Longshore sediment transport driven by sea breezes on low-energy sandy beaches, Southwestern Australia

This item was submitted to Loughborough University’s Institutional Repository by the/an author.

Additional Information:

- A Doctoral Thesis. Submitted in partial fulfillment of the requirements for the award of Doctor of Philosophy of Loughborough University.

Metadata Record: [https://dspace.lboro.ac.uk/2134/7644](https://dspace.lboro.ac.uk/2134/7644)

Publisher: © Aafke M. Tonk

Please cite the published version.
This item is held in Loughborough University’s Institutional Repository (https://dspace.lboro.ac.uk/) and was harvested from the British Library’s EThOS service (http://www.ethos.bl.uk/). It is made available under the following Creative Commons Licence conditions.

For the full text of this licence, please go to: http://creativecommons.org/licenses/by-nc-nd/2.5/
Longshore sediment transport driven by sea breezes on low-energy sandy beaches, Southwestern Australia

by

Aafke M. Tonk

A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

(June 2004)

ABSTRACT

Longshore sediment transport rate was measured during energetic sea breeze activity, on intermediate-to-reflective sandy beaches in Southwestern Australia. Estimates of suspended load were obtained using backscatter sensors, current meters and streamer traps. Total load was determined using fluorescent tracer sand and an impoundment study. The measurements were cross-compared and used to evaluate several widely-used longshore transport equations.

The streamer trap measurement revealed an exponential distribution of the suspended sediment flux with vertical mixing decreasing in the onshore direction. A continuous time series of the longshore suspended sediment flux across the surf zone was obtained by combining the streamer trap measurements with data collected using surf zone instruments. Comparison of the suspended longshore flux with the total longshore flux derived from the dispersal of the sand tracer indicated that the relative contribution of the suspended load to the total load was at least 59 %. The movement of sand tracer on four different beaches demonstrated that nearshore sediments were transported obliquely across the surf zone, challenging our conventional view of dividing nearshore sediment transport into cross-shore and longshore components. Furthermore, tracer was found to move from the outer surf zone to the swash zone and vice versa, indicating a cross-shore sediment exchange. The contribution of the swash zone to the total longshore flux was estimated around 30–40 %.

Despite large differences in the temporal and spatial scales of the measurement techniques, the littoral drift rates are comparable, suggesting a northward transport rate of 138,000–200,000 m$^3$year$^{-1}$. Longshore sediment transport during sea breezes is mainly the result of a high longshore energy flux exerted by wind waves. This is accurately predicted by the equations of Inman and Bagnold (1963) and CERC (1984). The bimodal wave field, characteristic of Southwestern Australia, renders the Kamphuis (1991b) formula unsuitable in this instance.

Keywords: longshore transport, littoral drift, suspended sediment, streamer trap, fluorescent tracer, impoundment study, sea breeze, transport equation
RESEARCH OUTPUT


In memory of
Esmée Tonk
20-10-1974 1-1-2004

Wat is het leven van een mens
een voetstap in het zand
die weer wordt weggevaagd
wanneer de vloed de grens verplaatst
tussen zee en strand
De voetstap is verdwenen
maar nooit vergeten

What is the life of man
a footprint in the sand
that is erased
when the tide moves the border
between sea and beach
The footprint gone
but never forgotten
ACKNOWLEDGEMENTS

I would like to first and foremost thank Dr. Gerd Masselink for his advice and guidance during my PhD research. He helped me to make the right decisions, and has been an enthusiastic and inspiring mentor throughout the years. This work would not have been possible without the insight, guidance, and support of my other supervisors in Loughborough (Dr. Joanna Bullard and Professor Ian Reid) and in Perth (Professor Charitha Pattiaratchi and Dr. Ian Eliot).

Discussions, suggestions and support from staff and fellow postgrads at both Loughborough University and the University of Western Australia have helped with this research. A special thank you goes to David Johnson for his much appreciated help with the fieldwork and making available his DIWASP Matlab® routines for directional wave analysis. I am also grateful to everybody who went out of his or her way to help me complete the fieldwork. Without you guys none of this would be possible!

Life is an amazing journey. These past four years of my personal life were filled with extreme events, mainly pleasant but some sad. It is a blessing to have a family and friends to share the joyous moments and lean on when in need: My partner Reza for his unconditional love, encouragement, patience and proofreading of all the different drafts, my parents who directed me to where I am today with their love and support, the memory of my grandfather for his everlasting happiness and positiveness, the ‘vriendengroep’ and ‘AEATvdBW’ for their gift of warmth and humour, Guus for the fun of living on the edge, Baukje for always thinking of me. I would also like to acknowledge Selma and Yubiri for their stimulating conversations over cups of tea, Stuart for the practical jokes and runs down the corridor, the ‘chiefs’ for the endless invitations to the pub and my introduction to Indian food, and Aili for praying for me...
I thank you and love you all dearly.

This research is funded by an EPSRC grant (GR/N05628).
# CONTENTS

Abstract ii
Research output iii
Acknowledgements v
Contents vi
List of figures ix
List of tables xi
Table of symbols xii

## Chapter 1: Introduction
1.1 Introduction 1
1.2 Experimental measurement of longshore transport 2
1.3 Objectives 3
1.4 Approach 4
1.5 Outline of the thesis 5

## Chapter 2: Longshore sediment transport - A literature review
2.1 Introduction 7
  2.1.1 Definitions 8
2.2 Experimental measurement of longshore transport 9
  2.2.1 Impoundment method 10
  2.2.2 Tracer sand 12
  2.2.3 Pump samplers 13
  2.2.4 Sediment traps 15
    2.2.4.1 Bulk water-column traps 15
    2.2.4.2 Bedload traps 15
    2.2.4.3 Streamer traps 16
  2.2.5 Suspended sediment sensors 18
  2.2.6 Utilisation of different measurement techniques 24
  2.2.7 Laboratory data 25
2.3 Longshore transport processes 27
  2.3.1 Factors influencing longshore transport of sediment 27
  2.3.2 Bedload versus suspended load 29
  2.3.3 Cross-shore distribution of longshore sediment transport 31
2.4 Prediction of potential longshore transport 34
  2.4.1 Development of longshore transport modelling 35
  2.4.2 Energy flux method: CERC (1984) 37
  2.4.3 Environmental factors influencing the K-coefficient 42
  2.4.4 Longshore current method: Inman and Bagnold (1963) 44
  2.4.5 Kamphuis et al. (1986) and Kamphuis (1991a, b) 46
  2.4.6 Application of bulk longshore transport models 48
2.5 Summary 50

## Chapter 3: Field site and measuring approach
3.1 Introduction 53
3.2 Morphological setting 53
### Chapter 4: Impoundment study - Longshore transport on large temporal and spatial scales

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>68</td>
</tr>
<tr>
<td>4.2</td>
<td>Methodology</td>
<td>68</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Impoundment study</td>
<td>68</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Collection and analysis of hydrodynamic data</td>
<td>71</td>
</tr>
<tr>
<td>4.3</td>
<td>Results from the impoundment study</td>
<td>73</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Beach morphology</td>
<td>73</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Beach width</td>
<td>77</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Beach volume</td>
<td>79</td>
</tr>
<tr>
<td>4.4</td>
<td>Wind climate and wave breaking conditions</td>
<td>84</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Directional wave data</td>
<td>84</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Regression models</td>
<td>87</td>
</tr>
<tr>
<td>4.5</td>
<td>Longshore sediment transport</td>
<td>88</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Transport related to hydrodynamic conditions</td>
<td>88</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Transport models</td>
<td>91</td>
</tr>
<tr>
<td>4.6</td>
<td>Discussion</td>
<td>94</td>
</tr>
<tr>
<td>4.7</td>
<td>Summary</td>
<td>97</td>
</tr>
</tbody>
</table>

### Chapter 5A: Fluorescent tracer - Tracer theories and previous experiments

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A.1</td>
<td>Introduction</td>
<td>99</td>
</tr>
<tr>
<td>5A.2</td>
<td>Tracer theories</td>
<td>99</td>
</tr>
<tr>
<td>5A.2.1</td>
<td>Two-layer model of tracer behaviour</td>
<td>100</td>
</tr>
<tr>
<td>5A.2.2</td>
<td>Advection velocity</td>
<td>102</td>
</tr>
<tr>
<td>5A.2.3</td>
<td>Tracer recovery rate</td>
<td>106</td>
</tr>
<tr>
<td>5A.2.4</td>
<td>Mixing depth</td>
<td>107</td>
</tr>
<tr>
<td>5A.3</td>
<td>Previous experiments using tracer sand</td>
<td>110</td>
</tr>
<tr>
<td>5A.3.1</td>
<td>Radioactive and fluorescent tracers</td>
<td>111</td>
</tr>
<tr>
<td>5A.3.2</td>
<td>Methodologies using fluorescent tracer sand</td>
<td>112</td>
</tr>
<tr>
<td>5A.4</td>
<td>Summary</td>
<td>115</td>
</tr>
</tbody>
</table>

### Chapter 5B: Fluorescent tracer - Longshore transport on medium temporal and spatial scales

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5B.1</td>
<td>Introduction</td>
<td>116</td>
</tr>
<tr>
<td>5B.2</td>
<td>Methodology</td>
<td>116</td>
</tr>
<tr>
<td>5B.2.1</td>
<td>Study area</td>
<td>116</td>
</tr>
<tr>
<td>5B.2.2</td>
<td>Collection and analysis of hydrodynamic data</td>
<td>116</td>
</tr>
<tr>
<td>5B.2.3</td>
<td>Collection and analysis of tracer data</td>
<td>117</td>
</tr>
<tr>
<td>5B.3</td>
<td>Results of the experiment at Brighton beach in 2001</td>
<td>123</td>
</tr>
<tr>
<td>5B.3.1</td>
<td>Wind climate and wave breaking conditions</td>
<td>123</td>
</tr>
<tr>
<td>5B.3.2</td>
<td>Nearshore morphology</td>
<td>126</td>
</tr>
<tr>
<td>5B.3.3</td>
<td>Mixing depth</td>
<td>127</td>
</tr>
<tr>
<td>5B.3.4</td>
<td>Spatial Integration Method</td>
<td>131</td>
</tr>
</tbody>
</table>
Chapter 6: Streamer trap & OBS - Longshore transport on small temporal and spatial scales

6.1 Introduction 158
6.2 Methodology 158
   6.2.1 Study area 158
   6.2.2 Collection and analysis of hydrodynamic data 158
   6.2.3 Collection and analysis of streamer trap data 161
   6.2.4 Combining suspended sediment sensor and streamer trap data 164
6.3 Results 165
   6.3.1 Wind climate and wave breaking conditions 165
   6.3.2 Nearshore hydrodynamic data 167
   6.3.3 Instantaneous suspended sediment data 168
   6.3.4 Streamer trap data 171
   6.3.5 Time series of the total suspended sediment flux 173
   6.3.6 Transport models 175
6.4 Discussion 177
6.5 Summary 179

Chapter 7: Synthesis and Conclusions 181

7.1 Introduction 181
7.2 Combining the field measurements 181
7.3 Comparison of sea breeze activity and longshore transport rates 184
7.4 Combining the model estimates 186
7.5 Comparison with previous studies 189
7.6 Implications and future research considerations 192
7.7 Conclusion 194

References 197
LIST OF FIGURES

Figure 1.1 Definition of spatial and temporal scales involved in longshore transport measurement techniques. 3

Figure 2.1 A selection of field data for immersed longshore transport rates as a function of the longshore energy flux factor. 40

Figure 3.1 Map of the study area 55

Figure 3.2 Time series of (A) wind speed; and (B) wind direction. 58

Figure 3.3 Time series of (A) root-mean-square wave height; (B) zero-upcrossing wave period; (C) mean cross-shore current; and (D) mean longshore current. 59

Figure 3.4 Time-Frequency plot of water surface elevation. 60

Figure 3.5 Vertically averaged longshore suspended sediment flux in kg m-1 s-1. 61

Figure 3.6 A directional spectrum and its frequency and direction spectrum. 64

Figure 4.1 General shoreline configuration of the study area. 69

Figure 4.2 Study area of the impoundment experiment. 69

Figure 4.3 (A) Original and (B) adjusted profiles 50 m updrift of the groyne. 70

Figure 4.4 Definition of the beach width. 71

Figure 4.5 Flow chart of the methodology followed to derive breaker wave data. 72

Figure 4.6 Beach profiles measured at Day 34, Day 62, Day 97 and Day 160. 74

Figure 4.7 Elevation model relative to mean sea level. 76

Figure 4.8 Change of the beach width (m) relative to the first measurements. 77

Figure 4.9 Beach width (m) against beach volume (m3 m-1). 79

Figure 4.10 Change of elevation relative to the first survey (Day 28). 80

Figure 4.11 Cumulative change of the beach volume (m3) relative to Day 28. 82

Figure 4.12 Envelope of the longshore transport rate. 83

Figure 4.13 Summary of wind and wave conditions near the study site. 85

Figure 4.14 Directional wave spectra before and during a sea breeze. 85

Figure 4.15 Spectral density, significant wave angle and longshore energy flux factor before and during a sea breeze. 86

Figure 4.16 Linear regression of breaker versus offshore wind-wave height; and breaker wind-wave angle versus longshore wind component. 88

Figure 4.17 Timeseries of nearshore data. 90

Figure 4.18 A: Normalised wave, and B: Predictions of longshore transport rates using littoral drift models. 92

Figure 4.19 Comparison of the longshore transport envelope derived from the impoundment study with predictions using littoral drift models. 94

Figure 4.20 Trigg Beach. Top of the photo represents north. 97

Figure 5A.1 Schematic overview of the active layer of longshore moving sediment. 101

Figure 5A.2 Spatial and temporal grids for monitoring sand-tracer motion. 103

Figure 5A.3 Example of a contour plot. 104

Figure 5B.1 Schematic overview of a typical multi colour tracer experiment. 118

Figure 5B.2 Bags of tracer sand; pre-soaking of tracer sand; and injection of tracer at the lower swash. 119

Figure 5B.3 Hand-operated extruder. 119
Figure 5B.4  Summary of wind, tide and wave conditions on Brighton beach.

Figure 5B.5  Cross-shore profile and zones of Brighton beach.

Figure 5B.6  Temporal changes of the cross-shore distribution of the mixing depth at y = 50 m.

Figure 5B.7  The changes in mixing depth over time at y = 50 m.

Figure 5B.8  Cross-shore distribution of the mixing depth, at y = 50 m

Figure 5B.9  Spatial distribution of three different sand-tracers, 60 minutes after injection.

Figure 5B.10 Spatial distribution of three different sand-tracers, 120 minutes after injection.

Figure 5B.11 Temporal concentration distribution of tracer, at y = 50 m.

Figure 5B.12 Cross-shore distribution of tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach.

Figure 5B.13 Cross-shore profiles and zones during the three tracer experiments.

Figure 5B.14 Cross-shore distribution of the mixing depth, based on the mixing depth during the second hour of the tracer study.

Figure 5B.15 Spatial distribution of three different sand-tracers for three experiments in 2002.

Figure 5B.16 Temporal concentration distribution of tracer.

Figure 5B.17 Tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach at South Leighton beach (18.01.02).

Figure 5B.18 Tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach at Mullaloo beach (25.01.02).

Figure 5B.19 Tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach at North Leighton beach (12.02.02).

Figure 6.1  Cross-shore profile of Brighton Beach on 10th January 2001.

Figure 6.2  Design of a streamer trap.

Figure 6.3  Example of a simultaneous deployment of streamer traps.

Figure 6.4  Wind speed at Swanbourne and Rottnest Island; significant breaking wave height and breaking wave angle.

