run-up appeared to be unaffected or in some cases, made worse. These insights are similar to those presented by other workers using different methods [Suzuki 2012, Da Silva 2022] While sand nourishment delivers clear beach amenity benefits we feel that for the cases considered, a full erosion solution will likely need to employ a combination of erosion control measures.

SCOPE for FUTURE WORK

Stockton Beach provides well-documented sub-aqueous profiles that show the effects of long-term (multi-decade) unchecked erosion extending to 20m water depths, and therefore provides a valuable test case for any future MSN campaign. Areas to progress and better validate results, are to consider 2D and 3D geometries and allow for variable incident wave directions. For Stockton beach itself and any proposed MSN project, we look also forward to details of documented, before and after sand profiles, to better understand how the total sand budget will be distributed.

NOMENCLATURE

α : Angle to horizontal [deg]
g : acceleration of gravity [m/s^2]
h : nominal water depth [m]
H_m : Monochromatic wave height
q : av. discharge/overtopping rate ($m^3/s/m$ or L/s/m)
R_c : Height of barrier to overcome

REFERENCES

AECOM (2010) Beach sand nourishment scoping study maintaining Sydney's beach amenity against Climate Change and sea level rise. Report prepared for Sydney Coastal Councils Group.

Carley and Cox (2017). Guidelines for sand nourishment. WRL Research Report 263 Oct. 2017.

Da Silva, Hansen, Ryan Lowe, Rijnsdor (2022). Wave run-up in the lee of submerged breakwaters. Australasian Coasts & Ports 2021 Conference, Christchurch.

EUROTOP (2007) Eurotop manual: wave overtopping of sea defenses and related structures https: //assets.publishing.service.gov.uk/media/602e883fe90e076605eab47e/_Wave_overtopping_assessment_manual.pdf

EUROTOP (2018). http://www.overtopping- manual.com /assets/downloads/EurOtop_II_2018_Final_version.pdf

Kudale, Bhalerao. Equivalent monochromatic wave height for the design of coastal rubble mound structures, Aquatic Procedia 4 (2015) 264 - 273.

Pilarczyk , van Overeem , Bakker (1986). Design of beach nourishment scheme. Coastal Engineering Proceedings, 1(20), 107. doi.org/10.9753/icce.v20.107

Shi, Kirby, Harris, Geiman, Grilli, (2012) A high-order adaptive time-stepping TVD solver for Boussinesq modeling of breaking waves and coastal inundation, Ocean Modelling, Volumes 43-44,2012,Pages 36-51, ISSN 1463-5003

Staudt, Gijsman. Ganal, Mielck, Wolbring, Hass, Goseberg, Schüttrumpf, Schlurmann, Schimmels (2021). The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. Journal of Coastal Conservation (2021) 25: 34 https: //doi.org/10.1007/s11852-021-00801-y

Suzuki, Verwaest, Veale, Trouw and Zijlema (2012). A numerical study on the effect of beach nourishment on wave overtopping in shallow foreshores. Coastal Engineering Proceedings, 1(33), waves.50. https://doi.org/10.9753/icce.v33.waves.50

Taggart, Jamieson, Goodwin, Nielsen (2022) A Century of Bathymetry changes at Stockton Beach. Australasian Coasts & Ports 2021 Conference - Christchurch.