Figure 6.5  Local water depth; significant wave height; longshore current velocity and suspended sediment concentration.

Figure 6.6  Wave spectra calculated from 12:30-17:30 hrs on 10th January for different locations in the surf zone.

Figure 6.7  Cross-shore and longshore suspended sediment flux measured in the mid-surf zone at 0.1 m from the bed on 10th January.

Figure 6.8  Average normalised co-spectra for cross-shore and longshore suspended sediment transport.

Figure 6.9  Temporal variation in the total suspended sediment fluxes for the different streamer trap locations.

Figure 6.10  Average normalised suspended flux profile in: outer surf zone; mid-surf zone; inner surf zone; and swash zone.

Figure 6.11  Average cross-shore distribution of the normalised, vertically-integrated suspended sediment flux.

Figure 6.12  Relation between local suspended flux q(x,z) and the vertically-integrated suspended flux q(x) obtained from streamer traps.
Figure 6.13  Estimated total suspended sediment flux across the surf zone (dry-weight).
Figure 6.14  Predicted and measured longshore sediment transport rates.
Figure 7.1  A compilation of field data, using the CERC-equation for immersed weight longshore sand transport rate II as a function of the longshore component of wave energy flux Pl.

TABLE OF CONTENTS

List of Tables

Table 2.1  Field data sources of longshore transport rates. 20
Table 2.2  Laboratory data sources of longshore transport rates. 26
Table 2.3  Parameters influencing longshore sediment transport. 28
Table 2.4  Summary of predicted versus measured longshore transport rates, using the equations of CERC, Inman and Bagnold and Kamphuis. 49
Table 3.1  Overview of longshore transport measurements performed during this study. 63
Table 3.2  Overview of the transport models used. 67
Table 4.1  Deep-water wave parameters 73
Table 4.2  Change in beach width during a period of 18 weeks. 78
Table 4.3  Beach volume during a 19-week period. 81
Table 4.4  Overview of linear regression equations. 88
Table 4.5  Average wind and wave parameters during each survey interval. 89
Table 4.6  Beach volume change during a 10-week period. 93
Table 5B.1  Overview of the average wind wave and current conditions. 125
Table 5B.2  Cross-shore distribution of the mixing. 131
Table 5B.3  Total immersed-weight longshore transport and tracer recovery rates. 137
Table 5B.4  Overview of the average environmental conditions during three tracer experiments. 137
Table 5B.5  Cross-shore distribution of the mixing depth. 140
Table 5B.6  Total immersed-weight longshore transport rate and tracer recovery percentage. 149
Table 5B.7  Total volume transport rates and the relative contribution of the swash load. 150
Table 5B.8  Longshore sediment transport rates during three tracer experiments. 151
Table 6.1  Summary statistics for the streamer trap deployments. 172
Table 6.2  Average volume of transported sediment during a single sea breeze 176
Table 7.1  Measured longshore sediment transport rates. 182
Table 7.2  Maximum recorded wind speed of the sea breeze at various coastal sites. 185
Table 7.3  Longshore sediment transport rates at various coastal sites. 186
Table 7.4  Values of the empirical proportionality coefficient. 191
Table 7.5  Comparison of techniques to measure longshore sediment transport. 193
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>depth of mixing</td>
<td>m</td>
</tr>
<tr>
<td>c</td>
<td>tracer concentration</td>
<td>grains gram⁻¹</td>
</tr>
<tr>
<td>c</td>
<td>suspended sediment concentration</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>(Cn)_b</td>
<td>wave group velocity at breaker line</td>
<td>m sec⁻¹</td>
</tr>
<tr>
<td>D</td>
<td>grain size</td>
<td>m</td>
</tr>
<tr>
<td>D_s0</td>
<td>median grain size</td>
<td>m</td>
</tr>
<tr>
<td>E</td>
<td>spectral density</td>
<td>m² Hz⁻¹</td>
</tr>
<tr>
<td>E</td>
<td>wave energy</td>
<td>N m⁻¹</td>
</tr>
<tr>
<td>F</td>
<td>number of tracer grains per unit mass</td>
<td>grains kg⁻¹</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity (= 9.81)</td>
<td>m s⁻²</td>
</tr>
<tr>
<td>h</td>
<td>water depth</td>
<td>m</td>
</tr>
<tr>
<td>H</td>
<td>wave height</td>
<td>m</td>
</tr>
<tr>
<td>I</td>
<td>immersed weight longshore transport rate</td>
<td>N s⁻¹</td>
</tr>
<tr>
<td>K</td>
<td>proportionality coefficient</td>
<td>-</td>
</tr>
<tr>
<td>L</td>
<td>wave length</td>
<td>m</td>
</tr>
<tr>
<td>M_0</td>
<td>zero moment of the wave spectrum (total variance)</td>
<td>m²</td>
</tr>
<tr>
<td>M_1</td>
<td>first moment of the wave spectrum</td>
<td>s m²</td>
</tr>
<tr>
<td>M_{SIM}</td>
<td>mass of recovered material, SIM-experiment</td>
<td>kg</td>
</tr>
<tr>
<td>M_{TIM}</td>
<td>mass of recovered material, TIM-experiment</td>
<td>kg</td>
</tr>
<tr>
<td>p</td>
<td>sand porosity (= 0.4)</td>
<td>-</td>
</tr>
<tr>
<td>P_l</td>
<td>longshore directed wave energy flux</td>
<td>W m⁻¹ or N sec⁻¹</td>
</tr>
<tr>
<td>q</td>
<td>volumetric transport rate per unit beach width</td>
<td>m³ s⁻¹</td>
</tr>
<tr>
<td>Q</td>
<td>volumetric longshore sediment transport rate</td>
<td>m³ s⁻¹</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>t_{we}</td>
<td>time at passage of the weighted centre of mass</td>
<td>s</td>
</tr>
<tr>
<td>t_i</td>
<td>elapsed time</td>
<td>s</td>
</tr>
<tr>
<td>T</td>
<td>wave period</td>
<td>s</td>
</tr>
<tr>
<td>u</td>
<td>cross-shore current velocity</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>u_m</td>
<td>maximum orbital velocity magnitude</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>v_a</td>
<td>longshore advection velocity</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>v_l</td>
<td>longshore current velocity</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>w</td>
<td>wind speed</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>w_s</td>
<td>settling velocity of sediment</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>ΔW</td>
<td>width through which transport takes place</td>
<td>m</td>
</tr>
<tr>
<td>x</td>
<td>cross-shore coordinate</td>
<td>m</td>
</tr>
<tr>
<td>y</td>
<td>longshore coordinate</td>
<td>m</td>
</tr>
<tr>
<td>Y_{wc}</td>
<td>location of centroid of tracer cloud</td>
<td>m</td>
</tr>
<tr>
<td>z</td>
<td>elevation above the bed</td>
<td>m</td>
</tr>
<tr>
<td>α</td>
<td>empirical decay coefficient</td>
<td>-</td>
</tr>
<tr>
<td>α</td>
<td>angle between wave crest and the shoreline</td>
<td>deg</td>
</tr>
<tr>
<td>tan β</td>
<td>slope of the intertidal beach</td>
<td>-</td>
</tr>
<tr>
<td>ε</td>
<td>surf-scaling parameter</td>
<td>-</td>
</tr>
<tr>
<td>γ</td>
<td>wave breaker index</td>
<td>-</td>
</tr>
<tr>
<td>ρ</td>
<td>mass density of seawater (= 1025)</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>ρ_s</td>
<td>mass density of quartz sand (= 2650)</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>ω</td>
<td>radian frequency</td>
<td>s⁻¹</td>
</tr>
<tr>
<td>ξ_b</td>
<td>Iribarren number</td>
<td>-</td>
</tr>
<tr>
<td>Ψ_b</td>
<td>Shields parameter at breaker line</td>
<td>-</td>
</tr>
<tr>
<td>Ψ_c</td>
<td>critical Shields parameter of oscillatory flow</td>
<td>-</td>
</tr>
</tbody>
</table>
Subscripts

- $b$: breaking wave conditions
- $\text{sig}$: significant
- $\text{rms}$: root-mean-square
- $\text{m}$: mean
- $\text{swell}$: swell waves
- $\text{wind}$: wind waves
- $\text{incident}$: incident waves
CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

At its most basic level, the breaking action of waves in the littoral zone combines with nearshore currents to transport beach sediments. The littoral zone is the area that extends from the shoreline to just beyond the most seaward breaking waves. Sometimes, sediment transport results only in a local rearrangement of sand, for example into bars and troughs, or into a series of rhythmic embayments cut into the beach. At other times there are extensive longshore displacements of sediments, possibly moving hundreds of thousands of cubic metres of sand along the coast each year. This longshore movement of sediment is referred to as littoral transport or longshore sediment transport, whereas the actual volume of sand involved in the transport is termed the littoral drift (Komar, 1998).

Longshore transport rates and directions are of fundamental importance to shoreline change and coastal evolution. An increase in the rate of sediment transport along a coast can only be maintained by the progressive removal of sediment from the beach, resulting in coastal erosion. Similarly, decreasing littoral drift rates along a coast indicate coastal accretion. The longshore movement of beach sediment is of particular importance in that the transport can either be interrupted by the construction of jetties and breakwaters (structures which block all or a portion of the longshore sediment transport), or can be captured by inlets and submarine canyons. The impacts may pose problems to adjacent beach communities, as well as threaten the usefulness of nearby navigable waterways (channels, harbours, etc.).

Accordingly, the understanding of longshore sediment transport processes is of crucial importance for the management and maintenance of the coastline. Attempts to maintain beaches by the building of coastal structures, or the establishment of beach nourishment schemes, rely on the accurate prediction of the littoral drift. Not surprisingly, numerous equations are available to predict the littoral drift from environmental parameters such as wave height, period and direction, sediment grain size and beach gradient. One of the main endeavours in nearshore research over the past four decades has been to collect data on longshore sediment transport rates, in order to calibrate these transport equations.
The large number of available transport equations does not, however, reflect our understanding of the processes controlling longshore sediment transport. A major point of criticism is that most equations are 'black box' models that do not take into account the wide range of processes and conditions under which littoral drift occurs. Another aspect of uncertainty is the relative contribution of bedload and suspended load to the total littoral drift. Many coastal researchers assume \textit{a priori} that suspended load is the dominant mode and continue to calibrate total load equations with suspended load measurements (e.g., Wang \textit{et al.}, 1998).

Reviews of data on longshore transport have concluded that there are large uncertainties regarding the distribution of sediment movement across the surf zone (Bodge, 1989). Further uncertainty arises from the contribution of swash processes to the total littoral drift. Longshore sediment transport by swash processes is often not considered in field measurements and this may result in an under-representation of measured littoral drift rates. Since the relative importance of swash versus surf zone processes increases as the wave energy level decreases, this shortcoming becomes particularly relevant for low-energy beach environments (significant wave height smaller than 1 m). Indeed, recent field studies by Ciavola \textit{et al.} (1997a) have demonstrated that under low energy wave conditions, measured littoral drift rates far exceed those predicted by conventional littoral drift equations.

1.2 EXPERIMENTAL MEASUREMENT OF LONGSHORE TRANSPORT

Several techniques are available to measure rates of longshore sediment transport. The total longshore sediment transport can be measured using impoundment studies or tracer sand. Other techniques are available for research into the movement of quantities in suspension or bedload transport. Techniques used to measure suspended sediment transport include water pumps, streamer traps and sensors (e.g., optical backscatter sensors), while the only device available to measure bedload transport is the bedload trap.

The different techniques are all characterised by specific temporal and spatial measurement scales (Figure 1.1). The spatial scale indicates the size of the area of measurement, for example, when using a backscatter sensor the suspended sediment
concentration is determined at a centimetre size area, while during an impoundment study hundreds of meters of beach are surveyed to determine the morphological change. The temporal scale is an indicator for the time it takes to complete the measurement, for example, when using tracer, fluorescent sand is released in the littoral zone and after a couple of hours samples are taken to monitor its movement. The techniques that measure on a larger spatial scale take a longer time to complete and thus operate on a larger temporal scale. The techniques characterised by the largest scales are those that measure the total load transport, these represent the impoundment and tracer studies. The other techniques account for suspension or bedload transport only.

![Figure 1.1: Definition of spatial and temporal scales involved in longshore transport measurement techniques.](image)

**1.3 Objectives**

The aim of this project is to gain a better understanding of the processes involved in longshore sediment transport on low-energy beaches. Transport data across the littoral zone of several low-energy beaches will be obtained over a range of spatial and temporal scales. The unique approach is the use of a combination of techniques, which will partly
overcome the shortcomings associated with each separate technique. The littoral drift will be measured on four scales (Figure 1.1), being:

- instantaneous, using arrays of high-frequency sensors spanning the littoral zone;
- interval of minutes, using arrays of streamer traps;
- during a two-hour period using tracer techniques; and
- weekly, using the impoundment method.

This combined data-set will enable a set of defined objectives to be addressed. These objectives are to:

- determine the relative contributions of bedload and suspended load to the littoral drift, by comparing transport estimates obtained using tracer sand (total load) with those obtained from streamer traps and nearshore instruments (suspended load);
- investigate the cross-shore variation in littoral drift rate, using data obtained from the different methods used;
- determine the contribution of swash processes to the total littoral drift under low-energy wave conditions;
- analyse the applicability of conventional transport equations to predict littoral drift rates on low-energy beaches.

1.4 APPROACH

The ideal 'natural laboratory' for this project would have a predictable, consistent occurrence of longshore sand transport events, a straight shoreline and an undisrupted continuous supply of sand. Additionally, during these transport events the environmental conditions, such as water level, beach profile, wave characteristics and meteorological conditions should remain stable.

These conditions are met along the Perth metropolitan coastline, Western Australia. The tidal range is limited (microtidal) and the arrival of strong sea breezes with a predominantly longshore component is consistent (Masselink and Pattiaratchi, 2001a). The sea breezes generate energetic obliquely-incident wind waves, strong longshore currents and large littoral drift rates (Masselink and Pattiaratchi, 1998a). Despite the strong longshore velocities generated by the sea breeze (velocities > 0.5 m/s), the wind waves are relatively small (significant wave height <1 m), and the beach may be classified as low-energy. When the sea breeze is not blowing, quiescent conditions
prevail. The sea breezes therefore drive punctuated littoral drift events alternated with periods of insignificant longshore transport. These conditions are ideal for the investigation of longshore transport processes.

In this study, longshore sediment transport was investigated on time scales ranging from seconds to weeks, for various low-energy sandy beaches. Data were recorded at five different beaches in the period 2000–2002, using four different methodologies. On the smallest scale a large number of sensors was deployed in an array across the littoral zone. These pressure sensors, bi-directional flow meters and optical backscatter sensors were positioned in the lower swash zone, surf zone and breaker zone of one beach. The second, also small-scale methodology, was used on the same beach. It was characterised by the placement of vertical arrays of portable streamer traps along the cross-shore profile. Ten measurements at 30-minute intervals were completed. On a medium scale, four tracer experiments were conducted using fluorescent sand. The first of these experiments took place on the same beach as the previous two methodologies, as well as on three other beaches. At the largest scale, the accumulation of sediment in front of a groyne field was monitored on a weekly basis for a period of five months to obtain long-term littoral drift data.

1.5 OUTLINE OF THE THESIS
The outline of this thesis is as follows.

In Chapter 2 a literature review on longshore sediment transport is presented. An overview is given of the present knowledge of longshore sediment transport, the different measurement techniques are described and a review of longshore sediment transport data is given. Furthermore, some transport models are discussed.

Chapter 3 gives an introduction to the study area and the methodologies used. A morphological and hydrodynamic description of the coastline of southwestern Australia is given. Special attention is paid to the environmental conditions of the study area. The general approach to measurement and methods of data acquisition are described. More in-depth discussion of the methodologies can be found be at the start of the following three chapters.
Chapter 1: Introduction

Chapters 4–6 focus upon the results of studies at three different spatial and temporal scales. Each chapter starts with an explanation of the theoretical background and methodology, followed by a presentation of the results and a discussion of the research objectives.

The results of large-scale longshore transport measurements are discussed in Chapter 4. Littoral drift rates were measured on a weekly basis during an impoundment study. The results are compared with wind conditions, wave parameters and littoral drift rates as estimated using three different transport equations.

In Chapter 5 the focus is on studies undertaken using fluorescent tracer, this is the medium scale measurement technique. In Part A, tracer theories and previous experiments are discussed. Part B focuses on the four tracer experiments conducted at different low-energy beaches. Both the Spatial Integration Method and the Temporal Integration Method are used to estimate the cross-shore distribution of the mixing depth, tracer advection velocities and longshore transport rates.

In Chapter 6 field data are used to determine the longshore transport on small spatial and temporal scales. More specifically, the suspended transport was determined using high-frequency sensors and streamer traps in a cross-shore array spanning the littoral zone. These measurements were combined to obtain a time series of suspended longshore sediment transport.

In Chapter 7 the different transport measurements and estimates are combined and compared with the findings of previous studies. This chapter is based on the information in the literature review and the process knowledge collected in Chapters 4, 5 and 6. Suggestions for future research are considered.

In the final chapter, Chapter 8, a summary of the major findings of the thesis is given.
CHAPTER 2: LONGSHORE SEDIMENT TRANSPORT -
A LITERATURE REVIEW

2.1 INTRODUCTION

The longshore transport of sediments is among the most important of the nearshore processes that control beach morphology, and largely determines whether a shoreline erodes, accretes, or remains stable. An understanding of coastal evolution requires at least a qualitative knowledge of beach sand transport. Accurate transport measurements are an indispensable part of the design and planning of coastal protection schemes as well as allowing the estimation of the environmental impact of structures and beach nourishment schemes.

Longshore transport volumes can be determined through direct measurement in the field or through the application of sediment transport models. Both methods have limitations and there is no independent measure of the accuracy of the calculated volumes. Pilkey and Cooper (2002) even concluded that the methods themselves are unsound and that a fundamental re-examination of both approaches is in order.

Other aspects of uncertainty are the relative roles of bedload and suspended load to the total littoral drift, the distribution of sediment movement across the surf zone and the contribution of swash transport to the total littoral drift. This shortcoming is particularly relevant for low-energy beach environments, since the relative importance of swash versus surf zone processes increases as the wave height and thus energy level decreases. Indeed, field studies by Ciavola et al. (1997b) and Nordstrom et al. (2003) have demonstrated that under low-energy conditions conventional littoral drift equations under-predict longshore transport rates.

This chapter defines the terms associated with the longshore transport of littoral material and discusses the different methods of measuring longshore sand transport in the field. This is followed by an overview of factors influencing littoral drift and a discussion of factors of concern, notably; bedload versus suspended load and the cross-shore distribution of longshore transport rates. Finally the development and application of a selection of transport models will be discussed.
2.1.1 Definitions

Littoral drift is the motion of the sediment (usually sand) in the littoral zone by the action of waves and currents. The littoral zone is the area where longshore transport takes place, bounded at the seaward side by the location where large waves begin to move bottom sediment and at the landward side by the swash runup limit.

Theoretically the total sediment transport is composed of two modes of transport:

- **suspended sediment transport**, in which sediment is carried above the bottom by turbulent eddies of water, supported by fluid-to-grain forces, and
- **bedload transport**, in which sediment moves close to the bed by rolling, sliding and colliding, supported by grain-to-grain or inter-granular forces (Nielsen, 1992; van Rijn, 1984a).

Saltating grains in water may be supported by a combination of grain-to-grain and fluid-to-grain forces, but they are usually considered as bedload because of their proximity, that of a few grain diameters, to the bed (Hanes, 1988).

The rate at which sediment is moved parallel to the shoreline is the longshore transport rate. Since this movement is parallel to the shoreline, there are two possible directions of motion, right or left, relative to an observer standing on the shore looking out to sea. **Gross longshore transport rate** is the sum of the amounts of littoral drift transported to the right and to the left, past a point on the shoreline during a given time period (Galvin, 1972). **Net longshore transport rate** is defined as the difference between the amounts of littoral drift transported to the right and to the left past a point on the shoreline in a given time period (CERC, 2002).

In engineering applications, the longshore sediment transport rate is expressed as the **volume transport**, $Q_t$ per time, having units such as cubic metres per day or cubic yards per year. This is the total volume that would be measured by a survey, for example impoundment at a jetty, and includes the generally accepted estimate of a 40% void space between the particles as well as the 60% solid grains. For computations of theoretical transport rates the littoral drift can also be expressed as **immersed-weight** (dry weight minus buoyancy) sediment transport rates, $I$, which is given in units of force per
unit time, such as Newton per second. With $Q_t$ expressed in m$^3$ s$^{-1}$ and $I_t$ in N s$^{-1}$, these two often-used measures of sediment transport are related as:

$$I_t = (\rho_s - \rho) g (1 - p) Q_t$$

(2.1)

And

$$Q_t = \frac{I_t}{(\rho_s - \rho) g (1 - p)}$$

(2.2)

where $\rho_s = \text{the mass density of the sediment grains (kg m}^{-3}\text{);} \; \rho = \text{the mass density of seawater (kg m}^{-3}\text{);} \; g = \text{acceleration due to gravity (9.8 m s}^{-2}\text{);} \; \text{and } p = \text{the sediment porosity}. \text{The parameter } p \text{ is a pore-space factor such that } (1 - p) Q_t \text{ is the volume transport of solids alone. Commonly used values for the parameters } \rho_s, \rho \text{ and } p \text{ are respectively } 2650 \text{ kg m}^{-3}, 1025 \text{ kg m}^{-3} \text{ and } 0.4. \text{ If site-specific estimates are known, they should be used in Equations 2.1 and 2.2.}

The term potential sediment transport rate is used in transport modelling. The amount of transported sand is calculated assuming sediment is available in unlimited quantities and coastal structures (such as groynes, jetties, breakwaters, submarine canyons, etc.) do not slow down or obstruct transport of sediment in an alongshore direction. The actual sediment transport rate can be smaller than the calculated potential rate.

2.2 EXPERIMENTAL MEASUREMENT OF LONGSHORE TRANSPORT

Accurate and reliable measurements of longshore sediment transport are necessary to increase knowledge of transport processes and to develop better predictive tools to quantify transport rates. The net and gross longshore sediment transport rates are probably the most important factors (and largest unknowns) in the design of any structure that substantially impedes the movement of sediment along a coast (White, 1998).
Several methods exist for measuring coastal sediment transport in the field (Figure 1.1). Each measurement technique has different characteristics, such as:

- mode of transport measured; either total load, suspended load, or bedload transport;
- direct transport measurement or indirect using a combination of sediment concentration and current velocity measurements;
- temporal scale; ranging from fractions of a second to months;
- spatial scale; from millimetres to kilometres.

The characteristics of the methods stated in Figure 1.1 will be discussed in the following sections. Furthermore, an overview is given of the field measurements of longshore transport available in the literature (Table 2.1). The table is adapted from research by Schoonees and Theron (1993) who compiled and reviewed almost all the available field data on longshore transport as recorded up to 1993. The table has been updated and includes the method of estimating sediment transport, location of the field site and the number of data points collected. Unfortunately, for some field studies not all information was available in the literature, as indicated by ‘not described’ in the table.

2.2.1 Impoundment method

The impoundment method can be used when the alongshore movement of sediment is impeded. This impediment may be natural, for example a spit or an inlet, or it can be caused by man-made coastal structures, for instance a jetty, a breakwater or a deposition basin. The amount of impeded sediment can be determined by repeatedly surveying the accreted or eroded area, where the volume changes of the littoral zone are a direct indication of the total longshore transport rates. Another method involves measuring the amount of material that is pumped past engineering structures when dredging the accreted area. The measurement frequency is typically hours to weeks, depending on the amount of transported sediment and the size of the area affected by the structure. The spatial scale usually ranges from tens to hundreds of metres (Figure 1.1). The measured transport rates are correlated with the appropriate wave characteristics, which are integrated over the temporal sampling interval of the impoundment study.

The earliest measurements were based on quantities of sediments blocked by jetties or other engineering structures (e.g. Watts, 1953a; Caldwell, 1956; and Moore and Cole,
1960; refer to Table 2.1). More recently, temporary structures have been built for measuring longshore sediment transport (e.g. Wang and Kraus, 1999).

The primary advantage of an impoundment experiment is the potential to accumulate large, and therefore easy to measure, quantities of sediment. With a measurement interval of days to weeks, the sediment is trapped over a significant period of time and the measured volumes can be quite large, which limits the percentage error in the transport estimates. Measurements can be done using an ordinary theodolite and staff, so no specialist equipment is needed. The method results in the direct measurement of the total transport rate, even including high energetic storm conditions. This is important since the largest transport rates occur during storms.

Major potential drawbacks of the impoundment method result from the temporal and spatial averaging or smoothing of the data. This method is not ideally suited for resolving spatial and temporal distributions of sediment transport. Furthermore, the hydrodynamic conditions change during the recording interval, and thus in order to relate the measured transport rates to the forcing hydrodynamic conditions, the constantly changing waves and currents need to be reduced to some sort of average over the temporal scale of the impoundment measurements.

Survey inaccuracies can have a major effect on the calculated longshore transport rate. The inaccuracies most often manifest as a failure for consecutive surveys to 'close' at the seaward or updrift edge of the survey area. In an order-of-magnitude examination of this error, Bodge and Kraus (1991) gave the following example: in a survey area which is 2000 m alongshore by 300 m offshore, a vertical datum or closure error of only 3 cm would yield an 18000 cubic meter error. This could be similar to a total net drift rate for an experiment on a moderate energy beach over a 6-week interval.

Other disadvantages are the impoundment of sand not related to longshore processes, for example, the local effects of the structures on waves and currents, diffraction currents leeward of a structure, the possibility of sediment by-passing the structures and unaccounted drift reversals. These spurious signals are difficult to isolate.
2.2.2 Tracer sand

Another method of directly measuring the total load is by using tracer sand. Measurement of sand tracer transport rates involves tagging the natural beach sediment with a coating of fluorescent dye or low-level radioactivity. Tracer grains are released in the surf zone to be later partially recovered, scattered in a downdrift direction. The longshore displacement of the centre of mass of the tracer on the beach between injection and sampling provides a measure of the mean transport distance. The sand advection velocity is obtained by dividing this distance by the elapsed time. The sediment transport rate is then given by the product of advection velocity, tracer mixing depth and the width of the zone of longshore transport (e.g. Inman et al., 1980; and Madsen, 1989). The time between tracer injection and sampling can range from minutes to a few hours, during which the tracer can cover distances in excess of a hundred metres (Figure 1.1).

Numerous studies have used sand tracers to determine sand transport rates (e.g. Komar and Inman, 1970; Knoth and Nummedal, 1977; Duane and James, 1980; Inman et al., 1980; and Kraus et al., 1982; refer to Table 2.1). Table 2.1 shows that while the use of radioactive tracer was predominant during the early years of transport measurement, it has largely been replaced by fluorescent tracer in more recent studies, as fluorescent dyes and paints are easier to use and safer for the environment.

The measurement is essentially the instantaneous longshore sand transport under a fixed set of wave conditions. This technique, therefore, provides data that are particularly suitable for correlations with hydrodynamic indicators, such as wave characteristics and longshore currents. These correlations can be used in time-dependent numerical models of longshore transport rates and beach change.

When using several fluorescent tracer colours simultaneously, cross-shore changes in mixing depth, advection velocity, transport rate and direction can be differentiated. The use of different tracer colours for different grain sizes allows the transport mechanisms to be related to particle size.

Additionally, a single tracer injection allows the calculation of several transport rates, for example samples taken in a longshore grid one and two hours after tracer injection allow two transport estimates (Spatial Integration Method). These can also be combined with the monitored passing of the tracer cloud along one cross-shore line (Temporal
Integration Method) (methodologies will be explained in Section 5A.2.2). The different transport estimates should all be similar, and form a useful check of the reliability of the method.

However, the use of tracer does have some disadvantages. Recently injected sand needs an undetermined period of time to enter equilibrium state and mix with the ambient bed. As a result, tracer might initially travel faster than native sand and samples taken at the start of the experiment might suggest an unreliably high transport rate. Ideally the weighted center of mass from a subsequent sampling is referred back to the first sampling, and not to the position of the tracer injection.

Another issue is that the identification of the appropriate sediment mixing depth limits the quantitative accuracy of the technique, because the transport rate is directly proportional to this mixing depth. The most widely used method is to compute mixing depth from the tracer concentration profiles in core samples that extend to the depth of burial of the tracer sand. However, there is no widely accepted definition of the mixing depth and the various existing techniques are not directly comparable.

Tracer experiments must be carried out during periods of relatively stable beach conditions. If the beach is in a phase of erosion or accretion, there is the possibility that portions of the tracer could be completely lost due to burial or a yield a false indication of mixing depth through local erosion or accretion. In addition, tracer experiments are limited to low-energy conditions, as the field crew needs to be in the water to retrieve the samples. The experiments are very labour-intensive in that they require a large field crew and the manual counting of grains requires considerable time.

2.2.3 Pump samplers

When using pump samplers, sampling nozzles mounted on pipes, piers or sleds are put in the surf zone, and samples are pumped into settling buckets for weighing (e.g. Watts 1953b; and Fairchild 1972, 1977; refer to Table 2.1). These measurements provide estimates of time-averaged sediment concentrations at discrete heights above the bed (Das, 1972). The concentrations, combined with simultaneous measurements of mean longshore current velocities, yield indirect estimates of the suspended sediment transport rate. The measurement frequency is typically seconds to minutes, depending on the pump
capacity and suspended sediment concentration. The spatial scale usually ranges from decimetres to metres (Figure 1.1).

An advantage of this technique is that samples can be taken at different heights above the bed and across the nearshore zone, yielding information on the vertical concentration profile of suspended sediment and the cross-shore concentration distribution.

Additionally, large sample quantities can be processed, leading to some confidence that the samples are representative of sediment concentrations found in the surf zone. The sediments recovered can also be used for grain size analysis, allowing further insight into the transport process.

The major disadvantage of this technique is that in order to take the sample, the sampling equipment itself must be positioned within, or upon, a structure that is within the body of water itself, disrupting the ambient transport conditions that would otherwise have prevailed. Accordingly, this technique is often undertaken from a pier or other existing structure, and its applicability to other locations can be limited. In addition, the sampling equipment itself is both expensive and difficult to move, rendering it most applicable to large-scale studies.

Other disadvantages of this technique include that one cannot investigate time variations in sediment concentrations during different phases of wave motion, and that there is no direct transport measurement, rather the sample results in only a concentration. To convert this into a transport estimate, measurement of the fluid velocity at the sampling point is also required.

Finally, the sampling efficiency of this technique is a point of discussion. Close to the bed, scouring (the artificial erosion of the bed) can be expected around the nozzle mouth. The nozzle mouth might also disturb the flow field and sediment transport around the mouth. Bosman et al. (1987) used suction samplers under uni-directional, steady flow conditions and measured a sampling efficiency ranging from 0.69 up to 0.80 %. Coastal zone measurements were only compared relatively and no sampling efficiencies were derived.
2.2.4 Sediment traps

Three types of sediment traps will be discussed below: bulk water-column traps, bedload traps and streamer traps. The three methodologies are all characterised by a spatial scale of millimetres to decimetres, and a temporal scale ranging from seconds to minutes.

2.2.4.1 Bulk water-column traps

A bulk water-column trap consists of a vertical array of spring-loaded tubes (Zampol and Waldorf, 1989). Each compartment captures the water column and its entrained sediment, from which the suspended sediment concentration can be derived (e.g. Kana, 1976 cited in White, 1998; and Inman et al., 1980; refer to Table 2.1). When combined with velocity measurements from current meters, the vertical profile of suspended-load transport rates is produced.

One advantage of this technique is that the trap can be positioned at various locations across the surf zone to investigate the cross-shore distribution of suspended transport rate. The mechanism can be triggered when either a wave crest or trough passes, and thus the transport rate can be related to different wave phases. Another advantage of using such a vertical array of traps is that the sand samples can also be used to determine grain size distribution of suspended sediment over the water column.

Disadvantages of this method include the need for a number of traps in an array to be positioned within the sample zones. These will disrupt the ambient transport conditions. Additionally, once again it is necessary to undertake a separate velocity measurement. The technique is also limited in scope, as it requires the entire sampling apparatus to be removed from the in situ sampling location, emptied, cleaned and repositioned before a second set of samples can be taken. This positioning is time consuming, and by the time the entire array is in place the conditions within the surf zone may have changed, preventing the results from being easily comparable. The method is limited to low-energy conditions, since the field crew needs to physically be in the water to deploy the sediment traps.

2.2.4.2 Bedload traps

The only method presently available for direct measurement of bedload transport is that of bedload traps. These are bins which are open-ended or dug into the seabed into which the bedload transport is to settle. The bedload transport rate is calculated from the
amount of collected sediment, the size of the bin opening and the duration of deployment. An example of a study using this method is Chadwick (1989) (Table 2.1).

However, the dynamics of this very thin layer of moving sediment are likely to be significantly altered by the presence of instrumentation. As a result there are questions as to sampling efficiency when used in the nearshore because of the potential for scour (e.g. Thornton, 1972; Walton et al., 1985; all cited in CERC 2002; Rosati and Kraus 1989.) Up to date, reliable and accurate bedload measurements in the field are unfeasible. It should be noted that bedload traps could be more effectively used in the controlled conditions of a laboratory experiment in a wave basin, where the traps can be located at the downdrift side of the basin.

2.2.4.3 Streamer traps

A streamer trap is made of a nozzle mouth attached to a bag of sieve cloth, which collects sediment but allows water to pass through. The sediment transport rate can be directly determined from the weight of collected sediment, the size of the nozzle mouth and the duration of deployment. Vertical arrays of streamer traps attached to portable racks can be used to measure transport rates at several distances above the bed. These short-term point measurements of the longshore transport can be directly related to the waves and currents that caused the sediment movements and the characteristics of the local bottom material and beach morphology.

When simultaneously deploying several racks of streamer traps, the spatial variation in longshore transport both across the surf zone and over the water column can be determined (e.g. Inman et al. 1980; and Kraus et al., 1989; refer to Table 2.1). In this way, changes in the beach morphology can be related to the imposed hydraulic forces. Additionally, knowledge of the spatial distribution of the longshore transport rate can assist in the design process for structures, which may intercept sand transported alongshore. Summation of the distributions through the water column and across the surf zone yields an estimate of the total littoral transport rate.

There is some discussion as to which mode of transport is measured by a vertical array of streamer traps. Several authors assume a vertical array of streamers can measure both bedload and suspended load transport, as during deployment the bottom-most trap mouth is situated at bed level capturing sand transported primarily along the bed, while the
remaining traps capture the suspended sediment movement (Kraus, 1987; and Allen, 1985).

This division between sediment transport modes is however based upon trap design rather than the underlying physics. For example, in the streamer trap design of Kraus, the nozzle mouths are 9 cm high and will clearly be expected to capture both bedload and suspended load and not just the suspended fraction. Accordingly, the results of a streamer trap deployment cannot be used to estimate both bedload and suspended load transport rate, but rather yield either the total transport rate, with the bottom-most trap deployed at bed level, or the suspended sediment transport rate, with the bottom-most trap deployed a small distance above the bed.

A major advantage of the streamer trap method is the direct measurement of the transport rate, without the need to measure current velocities near the site of trap deployment. Furthermore, the traps are easy and flexible with regard to their deployment and appear to be a good technique to examine the distribution of sediment transport across the surf zone. Another advantage is the possibility of examining transport over short time spans (minutes) during which the wave characteristics are essentially constant. Streamer traps are inexpensive to construct, maintain and store and the trapped sediment remains available for further analysis.

One disadvantage of streamer traps is that their use is limited to quasi-steady flows during low energy conditions and operators need to remain to attend the traps to monitor the deployment and prevent any tangling and twisting of the bags. As the traps must be emptied long before they fill, the deployment time is a few minutes, after which the streamer traps need to be removed from the surf zone, emptied and cleaned before the next deployment is possible. Hence, continuous monitoring of the transport rate is unworkable. Streamer traps can only be deployed where grains are sand-sized.

Another principle problem is that bed disturbance or scour around the bottom nozzle mouth and the supporting structure can cause the practical difficulty of keeping a trap nozzle level with the bed during streamer trap deployment. Scour may produce either an artificially high or low transport rate near the bed. Furthermore, a trap may disturb the flow field resulting in either acceleration or deceleration of the local flow, leading,
respectively, to an apparent increase or decrease in measured transport rate. These disturbances are referred to as trap efficiency (Kraus, 1987).

Rosati and Kraus (1988, 1989) performed laboratory experiments to determine the hydraulic and sand-trapping efficiencies for a variety of nozzle mouth configurations. It was noted that efficiency depends on location in the water column and nozzle type, with low efficiency at bed level but near unity efficiency above the bed. Similar tests carried out by CERC (1987) also yielded a hydraulic efficiency close to unity.

It should be noted that in complex fluid structures, such as exist within the surf zone, trap efficiencies remain impracticable to evaluate, and accordingly remain a source of uncertainty (Allen, 1985).

2.2.5 Suspended sediment sensors

The current state-of-the-art method to measure longshore sediment transport is the combined use of optical or acoustic suspended sediment sensors and current meters (e.g., Aagaard and Greenwood, 1994a; Aagaard et al., 1998; Sternberg et al., 1989; and Beach and Sternberg, 1988). An example of such a suspended sediment sensor is the optical backscatter sensor (OBS), which emits light and measures the reflected amount, which can be related to the sediment concentration. The flux of suspended sediment is estimated by assuming that the horizontal velocity of the suspended sediment at each elevation is equal to the horizontal fluid velocity measured by a current meter, for example, an electromagnetic current meter (EMCM). In this way the indirect estimation of longshore transport rates is possible. The sensors record the suspended sediment concentration at a centimetre size location at frequencies around fractions of seconds (Figure 1.1).

This technique allows the continuous measurement of instantaneous sediment transport rates that provide the means to partition the total suspended load into mean and fluctuating components (Jaffe et al., 1984). Deployment of a large number of suspended sediment sensors together with current meters allows the investigation of the vertical and cross-shore distribution of the longshore transport rate. An integration of these results over the water column and across the surf zone can be used to obtain the total suspended longshore transport across the surf zone. A major advantage of these sensors is that results can be obtained during high-energy conditions. However, the sensors can only
record the suspended load transport and cannot be mounted too close to the bed where sediment concentrations are potentially the highest (Aagaard et al., 1997).

Suspended sediment sensors might sample on a small spatial scale, but they need a prodigious array of equipment during deployment in the field, for example a frame to mount the instruments on, batteries and a data logger. Technical support is needed in order to deploy the instruments and to analyse the recorded data. As a result these sensors are expensive to employ.

Practically, it is difficult to deploy the sensors in the swash zone, since repeated drying and wetting of the sensors results in measuring spikes. A further source of potential error is that bed level changes will place the sensors closer to, or further from the bed, causing uncertainty about the vertical position of the sensors. It is unfeasible to quantify the degree of error in the measured transport rates associated with these bed elevation changes. During data collection an effort must be made to maintain the instrument elevations at the original levels, by regularly checking the sensors and adjusting the vertical position. Since these adjustments cannot be practically undertaken in the dark, reliable suspended sediment data can only be collected during daylight hours.

The most serious shortcoming of this technique is the need to calibrate the optical sensors using native sediment. The sediment is usually collected from the bed at the location of OBS deployment, but textural segregation within the water column and between the bed sediment and the suspended sediment is a source of error (Aagaard et al., 1997). The practical calibration is also prone to errors. This is usually done in the laboratory by stirring known concentrations of sediment in a container of water, while the sensor is immersed and measuring. Unfortunately, the sediment settles out too rapidly for high concentrations to reliably be kept in suspension. Moreover, the sediment tends to be suspended in 'bursts', making it difficult to obtain a spatially and temporally homogeneous suspension. Butt et al. (2002) investigated a solution to this using a glycerol suspension in place of water, to enable the sand to remain in suspension longer, especially at higher concentrations. This proved partially successful, however it required the sensors to be further calibrated for the glycerol. Furthermore, the calibration of these sensors in the laboratory is of limited value if the particle size distribution in the field varies in space and time (Agrawal and Pottsmith, 2000).
<table>
<thead>
<tr>
<th>Reference(s)</th>
<th>Location</th>
<th>No. of points</th>
<th>Transport measured by</th>
<th>Wave height and period measured by</th>
<th>Wave angle measured by</th>
<th>Survey method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watts (1953)</td>
<td>South Lake Worth Inlet, Florida</td>
<td>4</td>
<td>deposition at jetty &amp; pumping rate</td>
<td>staff gauge, pressure wave recorder</td>
<td>sighting bar &amp; auxiliary sights</td>
<td>not described</td>
</tr>
<tr>
<td>Caldwell (1956)</td>
<td>Anaheim Bay, California</td>
<td>6</td>
<td>profile changes of beach fill</td>
<td>hindcasting &amp; step, float gauge, photographs</td>
<td>hindcasting &amp; aerial photographs</td>
<td>hydro + topo echo sounder</td>
</tr>
<tr>
<td>Ishihara et al. (1958)*</td>
<td>North Akashi, Japan</td>
<td>10</td>
<td>accretion at temporary groyne</td>
<td>wind analysis</td>
<td>wind analysis</td>
<td>soundings</td>
</tr>
<tr>
<td>Ishihara et al. (1958)*</td>
<td>Miyazu, Japan</td>
<td>7</td>
<td>accretion at temporary groyne</td>
<td>wind analysis</td>
<td>wind analysis</td>
<td>soundings</td>
</tr>
<tr>
<td>Adachi et al. (1959)*</td>
<td>Miyazu, Japan</td>
<td>8</td>
<td>accretion at offshore breakwater</td>
<td>estimated wind analysis</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Moore and Cole (1960)</td>
<td>Cape Thompson, Alaska</td>
<td>1</td>
<td>growth of a spit (during 3-hour period)</td>
<td>visual estimate</td>
<td>visual estimate</td>
<td>plane table survey</td>
</tr>
<tr>
<td>Sato (1962)*</td>
<td>Fukue, Atsumie, Japan</td>
<td>5</td>
<td>accretion at breakwater</td>
<td>pressure gauge</td>
<td>wind analysis</td>
<td>not described</td>
</tr>
<tr>
<td>Siretyol (1964)*</td>
<td>Cotonou, Benin</td>
<td>1</td>
<td>accretion at breakwater</td>
<td>not described</td>
<td>visual estimate</td>
<td>air photo analysis</td>
</tr>
<tr>
<td>Castanho (1966)*</td>
<td>Lobito, Angola</td>
<td>2</td>
<td>accretion at breakwater &amp; spit</td>
<td>not described</td>
<td>calculated</td>
<td>not described</td>
</tr>
<tr>
<td>Sato and Tanaka (1966)*</td>
<td>Port Kashima, Japan</td>
<td>2</td>
<td>accretion at breakwater</td>
<td>pressure gauge</td>
<td>visual observed</td>
<td>echo-sounder, rod &amp; level</td>
</tr>
<tr>
<td>Ingle (1966)</td>
<td>several beaches, California</td>
<td>-</td>
<td>fluorescent tracer</td>
<td>graduated pole, stopwatch</td>
<td>visual observed</td>
<td>stake &amp; horizon technique</td>
</tr>
<tr>
<td>Bijker (1968)*</td>
<td>Ivory Coast, Abidjan</td>
<td>1</td>
<td>estimated</td>
<td>assumed estimated</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Boon (1969)</td>
<td>Virginia Beach, Virginia</td>
<td>1</td>
<td>tracer</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
</tbody>
</table>

Table 2.1: Field data sources of longshore transport rates. Adapted from Schoonees and Theron (1993).
<table>
<thead>
<tr>
<th>Reference(s)</th>
<th>Location</th>
<th>No. of points by</th>
<th>Transport measured by</th>
<th>Wave height and period measured by</th>
<th>Wave angle measured by</th>
<th>Survey method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Komar and Inman (1970)</td>
<td>Silver Strand Beach, California</td>
<td>4</td>
<td>fluorescent tracer</td>
<td>pressure gauges &amp; dig. wave staffs</td>
<td>visual observed, sensor array</td>
<td>not described</td>
</tr>
<tr>
<td>Komar and Inman (1970)</td>
<td>El Moreno Beach, Mexico</td>
<td>10</td>
<td>fluorescent tracer</td>
<td>pressure gauges &amp; dig. wave staffs</td>
<td>visual observed, sensor array</td>
<td>not described</td>
</tr>
<tr>
<td>Lee (1975)</td>
<td>Lake Michigan</td>
<td>8</td>
<td>sediment traps</td>
<td>hand-held graduated poles</td>
<td>visual observed &amp; photos transit &amp; stadia</td>
<td></td>
</tr>
<tr>
<td>Fairchild (1977)</td>
<td>Ventnor (New Jersey) Nags Head (North Carolina)</td>
<td>2</td>
<td>pump sampler</td>
<td>pressure gauge &amp; staff gauge</td>
<td>not described</td>
<td>profiles &amp; lead lines</td>
</tr>
<tr>
<td>Kana (1977)</td>
<td>Price Inlet, South Carolina</td>
<td>25</td>
<td>sampler</td>
<td>visual observed, staff</td>
<td>visual observed</td>
<td>not described</td>
</tr>
<tr>
<td>Knoth and Nummedal (1977)</td>
<td>North Bull Island, South Carolina</td>
<td>6</td>
<td>fluorescent tracer</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Chang and Wang (1978)<em>, Wang and Chang (1978)</em></td>
<td>Bayside, Santa Rosa Island</td>
<td>35</td>
<td>tracer</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Duane and James (1980)</td>
<td>Point Mugu, California</td>
<td>1</td>
<td>tracer</td>
<td>pressure gauges</td>
<td>visual observed</td>
<td>not described</td>
</tr>
<tr>
<td>Hou et al. (1990)*</td>
<td>Taichung Harbour, Taiwan</td>
<td>4</td>
<td>accretion at breakwater</td>
<td>ultrasonic gauge</td>
<td>wind analysis</td>
<td>profile &amp; bathymetric</td>
</tr>
<tr>
<td>Inman et al. (1980)</td>
<td>Torrey Pines, California</td>
<td>12</td>
<td>tracer &amp; sampler</td>
<td>pressure gauges array, EMCM's &amp; wave staffs</td>
<td>pressure gauges array</td>
<td>not described</td>
</tr>
<tr>
<td>Kana and Ward (1980)*</td>
<td>Duck, North Carolina</td>
<td>2</td>
<td>sampler</td>
<td>pressure gauge</td>
<td>radar &amp; LEO**</td>
<td>not described</td>
</tr>
<tr>
<td>Delorme (1981)*</td>
<td>North &amp; Central Africa</td>
<td>5</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Bruno et al. (1980, 1981)</td>
<td>Channel Islands Harbor, California</td>
<td>7</td>
<td>accretion at offshore breakwater</td>
<td>pressure gauge &amp; LEO**</td>
<td>pressure gauge &amp; LEO**</td>
<td>topo &amp; bathy (fathometer)</td>
</tr>
<tr>
<td>Reference(s)</td>
<td>Location</td>
<td>No. of points</td>
<td>Transport measured by</td>
<td>Wave height and period measured by</td>
<td>Wave angle measured by</td>
<td>Survey method</td>
</tr>
<tr>
<td>--------------</td>
<td>----------</td>
<td>---------------</td>
<td>----------------------</td>
<td>---------------------------------</td>
<td>----------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Gable (1981)<em>, Dean et al. (1982)</em>, Sternberg et al. (1984)</td>
<td>Leadbetter, Santa Barbara, California</td>
<td>9</td>
<td>accretion at breakwater</td>
<td>pressure gauges array</td>
<td>pressure gauge array</td>
<td>rod &amp; level (fathometer)</td>
</tr>
<tr>
<td>Kraus et al. (1982)</td>
<td>Ajigaura, Japan</td>
<td>3</td>
<td>tracer</td>
<td>stereo photos, pressure gauge</td>
<td>stereo pictures &amp; radar images</td>
<td>not described</td>
</tr>
<tr>
<td>Kraus et al. (1982)</td>
<td>Shimokita, Japan</td>
<td>2</td>
<td>tracer</td>
<td>memo-motion camera</td>
<td>stereo pictures &amp; radar images</td>
<td>not described</td>
</tr>
<tr>
<td>Kraus et al. (1982)</td>
<td>Hirono, Japan</td>
<td>2</td>
<td>tracer</td>
<td>memo-motion camera</td>
<td>stereo pictures &amp; radar images</td>
<td>not described</td>
</tr>
<tr>
<td>Kraus et al. (1982)</td>
<td>Oarai, Japan</td>
<td>4</td>
<td>tracer</td>
<td>pressure gauge &amp; memo-motion camera</td>
<td>stereo pictures &amp; radar images</td>
<td>not described</td>
</tr>
<tr>
<td>Mangor et al. (1984)*</td>
<td>Danish North Sea</td>
<td>6</td>
<td>deposition in trap &amp; trench-backfill</td>
<td>waverider &amp; wind analysis</td>
<td>wind analysis</td>
<td>profiles &amp; echosounder</td>
</tr>
<tr>
<td>Kooistra and Kamphuis (1984)*</td>
<td>Pointe Sapin, Canada</td>
<td>2</td>
<td>accretion at offshore breakwater &amp; tracer</td>
<td>pressure gauge</td>
<td>electromagnetic current meter</td>
<td>beach &amp; bathymetric</td>
</tr>
<tr>
<td>Allen (1985)</td>
<td>Sandy Hook, New Jersey</td>
<td>59</td>
<td>portable sediment trap</td>
<td>hand-held staff &amp; stopwatch</td>
<td>mariner's compass sighting</td>
<td>not described</td>
</tr>
<tr>
<td>Bodge (1986)*</td>
<td>Duck, North Carolina</td>
<td>8</td>
<td>accretion at mobile groyne</td>
<td>pressure gauge &amp; visual observed</td>
<td>radar imagery &amp; visual observed</td>
<td>rod, level &amp; transit</td>
</tr>
<tr>
<td>Voitsekhovich (1986)*</td>
<td>Ros., Pri, Kin., Black Sea</td>
<td>39</td>
<td>samples (siphon)</td>
<td>string gauge &amp; poles</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Dean et al. (1987)</td>
<td>Rudee Inlet, Virginia</td>
<td>3</td>
<td>deposition in trap (weir)</td>
<td>pressure gauges array</td>
<td>pressure gauge array</td>
<td>rod, level &amp; soundings</td>
</tr>
<tr>
<td>Hou (1980)*</td>
<td>Lin-Kou, Northwest Taiwan</td>
<td>1</td>
<td>accretion at breakwater</td>
<td>measured</td>
<td>wind analysis</td>
<td>profile &amp; echosounder</td>
</tr>
<tr>
<td>Reference(s)</td>
<td>Location</td>
<td>No. of points by</td>
<td>Transport measured by</td>
<td>Wave height and period measured by</td>
<td>Wave angle measured by</td>
<td>Survey method</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------------</td>
<td>------------------</td>
<td>-------------------------------------</td>
<td>------------------------------------</td>
<td>------------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Laubscher et al. (1989)*</td>
<td>Richards Bay, South Africa</td>
<td>5</td>
<td>deposition in trap &amp; dredging</td>
<td>wavemeter</td>
<td>clinometer &amp; VOS</td>
<td>survey beach &amp; hydro</td>
</tr>
<tr>
<td>Chadwick (1989)*</td>
<td>Shoreham, Sussex, England</td>
<td>7</td>
<td>gravel trap</td>
<td>mes. SEM &amp; visual, pole array</td>
<td>visual, pole array</td>
<td>tache survey &amp; hydrographic</td>
</tr>
<tr>
<td>Nicholls and Wright (1991)*</td>
<td>Castle Spit, Southern England</td>
<td>6</td>
<td>tracer (aluminium)</td>
<td>visual observed</td>
<td>visual observed</td>
<td>beach profiles</td>
</tr>
<tr>
<td>Caviglia et al. (1991)*</td>
<td>Mar del Plata, Argentine</td>
<td>4</td>
<td>accretion at breakwater, dredge</td>
<td>pressure gauge</td>
<td>visual observed</td>
<td>hydrographic</td>
</tr>
<tr>
<td>Ciavola et al. (1996, 1997a, b, 1998, 1999b), Taborda et al. (1999)</td>
<td>Culatra Beach, Portugal</td>
<td>3</td>
<td>fluorescent tracer</td>
<td>pressure transducer</td>
<td>refracted deep water waves &amp; visual observed</td>
<td>theodolite</td>
</tr>
<tr>
<td>Anfuso et al. (1997)</td>
<td>Rota Beach, SW Spain</td>
<td>1</td>
<td>tracer (black and fluorescent)</td>
<td>pole</td>
<td>visual observed</td>
<td>theodolite</td>
</tr>
<tr>
<td>Miller (1998, 1999)</td>
<td>Duck, North Carolina</td>
<td>8</td>
<td>OBS &amp; EMCM</td>
<td>pressure gauge array</td>
<td>pressure gauge array</td>
<td>sonar</td>
</tr>
<tr>
<td>Badr and Lotfy (1999)</td>
<td>Nile Delta, Egypt</td>
<td>6</td>
<td>tracer (fluorescent)</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Munoz-Perez et al. (1999)</td>
<td>Regla Beach, Chipiona, SW Spain</td>
<td>2</td>
<td>tracer</td>
<td>wave gauge</td>
<td>visual observed</td>
<td>not described</td>
</tr>
<tr>
<td>Sanil Kumar et al. (2003)</td>
<td>Arge Beach, India</td>
<td>81</td>
<td>mesh &amp; streamer traps</td>
<td>wave buoy</td>
<td>wave buoy</td>
<td>not described</td>
</tr>
<tr>
<td>Nordstrom et al. (2003)</td>
<td>Fire Island, New York</td>
<td>2</td>
<td>tracer</td>
<td>pressure transducer</td>
<td>current meter &amp; pressure survey at 1 m intervals</td>
<td>current meter &amp; pressure survey at 1 m intervals</td>
</tr>
</tbody>
</table>

* cited in Schoonees and Theron (1993)
** LEO=Littoral Environmental Observations
2.2.6 Utilisation of different measurement techniques

From the aforementioned description of methods available to measure longshore transport in the field, it becomes clear that each method has unique characteristics, enabling researchers to choose a method that fits their specific objectives. For example, if one is interested in the different wave frequency contributions to longshore suspended transport then the use of suspended sediment sensors might be ideal.

Similarly, it might be of interest to investigate the dynamics of landforms at longer time scales, such as a sea breeze event. This is possible by using tracers to track sediment pathways and to estimate time-average patterns of transport. Likewise, it might be of interest to know the net annual volume of longshore sediment transport, yet care should be taken when using shorter term measurements for this purpose since small uncertainties can have a disproportionate effect upon the extrapolated value. This is especially true given that the beach and wave characteristics during the measurement will probably not be broadly representative of the average annual conditions. Bearing in mind that usually a few storms a year contribute to almost all the longshore transport at a site, it is critical to measure longshore transport during such conditions.

Perhaps the greatest weakness in field measurements is the inability to meaningfully measure storm-related transport. The studies of Miller (1998, 1999) are a significant step forward in the direction of storm-related sand transport measurement. Direct measurements of velocities and suspended sediment concentrations were conducted using a sensor insertion system at several cross-shore locations along a pier. The research facility and its measurement technique are unique and this expensive methodology will not be easily repeated at other beaches. At the date of writing, there are no other storm-related transport measurements against which to compare the data of Miller.

Comparing the results of several measuring techniques is complicated by the scale differences (both temporal and spatial) and the mode of transport they account for. For example, streamer trap measurements of suspended load transport during five-minute deployments need to be converted to a total load transport during an hour, in order to compare the results with a sand tracer measurement. The means of aggregating up surf zone sand volumes determined in experiments of a few minutes, hours or days, to a
number encompassing all transport that occurred in a year, remains a huge uncertainty (Pilkey and Cooper, 2002).

However, such comparisons can be informative in a number of ways. For example, the reliability of transport data increases when verified by the use of different methods that result in similar transport rates. In this way Drapeau et al. (1990) used consistent impoundment and tracer data to investigate the accuracy of transport models. In addition, time series analysis of cross-shore and longshore suspended sediment fluxes can help interpret the dispersal of sand tracer. Furthermore, the relative contributions of suspended load and bedload to the total load can be investigated by comparing sediment transport estimates obtained from sand tracer with those derived from streamer traps or suspended sediment sensors.

Only very few investigations have compared estimates for longshore sediment rates obtained using different techniques, and then usually in a rather ad hoc manner (e.g. Rosati et al., 1991; Wang et al., 1998; Ciavola et al., 1999b). In sharp contrast, Inman et al. (1980) conducted simultaneous measurement of the longshore transport using sand tracers and suspended sediment samplers and estimated the ratio of bedload versus suspended load transport.

2.2.7 Laboratory data
The difficulty of studying sediment transport processes on natural beaches has resulted in investigators turning to wave-basin experiments. A typical laboratory experiment involves the generation of waves with an oscillating paddle along one length of a basin, with a sandy beach oriented such that waves break at an angle to the shore. The longshore currents transport sand along the beach. At the downdrift end of the beach the volume of sand is then trapped within a stilling basin. Such a laboratory arrangement permits full control over the experimental conditions, including sediment grain sizes, the heights and periods of the waves, and breaker angles (Komar, 1998).
<table>
<thead>
<tr>
<th>Reference(s)</th>
<th>Location</th>
<th>No. of points</th>
<th>Transport measured by</th>
<th>Wave height and period measured by</th>
<th>Wave angle measured by</th>
<th>Survey method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krumbein (1944)*</td>
<td>University of California, Berkeley</td>
<td>15</td>
<td>rate of feed of material to a hopper</td>
<td>combination point and hook gage</td>
<td>not measured</td>
<td>not described</td>
</tr>
<tr>
<td>Saville (1950)*</td>
<td>University of California, Berkeley</td>
<td>9</td>
<td>weighing device &amp; hopper</td>
<td>not described</td>
<td>vertical photographs</td>
<td>not described</td>
</tr>
<tr>
<td>Shay and Johnson (1951)*</td>
<td>University of California, Berkeley</td>
<td>99</td>
<td>hoppers</td>
<td>point and hook gage</td>
<td>vertical photographs</td>
<td>not described</td>
</tr>
<tr>
<td>Sauvage and Vincent (1954)*</td>
<td>Grenoble, France</td>
<td>17</td>
<td>trap at downdrift end</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Savage (1962)* Fairchild (1970)*</td>
<td>CERC, U.S.</td>
<td>35</td>
<td>sand traps</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Price and Tomlinson (1968)*</td>
<td>Wallingford, England</td>
<td>2</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
<td>not described</td>
</tr>
<tr>
<td>Bodge and Dean (1997)</td>
<td>Gainesville, Florida</td>
<td>5</td>
<td>impoundment</td>
<td>capacitance wave probe</td>
<td>overhead photography</td>
<td>mechanical profiler</td>
</tr>
<tr>
<td>Kamphuis (1991a, b)</td>
<td>not described</td>
<td>28</td>
<td>bedload and suspended load traps</td>
<td>not described</td>
<td>overhead video camera</td>
<td>automatic bed profiler</td>
</tr>
<tr>
<td>Wang et al. (2002a, b, c)</td>
<td>Army Eng. Res. and Dev. Center, U.S.</td>
<td>2</td>
<td>bottom traps &amp; optical backscatter sensors</td>
<td>capacitance wave gages</td>
<td>visually using compass and total station</td>
<td>bottom-tracking profiler</td>
</tr>
</tbody>
</table>

* cited in Schoonees and Theron (1993)
While several of the laboratory studies pre-date the field studies discussed above, more recent work has also been undertaken, including that by Kamphuis (1991a, b) and Wang et al. (2002a, b, c) (Table 2.2). Laboratory measurements of longshore transport have contributed to the understanding of transport processes, have yielded carefully controlled measurements relating transport rates to wave conditions and have aided in the development of longshore transport formulae. However, there are uncertainties as to how these laboratory measurements relate to those collected on larger scale natural beaches. It is generally thought laboratory measurements underestimate field transport rates, due to the scaling issues of a lab-scale experiment compared to a 'natural' site. Kamphuis (2002) has disputed this assumption, showing a continuous relationship between measured and calculated transport rates for field and laboratory data.

2.3 LONGSHORE TRANSPORT PROCESSES

2.3.1 Factors influencing longshore transport of sediment

As Table 2.1 and Table 2.2 indicate, longshore sediment transport has been the focus of both field and laboratory studies for decades and is still a topic that attracts considerable research. The amount of data collected does not, however, reflect the understanding of processes involved in the longshore transport of sediment. Longshore sediment transport is a complicated process to investigate with many parameters having, or at least possibly having, an impact (Table 2.3). The categories in Table 2.3 (systems, subsystems, components and factors) reflect an attempt to order the parameters in order of decreasing global importance (Pilkey and Cooper, 2002). For example, wave height and angle are of primary, global importance to the longshore transport rate on any beach and need to be incorporated in any model that estimates longshore sediment transport rate. Since the armouring of the substrate by a gravel lag is of importance on a more local level it doesn't need to be included in all transport models.

It has to be acknowledged that the parameters at all levels will vary hugely in importance in time and space. An example of how important the minor parameter wind can be is noted by the studies of Ciavola et al. (1997a) and Masselink and Pattiaratchi (1998b, 2001a). Both studies demonstrate a dramatic increase in longshore transport when locally brisk winds were blowing in the same direction as the longshore currents. In the latter
paper, the sea breeze on a Western Australian beach was observed to increase longshore suspended sediment transport by a factor of up to 100.

<table>
<thead>
<tr>
<th>Global importance</th>
<th>Components</th>
<th>Local importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems</td>
<td>Subsystems</td>
<td>Factors</td>
</tr>
<tr>
<td>Wave height</td>
<td>Offshore bar configuration</td>
<td>External factors (wind)</td>
</tr>
<tr>
<td>Wave angle</td>
<td>Wave current interaction</td>
<td>Bed liquefaction</td>
</tr>
<tr>
<td>Storms</td>
<td>Coastal type</td>
<td>Bed forms</td>
</tr>
<tr>
<td>Morphologic feedback</td>
<td>Grain size</td>
<td>Bed roughness</td>
</tr>
<tr>
<td>Shoreface morphology</td>
<td>Sediment supply</td>
<td>Beach state</td>
</tr>
<tr>
<td>Underlying geology</td>
<td>Engineering structures</td>
<td>Bottom currents</td>
</tr>
<tr>
<td></td>
<td>Beachrock</td>
<td>Storm surge</td>
</tr>
<tr>
<td></td>
<td>Nearshore winds</td>
<td>Tide range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tidal currents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coastal currents</td>
</tr>
</tbody>
</table>

With increasing knowledge of parameters that influence longshore transport rate and accurate transport measurements across the surf zone, the insight into the underlying longshore transport processes increases. The techniques available to measure longshore sediment transport rate all have different characteristics, both in the equipment utilised, the temporal and spatial scales in which the results are obtained and, critically, in the mode of transport that they measure.

In order to compare the results of different techniques, knowledge of the contribution of suspended load and bedload to the total amount of littoral drift is needed (Section 2.3.2). As pointed out in Chapter 1 there are large uncertainties regarding the distribution of sediment movement across the surf zone and the contribution of swash zone transport to the total longshore transport rate (Bodge, 1989). These uncertainties will be further discussed in Section 2.3.3. Using this knowledge together with the ever-growing database of transport measurements, existing equations that estimate longshore sediment...
transport can be evaluated, updated or improved and new models can be developed (Section 2.4).

2.3.2 Bedload versus suspended load

A longstanding research question has been the relative contributions of suspended load and bedload to the total load longshore sediment transport. Although this distinction may be made conceptually, the separation of sediment transport into bedload and suspended load in the field has long been a source of difficulty. To address this problem properly, at least two of the three transport components must be known with a reasonable amount of confidence. Even utilizing current ‘state of the art’ instrumentation it is only possible to study the suspended and total sediment components of transport in the field.

Unfortunately, few simultaneous measurements of any two transport-modes have been made in previous studies. Most investigations have gone about this in a rather half-hearted way, for example, by measuring suspended load and inferring total load from predictive equations (Komar, 1978, Sternberg et al., 1989), by investigating the sediment flux profile from bed level upwards using streamer traps (Kraus and Dean, 1987; Kraus et al., 1989), or by comparing longshore current velocities with maximum tracer advection rates (Komar, 1978).

Although the above mentioned studies might not be ideal to investigate the exact amount of bedload versus suspended load transport, they can be indicative of the relative contributions of the two different transport modes. Both Komar (1978) and Kraus et al. (1989) reasoned that the bedload transport is more important than the suspended load transport. Komar concluded that the suspended load comprises some 25% or less of the total drift, the bedload forming the remaining 75%. Kraus et al. suggested 30% of the total transport occurs in the lower 10% of the profile (between bed level and \( z = 0.10 \ h \)) indicating that the major portion of the sediment moved alongshore as bedload. This contrasts with Sternberg et al. (1989) who found that almost all of the transport was accounted for by suspended sediment transport.

If suspended transport were significant, one might expect that the total load transport rate would depend on the settling velocity or grain size of the beach sediment. Komar (1978) sought such a dependence using available data on the total transport rate from field and
laboratory beaches, but no relationship was found. However, more recent laboratory experiments, for example Deigaard et al. (1986), Kamphuis (1991a, b), do indicate that the total load transport does depend, at least to some extent, upon the relative grain size, thus indicating that the suspended sediment transport makes up a reasonable proportion of the total load.

Only Inman et al. (1980) conducted simultaneous measurements of total transport using sand tracers and suspended transport with traps. Unfortunately, suspension concentrations were determined only down to 10 cm from the bed, so their conclusion that suspension transport accounts for approximately 15–20% of the total transport should be considered rather tentative. Frequently, operational considerations prevail over dynamics, and bedload is regarded as that portion of the total load travelling below a certain level. Such operational definitions result in conflicting interpretations of several observations (Hanes, 1988).

The swash zone is an area of controversy. The question is whether the movement of sediment in the swash-zone should indeed be separated into bedload and suspended load modes or whether it occurs under sheet flow conditions, where the whole bed surface is mobilised under high flow speeds (Hardisty, 1994). This is still being debated (e.g. Hughes et al., 1997; Masselink and Hughes, 1998).

The contrasting findings of two papers that appeared in a single volume reporting on the results of the same series of field experiments (Seymour, 1989) are perhaps indicative of the amount of disagreement and/or confusion in the literature. White and Inman (1989b) focus on sand tracer experiments and believe that these yield estimates of bedload transport that are only marginally affected by suspended transport. By contrast, Sternberg et al. (1989) used vertical arrays of suspended sediment sensors and current meters and found that the total rate of suspended longshore transport derived from these instruments accounted for the entire total longshore transport rate as predicted by transport formulae. Considering the difficulty in measuring bedload in the field, the range of results and the contrasting conclusions of the various studies, there is still no consensus on the relative roles of suspension versus bedload transport on beaches (Komar, 1998; Aagaard, 2002). The question must remain open and is thus in need of additional research.
2.3.3 Cross-shore distribution of longshore sediment transport

Many applications require evaluations of the cross-shore distribution of the longshore transport. For example, this information is needed in the design of jetties and groynes, especially when deciding on the length of the structure, the capacity of sand bypassing or dredging systems and weirs. Furthermore, computer models that analyse the changes in morphology of beaches and the effect of structures require details of longshore transport rates along the cross-shore profile. In this section typical cross-shore distributions for non-barred, low-energy beaches, as per the focus of this thesis, will be discussed.

The distribution of longshore sediment transport is largely controlled by cross-shore patterns of the wave energy dissipation and the longshore current velocity, as well as the beach slope, nearshore morphology and breaker type. Four types of breakers (spilling, plunging, surging and collapsing) have been summarised by Komar (1998). A spilling breaker gradually peaks until the crest becomes unstable and cascades down as “white water”-bubbles and foam. For a plunging breaker, the shoreward face of the wave becomes vertical, curls over, and plunges forward and downward, impinging onto part of the wave trough, with the “white water” often penetrating the entire water column and impacting the water-sediment interface directly. In surging breakers, the base of the wave surges up the beach face so that the crest collapses and disappears. Collapsing breaker is an intermediate condition between plunging and surging breakers.

Since several beach parameters are interrelated, a morphodynamic classification scheme for beaches has been developed by Wright and Short (1983). In general, spilling breakers tend to occur on beaches of very gentle slope with steep waves, such that the waves first break well offshore and continuously lose energy when they travel as breaking bores across the wide surf zone. This is classified as a dissipative beach. In contrast, on the high-gradient, reflective beach, steep plunging to surging waves break close to the shoreline with little prior loss of energy. As a result the surf zone is narrow and the swash zone is energetic. The plunging breakers occur in intermediate conditions.

Wright and Short (1983) went on to suggest criteria to distinguish between the various beach states, via means of a ratio between wave steepness and beach slope. They applied the dimensionless surf-scaling parameter:
\[ \varepsilon = \frac{H_b \omega^2}{2g(tan \beta)^2} = \frac{2\pi^2 H_b}{gT^2(tan \beta)^2} \]  

(2.3)

where \( \omega = 2\pi/T \) = radian frequency (s\(^{-1}\)), and \( tan \beta \) = beach slope. This ratio can be rearranged into the form of an Iribarren number, or surf similarity parameter, using \( L_\infty = gT^2/2\pi \) for the deep-water wave length (Komar, 1998), yielding:

\[ \xi_b = \frac{tan \beta}{(H_b/L_\infty)^{V2}} = \left( \frac{\pi}{\varepsilon} \right)^{V2} \]  

(2.4)

The dissipative beach state was found by Wright and Short (1983) to occur when \( \varepsilon \) ranges from 30 to 100, corresponding to very low values of the Iribarren number (\( \xi_b = 0.2-0.3 \)). At the opposite extreme, the reflective-beach condition occurred when \( \varepsilon < 1 \) or approximately \( \xi_b > 2 \).

Both field and laboratory measurements have found that the rate and distribution of longshore sediment flux are strongly influenced by breaker type and beach state (e.g., Bodge, 1989; Kraus et al., 1982; Kraus and Dean, 1987; Bodge and Dean, 1987; Kamphuis, 1991a, b). Significantly greater total rates of longshore sediment transport have been reported under plunging breakers in comparison to spilling breakers of similar breaker height and breaker angle (Beach and Sternberg, 1996; Wang et al., 2002a, b, c). Applying comparable repeated measurements in the field is difficult since the nearshore zone is dynamic and non-controllable, which increases the difficulties of isolating and examining the contributions of, and interactions among, individual parameters.

Field measurements demonstrate great variability in the shape of the transport distribution profile (Bodge, 1989). Nevertheless, four different transport distributions have been described for non-barred, low-energy beaches, being: single peak in the swash zone, single peak near the breaker line, bimodal with peaks near swash zone and breaker line, and a uniform distribution. These distributions have been determined using several measurement techniques, for example suspended sediment sensors (Sternberg et al., 1984), streamer traps (Wang, 1998), short-term impoundment (Bodge and Dean, 1987) and fluorescent tracer (Kraus et al., 1981, 1982).
A pattern with a peak in the swash zone was typically found at steep, reflective beaches with a narrow surf zone and collapsing breakers. The incident waves were breaking close to the shoreline, the surf-bore area was usually narrow or nonexistent and as a result the breakers run-up the swash zone as turbulent bores immediately after the wave breaking (Kraus et al., 1982; Wang, 1998). As a result of these conditions, sediment transport in the swash can be a significant contribution to the total longshore transport, as emphasised in several studies, including both field and laboratory experiments (Kraus et al., 1982; Kraus and Dean, 1987; Wang, 1998; Butt and Russell, 2000; Kamphuis, 1991a). Bodge and Dean (1987) concluded from laboratory impoundment experiments that, under collapsing breakers, over 60% of total sediment flux was transported in the swash zone.

The opposite pattern, with a peak at mid- to outer surf zone, was usually found in wide surf zones of low slope beaches with plunging or spilling breakers where a significant amount of energy was dissipated at the breaker line. The energy was further dissipated in the wide surf-bore area such that most of the energy had already been dissipated by the time the breaking waves reached the swash zone (Kraus and Dean, 1987; Wang, 1998). The occurrence of decreased longshore transport in the swash zone was also related to the fluid motion in the swash zone. The flow direction was perpendicular to the wave crest during run-up, but perpendicular to the beach orientation during backwash (not taking into account the mean longshore current). This effect decreased with decreasing bed slope, or rather surf-similarity parameter (Elfrink and Baldock, 2002). Bodge and Dean (1987) found longshore transport in the swash zone to represent some 5% of the total transport with spilling breakers.

The bimodal distribution represents the transition between the opposites of peaks near either the swash or breaker zone. In this case, the energy dissipation is uniform and thus the longshore sediment transport distribution can be uniform, as reported by Kraus et al. (1982) and Wang (1998). Bodge and Dean (1987) investigated the bimodal distribution both in the field and in the laboratory under plunging wave conditions. They estimated the contribution of the swash zone longshore transport to the total transport was about 26%, with contributions seaward of the breakpoint of about 14%.

Laboratory tests on transport rate distributions have revealed a fairly constant ratio of suspended load to bedload transport across the surf zone. The sole exception to this has
been noted when a large transport peak occurs within the swash zone, whereupon this peak will primarily consist of bedload transport (Kamphuis, 1991a, b).

Generalising, the results suggest that the longshore transport is bimodal with peaks in the swash zone and the outer surf zone. However, the relative significance of the peaks shifts from the near-breakpoint to the near-shoreline peak as the surf changes from, spilling, via plunging to collapsing wave conditions, or rather increasing surf-similarity parameter. In the collapsing limit, the near-breakpoint peak vanishes.

An important factor not included in the above discussion of the cross-shore pattern of longshore sediment transport is the amount of longshore transport in the wave shoaling area. Kraus and Dean (1987) deployed streamer traps and found a large decrease in transport rate at the seaward side of the breaker zone. Under both laboratory and field conditions Bodge and Dean (1987) found the longshore transport seaward of the breakpoint to represent about 10-20% of the total transport. Under storm conditions with breaker wave heights up to 2.8 m, similar rates of around 20% were reported by Miller (1999).

The discussed studies emphasise that breaker type has significant influence on the magnitude and pattern of longshore transport. Parameterisation of predictive formulae should include factors that reflect the breaker type; however, additional data and research are needed to derive the relationship between longshore sediment transport rate and breaker type.

2.4 PREDICTION OF POTENTIAL LONGSHORE TRANSPORT

A long-standing desire of coastal scientists and engineers has been to estimate longshore sediment transport rates by means of the measurement of waves and currents. With such a capability, estimates can be made of how much sediment will be blocked by the construction of jetties or a breakwater, and thus allow the design of bypassing systems to limit the adverse impacts of such structures. Equations relating sand transport rates to waves and currents also have an important application in the development of computer simulation models of shoreline change resulting from longshore sediment transport.
The number of parameters in Table 2.3 indicates the complexity of the longshore sediment transport process. As all beaches are different and each beach is a highly complex system, a universal model to predict beach behaviour would require that the importance of the different parameters and their interrelationships are understood and taken into account. So far however, the influences of the different parameters are not fully understood. As a result, most longshore transport models use the input of only the few parameters thought to be the most influential. For instance, the widely used CERC-equation, discussed below, relates transport to a breaker wave height, breaker water depth and angle of wave approach.

In this section the development of mathematical modelling for longshore transport rates will be discussed, followed by a description of a number of bulk transport equations. First, the very basic but widely-used CERC (1984)-equation is to be reviewed, then the slightly more process-based Inman and Bagnold (1963) equation, followed by a description of the Kamphuis models (Kamphuis et al., 1986; Kamphuis, 1991a, b). Finally, the application of these longshore transport models is discussed.

2.4.1 Development of longshore transport modelling

The volume of littoral transport along coasts was initially estimated from observed rates of erosion or accretion, most commonly in the vicinity of coastal engineering structures such as groynes or jetties. Munch-Peterson (1938) first related the rate of littoral sand transport to deepwater wave energy in conjunction with harbour studies on the Danish coast. A lack of wave data led Munch-Peterson to use wind data in practical applications, which gave preliminary estimates of the littoral drift direction.

The first study that was successful in making quantitative correlations relating sand transport rate to environmental factors of waves and currents was that of Watts (1953a cited in Komar, 1998) (Table 2.1). The best correlation was obtained using month-long net quantities of sand pumped past jetties, related to a balance of the wave parameters measured throughout the month. The next significant contribution was that of Caldwell (1956, cited in Komar, 1998) (Table 2.1). Although the data gathered during the experiments of both Watts and Caldwell are extremely scattered, their studies represent pioneering attempts to obtain quantitative measurements of longshore sediment transport rates in order to establish empirical correlations with the wave conditions.
In the 1970s the application of tracers to measure longshore transport became more widespread. The study by Komar and Inman (1970) was the first to employ sand tracers to obtain quantitative measurements relating the littoral sand transport rate to waves and currents. They carried out several experiments on the western coast of the USA in order to build a database of longshore transport rates, beach conditions and wave parameters.

Since then, many more measurements of longshore transport have been undertaken. Table 2.1 gives an overview of the data available in literature, including the location of the experiment, the number of data points collected, the methodology of sediment transport estimation, the wave parameter measurements and the surveying method used. The quality of available longshore transport data was reviewed by several researchers (e.g. Komar, 1990; Schoonees and Theron, 1993). They concluded that only high-quality field studies that have yielded measurements of the total longshore transport of sand, together with the causative waves and currents should be used to develop longshore transport models.

Several models to estimate bulk longshore transport rate have been developed. The most simplified and widely used models being the CERC-equation (CERC, 1984), the equation of Inman and Bagnold (1963) and the Kamphuis-formulae (Kamphuis et al., 1986; Kamphuis, 1991a, b). The resulting estimates of longshore sediment transport are based on the parameters wave height, wave period, wave angle, beach slope, grain size and longshore current velocity. The equations are discussed in Sections 2.4.2, 2.4.3 and 2.4.4 respectively.

From a modelling point of view, it appears reasonable to include more parameters in order to realise more sophisticated numerical models for the prediction of spatial and temporal differences in longshore sediment transport. Such a model may include underlying geology of the shoreface, wind, coastal currents, bottom roughness and bed forms, various wave theories and wave conditions and offshore bars that are allowed to change shape and position with time. Several of these models have emerged over the last few decades, for example, the GENESIS, LITPACK and DELFT-model. As a result of the assemblage of more parameters in such a ‘state of the art’ model, the results might be assumed to come close to reality. But including more parameters makes is more difficult to apply such a model, unless the influence of single parameters on the longshore
transport and the interaction with other parameters are well understood. Even in the relatively simple CERC-equation there are uncertainties regarding processes and morphological feedback, and when adding more parameters to the model these uncertainties would increase the inaccuracy of the results. As pointed out by Pilkey and Cooper (2002), the operational basis of these "state of the art" models is questionable, since they are black-box systems where the user cannot determine how the model parameters are used. Therefore these sophisticated models are not relevant for this study and will not be further considered in this thesis.

A number of expressions have been suggested in order to describe the local (at a specific point) distribution of longshore sediment transport. Bodge (1989) pointed out shortcomings such as discontinuities in transport at the breaker line and the lack of application regarding longshore transport in the swash zone. Bayram et al. (2001) reviewed transport formulae and concluded that additional calibration of the formulae against field data sets would increase the predictive capability of all formulae. These expressions will not be further discussed as the application of these equations lies beyond the scope of this thesis.

2.4.2 Energy flux method: CERC (1984)

Different transport models can be used to predict the littoral drift rate, the energy flux method being the most basic and also the most commonly applied formula. This method is generally known as the CERC-equation (CERC, 1984). Following empirical studies, Inman and Bagnold (1963) were able to suggest that the immersed weight, \( I_i \), of sediment in transport would be proportional to the longshore component of wave energy flux in the surf zone, \( P_l \). Wave energy flux is the product of energy density and the rate at which this energy is transmitted in the direction of wave propagation, and is calculated using small-amplitude theory while assuming conservation of energy flux in shoaling waves.

The CERC-equation reads:

\[
I_i = K P_l
\]  
(2.5)
where $K$ = proportionality coefficient (non-dimensional) to be empirically determined; and $P_I$ = longshore energy flux, in wave power per length of shore at depth-limited wave breaking ($N \text{ sec}^{-1}$), given by

$$P_I = \left( E_b \, Cn_b \right) \sin \alpha_b \cos \alpha_b = \left( \frac{\rho \, g \, H_b^2}{16} \right) \left( \sqrt{\frac{g \, H_b}{\gamma}} \right) \sin 2\alpha_b$$

(2.6)

where $E_b$ = wave energy evaluated at the breaker line ($N \text{ m}^{-1}$); $(Cn)_b$ = wave group velocity at the breaker line ($m \text{ sec}^{-1}$); $\alpha_b$ = breaking wave angle with respect to the shoreline (deg); $\rho$ = mass density of water ($kg \text{ m}^{-3}$); $g$ = gravitational acceleration ($m \text{ sec}^{-2}$); $\gamma$ = wave breaker index (non-dimensional); and $H_b$ = breaker wave height (m). Thus, the CERC-equation can be written as:

$$I_I = \frac{K}{16 \sqrt{\gamma}} \rho \, g^{3/2} H_b^{5/2} \sin 2\alpha$$

(2.7)

where the immersed transport rate is proportional to the variable parameters $H_b^{5/2}$ and $\sin \alpha_b$.

The value of the wave power, $P_I$, depends on the method used to calculate the breaker wave height. The wave height, $H_b$, can be either the root-mean-square breaking wave height ($H_{b,\text{rms}}$) or the significant breaker wave height ($H_{b,\text{sig}}$). For Rayleigh-distributed heights, $H_{b,\text{sig}}/H_{b,\text{rms}} = \sqrt{2}$ (Bodge and Kraus, 1991), hence the calculated wave energies would differ by a factor $(\sqrt{2})^2 = 2$ and the wave group velocities by $(\sqrt{2})^{1/2} = 1.2$, so the wave power differs by $2 \cdot 1.2 = 2.4$.

The volume longshore sediment transport rate, denoted by $Q_I$ may be calculated by solving Equation 2.5 for $Q_I$ using Equation 2.2, which gives

$$Q_I = \frac{KP_I}{(\rho_s - \rho)g(1 - p)}$$

(2.8)

In the formulation of the CERC-equation, the fluid is regarded as the transporting mechanism, applying the principle of energy conservation. The whole fluid power transmitted per unit width of the breaking wave is given by the quantity $(ECn)_b$ in
Equation 2.6. If the whole of the power in the breaking wave is dissipated by bottom friction between the plunge line and the shore, then \((Ecn)_b\) would be the power available to move sediment over the entire width of the surf zone. However, a proportion of the power dissipated in the surf zone is dissipated by means other than bottom friction, and thus the factor \(K\) represents the ratio of the rate of the work done in transporting the sediment to the total power available, and can be considered as an efficiency coefficient (Bagnold, 1963).

The value of the \(K\)-coefficient has to be determined from the relationship between the measured immersed weight transport rate and the estimated longshore energy flux factor. Considering some field measurements of sand transport rates on beaches, it can be seen in Figure 2.1 that there is considerable scatter within the data, which is reflected in the variations in suggested values of \(K\). This wide range of estimated average \(K\)-coefficients depends on which data sets are included and excluded in the calculations.

Komar and Inman (1970) used 41 data points, of mainly fluorescent tracer studies, to suggest that \(K = 0.77\) when \(H_{b,\text{rms}}\) is used or that \(K = 0.39\) when \(H_{b,\text{sig}}\) is used. These \(K\)-coefficients became the recommended values in the Shore Protection Manual (CERC, 1984), and are often used when making sand transport evaluations. Other values of \(K\), based on smaller data-sets, have been suggested (e.g. Das, 1971; Bruno et al., 1981; Dean et al., 1987) ranging from 0.014 up to 1.23. It is uncertain which \(K\)-value is the best choice (Thieler et al., 2000). Bodge and Kraus (1991) have pointed out that if the coefficient to use with \(H_{\text{rms}}\) is 0.77, then, using a Rayleigh-distribution, \(K = 0.32\) for use with \(H_{\text{sig}}\). This value is 18% less than the \(K = 0.39\) value suggested in the Shore Protection Manual. This could be a potential error in the practical application of the CERC-equation.
Variations in the $K$-coefficient can be caused by measurement errors in the field or real variations with environmental factors that are not included in the CERC-equation. The measurement errors can be caused by either random errors in the field methods or systematic differences in procedures between studies. As there are several methods available to determine the wave parameters and to measure the sand transport rate (see Section 2.2 for an overview) the methodology used varies between studies. Accordingly it is appropriate to compile a database of all relevant references and to investigate the variation of the proportionality factor with different data sets.

Schoonees and Theron (1993) investigated the CERC-equation and its $K$-coefficient using a database consisting of 273 measurements. It appeared that most of the data were obtained during mild wave conditions for fine to medium sand ($Q < 0.2 \times 10^6 \text{ m}^3/\text{year}$; $H_{b,\text{sig}} < 1.8 \text{ m}$, $D_{50} < 0.6 \text{ mm}$, $\tan \beta < 0.06$), and as a result the $K$-value is only accurate.
Chapter 2: Longshore sediment transport

over this narrow range of conditions. The number of transport measurements during storms is sparse and consequently the transport model is not calibrated for storm conditions while a few storms a year greatly contribute to the total sediment transport budget. It is critical that longshore transport formulae be verified against such conditions.

The quality of the database was reviewed by Schoonees and Theron (1994) and the 46 most reliable field measurements were selected, which resulted in a coefficient of $K_{\text{sig}} = 0.41$ (or $K_{\text{rms}} = 0.82$) with $r^2 = 0.77$. This $K$-values almost resembles the $K_{\text{sig}} = 0.39$ of Komar and Inman (1970). The $r^2$ is the coefficient of determination, showing that 77% of the variation in immersed rate transport rates can be accounted for by the longshore energy flux factor. The remaining 23% represents the error in the field measurements and indicates that variations in the transport rate are partly related to environmental factors that are not included in the CERC-equation. In effect this can be seen as a theoretical basis for a new variable $K$-coefficient or a different longshore transport formula.

The CERC-equation provides a simple correlation between the wave conditions and the resulting rates of longshore-sediment transport. However, the equation is empirical with little thought given to the physical processes involved in longshore transport of sediments and hence it fails to suggest what other relevant factors may affect the transport rate. The equation is not applicable to evaluations of longshore sediment transport that occur when longshore currents are the result of more than just the obliquely-incident waves, as a result of contribution by cell circulation, tides or the wind (Komar, 1998).

Nevertheless, there are many reasons for using the CERC-equation, for example the formula is convenient in use, it needs only a few input parameters, the parameters are relatively easy to measure, the equation is ideal if only a rough estimate of the transport is needed. While alternative models are needed that consider the processes of transport and are broader in their potential applications, as long as the drawbacks and limitations of the CERC-equation are considered during the calculations, there is no reason to cease use of the equation in light of its aforementioned advantages.
2.4.3 Environmental factors influencing the $K$-coefficient

Longshore sediment transport rate is influenced by factors such as sediment grain size, beach slope and wave steepness (Table 2.3). These factors are not included in the CERC-equation and as a result the value of the $K$-coefficient might depend on these environmental conditions. This could go some way to explaining why recent field investigations have revealed that the CERC-equation significantly under-predicts longshore transport rates on beaches with low-energy, plunging breaker conditions (Ciavola et al., 1997a, 1998; Nordstrom et al., 2003).

Investigating the dependency of the $K$-coefficient on environmental factors using solely field experiments is problematic, due to the largely uncontrollable nature of the forcing factors and the difficulties associated with obtaining accurate sediment transport measurements on natural beaches. A number of studies have searched for environmental controls on transport rates and tried to relate them to the proportionality coefficient of the CERC-equation. The studies produced controversial results and have generated debate amongst investigators.

The most obvious dependence that might be expected would be with the sediment grain size, where beaches composed of coarser sediment experience smaller rates of longshore transport, assuming other factors remain equal. Numerous investigators have attempted to explain the scatter in the $K$-coefficient as a result of differences in beach-sediment grain sizes or settling velocities (e.g. Komar and Inman, 1970; Komar, 1978; Bruno et al., 1981; and Dean et al., 1987).

Schoonees and Theron (1994) used a data set of 240 points with a distinction made between fine- ($D_{50} < 1$ mm) and coarse-grained ($D_{50} > 1$ mm) sediment. It was clear that two different populations of points were apparent. The average $K$-coefficient for the fine sediment was a factor of 20 higher than that for the coarse sediment. Bruno et al. (1981) presented a relationship between $K$ and $D_{50}$ for data having median grain sizes below or equal to 1 mm. Both investigations show that the scatter in the data cannot be explained by a single relationship between $K$ and $D_{50}$, indicating other parameters also influence the transport rate. The same applies if the settling velocity is used instead of the median grain size. As a result, a longshore transport formula must at least contain a dependency on the grain size or the settling velocity.
Bailard (1984) developed a model, which presents $K$ as a function of not only the grain size (represented as settling velocity) but also the breaker wave angle and the ratio of the orbital velocity magnitude. Based on root-mean-square wave height at breaking the equation reads:

$$K = 0.05 + 2.6\sin^2(2\alpha_b) + 0.007 \frac{H_m}{w_s}$$  \hspace{1cm} (2.9)$$

where $u_m =$ maximum orbital velocity magnitude ($\text{m s}^{-1}$); and $w_s =$ the settling velocity of the sediment ($\text{m s}^{-1}$), either calculated using a spherical grain assumption or measured experimentally. Using linear-wave theory the orbital velocity can be expressed as:

$$u_m = \left(\frac{2E_b}{\rho h_b}\right) = \left(\frac{2\rho g H_b^2}{8\rho h_b}\right) = \frac{\sqrt{\gamma g H_b}}{3}$$  \hspace{1cm} (2.10)$$

Bailard (1984) calibrated the model using eight field and two laboratory data sets with a limited data range. As a result, the predicted $K$-coefficients may be highly variable for other field sites (CERC, 2002). The evaluations suggest that the transport dependencies on environmental parameters are complex.

As pointed out in Section 2.3.3, the breaker type has a significant influence on the magnitude and pattern of longshore transport. As a result it is appropriate that predictive formulae include factors that reflect the breaker type. The possible relationship between $K$ and the surf-similarity parameter, $\xi_b$ (Equation 2.4), which controls breaker type, has been discussed in several studies.

Laboratory studies (Kamphuis and Readshaw, 1978 cited in White and Inman, 1989a) have suggested that the $K$-coefficient is a variable, dependent upon the nature of the breaking waves and the slope of the beach. They indicated a relation between $K$ and a form of the surf similarity parameter and the results of their experiments became:

$$K = 0.74 \left(\frac{\xi_b^2}{\pi}\right) \text{ for } 1.23 < \xi_b < 1.40$$  \hspace{1cm} (2.11)$$
White and Inman (1989a) calibrated this equation for their data on spilling and plunging breakers (but not surging) in the range $0.25 < \xi_b < 1.15$ and found a coefficient of 2.16 instead of 0.74. Similar equations are discussed in Bodge and Kraus (1991) and they all suggest that the value of $K$ increases with increasing value of the surf similarity parameter (i.e. as the breaking waves tend from spilling to plunging condition) which implies that the transport is more efficient for plunging waves on steep beaches with narrow surf zones. This is probably because plunging waves produce more bottom stress and turbulence, and steeper beaches result in a higher concentration of bottom dissipation per unit area of surf zone.

While the $K$-coefficient might be dependent on environmental factors such as grain size and wave breaker type, no dependency that explains all scatter in the data can be found in the literature. As a result none of the above-discussed $K$-formulae are generally accepted and widely used. Instead the CERC-equation is generally used in its original form (Equation 2.7).

2.4.4 Longshore current method: Inman and Bagnold (1963)

Inman and Bagnold (1963) proposed a transport equation based on the combined effect of the horizontal component of wave motion and the longshore current velocity in the surf zone:

$$I_x = K' \frac{(ECn)_b}{u_m} \bar{v}_i$$

(2.12)

where $K' = \text{dimensionless proportionality coefficient (non-dimensional)}$ to be calibrated using sediment transport measurements; $v_i = \text{longshore current velocity (m sec}^{-1})$; and $u_m = \text{maximum orbital velocity near the bottom just before a wave breaks (m sec}^{-1})$.

Similar to the CERC-equation, the equation of Inman and Bagnold assumes that the rate of wave energy dissipation by friction on the bottom is proportional to $(ECn)_b$. The frictional force applied to the bed per unit of wave crest length is related to both $(ECn)_b$ and the frictional velocity, $u_m$, as the ratio $(ECn)_b/u_m$. In effect this ratio represents the stress exerted by the waves, which moves the sand to-and-fro. Once the sediment is
mobilised by the waves, it becomes available for transport by any current, such as the longshore current, $v_l$.

Using linear-wave theory the orbital velocity can be expressed as (Carter, 1988):

$$ u_m = \left( \frac{2E_b}{\rho h_b} \right) = \left( \frac{2\rho g H_b^2}{8 \rho h_b} \right) = \sqrt{\gamma g H_b} $$  \hspace{1cm} (2.13)

The wave stirring factor can be rewritten as

$$ \frac{(ECn)_b}{u_m} = \left( \frac{\rho g H_b^2}{8} \right) \left( \frac{g H_b}{\gamma} \right) \left( \frac{2}{\sqrt{\gamma g H_b}} \right) = \frac{\rho g H_b^2}{4\gamma} $$  \hspace{1cm} (2.14)

Therefore, Equation 2.9 can be reworked as

$$ I_1 = \frac{K'}{4} \left( \frac{\rho g H_b^2}{\gamma} \right) v_l $$  \hspace{1cm} (2.15)

In the derivation of Equations 2.12 and 2.15, the origin of the longshore current velocity was never specified, so its generation could be due to an oblique-wave approach, tidal currents or part of the cell circulation with rip currents, and could also be driven by local winds. In the event that the longshore current is not measured, it can be assumed this current is the result of simple gravity waves striking an infinite, plane beach at an oblique angle (Basco, 1983). Then, using linear-wave theory, the current can be estimated as suggested by Komar and Inman (1970) as:

$$ v_l = 2.7 u_m \sin \alpha_b \cos \alpha_b = \frac{2.7}{4} \sqrt{\gamma g H_b} \sin 2\alpha_b $$  \hspace{1cm} (2.16)

where $v_l$ is specifically the longshore current measured at the mid-surf position, halfway between the breaker zone and the shoreline, while $u_m$ and $\sin \alpha_b$ are evaluated at the breaker position. Several equations to estimate the longshore current velocity are available in the literature but according to Komar (1975) Equation 2.16 provides the best predictions of the current as measured at the mid-surf position up to breaker angles of 45 degrees. Balsillie (1975) observed however, that currents might introduce less
deviation from actual conditions than those predicted using wave parameters. Using the current velocity estimation of Equation 2.16, the Inman and Bagnold Equation 2.15 can be rewritten as:

\[ I_t = \frac{2.7K'}{16\sqrt{\gamma}} \rho g^{3/2} H_b^{5/2} \sin 2\alpha \]  

(2.17)

This equation is valid if the longshore current is induced by obliquely incident waves only. According to this approach, the wave stirring term is proportional to \( H_b^2 \) while the longshore current is proportional to \( H_b^{1/2} \) and \( \sin \alpha_b \). As a result the immersed transport rate is proportional to \( H_b^{5/2} \) and \( \sin \alpha_b \), and thus similar to the proportionalities achieved using the CERC-Equation 2.7.

Several researchers used their field data of longshore transport rates to test the longshore current method and determine the value of the \( K' \)-coefficient (e.g. Komar and Inman, 1970; and Kraus et al., 1982). The data yields values of \( K' \) between 0.091 and 0.35 but \( K' = 0.28 \) is generally the accepted value for use with \( H_{rms} \), and \( K' = 0.12 \) for use with \( H_{sig} \). As a result of the scatter in the data there is some uncertainty as to the correct value of \( K' \), similar to the uncertainties in determining the \( K \)-coefficient in the CERC-equation.

The longshore current method has several advantages over the CERC-equation. From a practical standpoint, it can be easier and more accurate to measure the longshore current \( v_L \) than to determine the breaker angle \( \alpha_b \) needed in the CERC-equation. Theoretically, Equation 2.15 was derived on the basis of considerations of the processes of sand transport, and accordingly should be viewed as more fundamental than the empirical correlations of the CERC-formula (Equation 2.7). However, the uncertainty of the \( K' \)-coefficient may indicate that more environmental parameters need to be included in an accurate longshore transport equation.

### 2.4.5 Kamphuis et al. (1986) and Kamphuis (1991a, b)

On the basis of both empirical and experimental data, Kamphuis et al. (1986) proposed the following equation for predicting longshore sediment transport:

\[ Q = 1.28((\tan \beta H_s^{3.5})/D) \sin 2\alpha_b \]  

(2.18)
where \(\tan \beta = \) beach slope; and \(D = \) sediment diameter \((m)\). Equation 2.18 suggests that the transport rate increases for increasing steepness of the beach slope, as the breaking process will be more intensive on steeper slopes resulting in larger concentrations and transport rates.

With additional laboratory study and further analysis of the existing field data, Kamphuis (1991b) modified the Equation 2.18 by including the influence of wave period:

\[
Q = 2.03 \times 10^{-3} H_s^2 T_p^{1.5} \tan \beta^{0.75} D_{50}^{-0.25} \sin^{0.6}(2\alpha_s)
\]

where \(T_p = \) peak wave period \((s)\). The dependencies on grain size and wave height are greatly reduced when compared to Equation 2.18. The influences of beach slope and incident wave angle are also reduced. The wave period is linked to the wavelength through the dispersion relation. The ratio between wavelength and wave height represents the wave steepness, which in turn is used, together with the beach slope, to calculate the Iribarren number (Equation 2.4). This Iribarren number is used to classify beach states and breaker types. In other words, the wave period, has significant influence on the wave steepness and hence breaker type. Wave period also has considerable influence on the range of up-rush and back-wash, which in turn influences transport rate in the swash zone (Wang et al., 2002a, b). In this thesis, Equation 2.19 will be referred to as the ‘Kamphuis’ formula.

Kamphuis (2002) discussed the Kamphuis formula in the light of new field data in order to prove or improve Equation 2.19. The equation was calibrated using laboratory data and then verified by application to the most recent available field data. No further calibration was needed which indicated that there is little scale effect in the laboratory tests. Since the most recent field data contain the same uncertainties as the old field data, it is difficult to improve the formula by using field data alone. Kamphuis (2002) recommends the combined use of field and laboratory data to determine any alongshore sediment transport relationship.

The ‘Kamphuis’ model is the most realistic currently available. The model includes the effect of sediment size and breaker type, which are environmental factors considered as
being important to longshore transport rates (discussed in Section 2.4.3). The ‘Kamphuis’
model has been based on both laboratory and field data and is widely applicable.

2.4.6 Application of bulk longshore transport models

The application of the CERC (1984), Inman and Bagnold (1963) and the Kamphuis-1991
formulae will be further discussed in this section. A wide range of data has been
compared to transport estimates to investigate the applicability of the different equations
(Wang et al., 1998, 2002a, b, 2003; Miller, 1998, 1999; Ciavola et al., 1997a, b; and
Nordstrom et al., 2003).

Nordstrom et al. (2003) measured the longshore sediment transport on a steep, reflective
beach with low-energy, plunging breakers (\(\tan\beta \approx 0.11, H_b \approx 0.08\) m, \(D_{50} \approx 0.5\) mm and
\(\zeta \approx 1.15\)). The three bulk transport equations predicted similar longshore transport rates,
although they all under-predicted the measured rates. This is comparable to the findings
of Ciavola et al. (1997a, b) who concluded that the Inman and Bagnold-equation under-
predicts measured rates on a similar steep reflective beach with plunging breakers
(\(\tan\beta \approx 0.11, H_b \approx 0.36\) m, \(D_{50} \approx 0.3\) mm and \(\zeta \approx 1.3\)).

The opposite was found by Wang et al. (1998), when investigating the longshore
transport rates at 29 low-energy beaches (\(\zeta\) ranges from 0.15 to 1.93). On average the
CERC-equation estimates transport rates twice that of the Kamphuis formula and both
equations over-predict the measured transport rates. For the most reflective beaches the
over-prediction of both equations worsens (\(\tan\beta \approx 0.16, H_b \approx 0.25\) m, \(D_{50} \approx 0.87\) mm and
\(\zeta \approx 1.41\)). For the five most dissipative beaches the Kamphuis equation predicts transport
rates only a factor of two higher than the measured rates. The average characteristics of
these beaches are \(\tan\beta \approx 0.03, H_b \approx 0.39\) m, \(D_{50} \approx 0.46\) mm and \(\zeta \approx 0.24\). Transport
measurements in laboratory experiments under similar conditions (\(\tan\beta \approx 0.04, H_b \approx 0.26\) m, and \(\zeta \approx 0.15\)) (Wang et al., 2002a, b, 2003) show similar results where the
CERC equation over-predicts and the Kamphuis formula estimates rates close to the
measured transport rates. This suggests that the Kamphuis formula is a better estimator of
longshore sediment transport than the CERC equation on low-energy beaches, especially
for dissipative conditions.
On the other hand, Miller (1998, 1999) found that the predictions by the CERC and Inman and Bagnold formulae matched storm measurements with breaker heights up to 3.8 m more closely than the Kamphuis predictions, which were nearly one order of magnitude lower than the measured rate. These field measurements do not capture swash transport. If swash transport was significant during the storm events that were studied, the CERC-formula and the equation of Inman and Bagnold (1963) may in fact under-predict longshore transport rates during high-energy conditions.

Both Ciavola et al. (1997a) and Miller (1999) indicated that the CERC-equations could not always be utilised for transport rate estimates. This was the case when opposing processes complicated the transport, for example when the winds and local seas opposed the swell, causing a spreading of the wave energy over several wave angles and association of the longshore current with several different wave trains. Since this situation is not atypical of incident waves, it seems that the CERC-formula may not be able to provide accurate estimates of total longshore transport rates for some wave conditions. Included below is a table summarising the aforementioned studies (Table 2.4).

<table>
<thead>
<tr>
<th></th>
<th>tanβ</th>
<th>H_b</th>
<th>D_50</th>
<th>CERC</th>
<th>Inman &amp; Bagnold</th>
<th>Kamphuis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nordstrom et al. (2003)</strong></td>
<td>0.11</td>
<td>0.08</td>
<td>0.5</td>
<td>1.15</td>
<td>under</td>
<td>under</td>
</tr>
<tr>
<td><strong>Ciavola et al. (1997a,b)</strong></td>
<td>0.11</td>
<td>0.36</td>
<td>0.3</td>
<td>1.3</td>
<td>-</td>
<td>under</td>
</tr>
<tr>
<td><strong>Wang et al. (1998)</strong></td>
<td>0.16</td>
<td>0.25</td>
<td>0.87</td>
<td>1.41</td>
<td>over</td>
<td>-</td>
</tr>
<tr>
<td><strong>Wang et al. (1998)</strong></td>
<td>0.03</td>
<td>0.39</td>
<td>0.46</td>
<td>0.24</td>
<td>over</td>
<td>-</td>
</tr>
<tr>
<td><strong>Wang et al. (2002a, b, 2003)</strong></td>
<td>0.04</td>
<td>0.26</td>
<td>?</td>
<td>0.15</td>
<td>over</td>
<td>-</td>
</tr>
<tr>
<td><strong>Miller (1998, 1999)</strong></td>
<td>3.8</td>
<td>similar</td>
<td>similar</td>
<td>similar</td>
<td>similar</td>
<td>similar</td>
</tr>
</tbody>
</table>

Based on the presently available information from a number of sources, the following can be concluded. The Kamphuis formula generally predicts lower longshore transport
Chapter 2: Longshore sediment transport

rates than the CERC and Inman and Bagnold equations, which estimate similar rates. When attempting general longshore sediment transport estimates, the Kamphuis formula should be considered as a lower-bound estimate and the CERC and Inman and Bagnold-formulae to derive an upper bound estimate. For special events, at present, it is most appropriate to use the CERC or Inman and Bagnold formula for storm events and the Kamphuis formula for low-energy events (waves less than 1 m in height). The findings are inconclusive as to whether the applicability of the transport equations depends on the morphodynamic beach state, as might be expected.

2.5 Summary

The longshore transport of sand is an important nearshore process that controls beach morphology. Therefore, a qualitative and quantitative sense of longshore transport rates is essential in determining coastal evolution and the environmental impact of coastal structures and beach nourishments. However, longshore sediment transport is a complicated process to investigate, and is influenced by many parameters. Unfortunately, the amount of transport data collected both in the field and in the laboratory does not reflect the understanding of longshore sediment transport processes.

Diverse field methods are available to determine longshore transport volumes, for example, impoundment, streamer traps, or fluorescent tracer. The techniques all have different characteristics, both in the equipment utilised, the temporal and spatial scales over which the results are obtained and, critically, in the mode of transport that they measure. These unique characteristics enable researchers to choose a method that best fits their specific objectives.

It has to be noted that the scale differences of the measuring techniques complicate a direct comparison of measured transport rates. However, the simultaneous deployment of several techniques can be informative, since through repeated measurement trials and inter-comparison of results, the techniques can be reviewed and refined for reliability. Unfortunately, few researchers have chosen to investigate this. Furthermore, care should be taken when using shorter-term measurements to estimate longer-term volumes of longshore sediment transport. Bearing in mind that usually a few storms a year contribute almost all the longshore transport at a site, it is critical to measure longshore transport
during such conditions. Perhaps the greatest weakness in field measurements is the inability to accurately measure storm-related transport.

With accurate transport measurements across the surf zone and increasing knowledge of the parameters that influence longshore transport rate, the insight into the underlying longshore transport processes increases. In order to compare the results of different measuring techniques, knowledge of the contribution of suspended load and bedload to the total amount of littoral drift is needed. This distinction is still a source of difficulty, due to lack of suitable instrumentation for measuring bedload transport, poor theoretical knowledge and general observation difficulties. Additional research is needed into the relative roles of suspended load versus bedload transport.

Many applications require evaluations of the cross-shore distribution of the longshore transport, but there are large uncertainties regarding this distribution and the contribution of swash zone transport to the total longshore transport rate. It is suggested that the longshore transport distribution is bimodal with peaks in the swash zone and the landward side of the breaker zone. However, the relative significance of the peaks shifts from the near-breakpoint to the near-shoreline peak as the surf changes from spilling, via plunging to collapsing wave conditions, or rather increasing surf-similarity parameter while the beach state changes from dissipative to reflective. In the collapsing limit, the near-breakpoint peak vanishes.

A complete study might ideally include measurements across the swash and surf zones of local sediment transport, wave height, wave period, longshore current, bed profile, vertical suspended sediment distribution and grain size. Only then can the longshore sediment transport processes be properly evaluated, including an identification of the cross-shore distribution of longshore sediment transport rates and the ratio of suspended versus bedload transport. Such reliable measurements of longshore sediment transport will make the further testing of existing transport equations and development of accurate longshore transport models achievable. Once satisfied, the appropriate techniques should be applied over a wide range of surf conditions in order to collect high quality transport data.

The two most basic models that estimate the total transport rate are the CERC (1984) and the Inman and Bagnold (1963) equations. Although both models have their complications
and uncertainties, they are widely applied, both because of their ease in use and the small number of input parameters needed. A more realistic equation was developed by Kamphuis (1991b) and includes the effects of sediment size and breaker type. The model fits the available laboratory and field data on longshore transport well and appears to be widely applicable. At the present time, there is no well-established transport formula that takes into account all the different factors that control longshore sediment transport. Such a formula should quantify bedload and suspended load, include transport in the swash zone and incorporate a description of the morphodynamic beach state, the hydrodynamic conditions and sediment size.
CHAPTER 3: FIELD SITE AND MEASURING APPROACH

3.1 INTRODUCTION

As pointed out in Chapter 1, the ideal field site for this project requires a predictable, consistent occurrence of longshore sand transport events, a straight shoreline and an undisturbed continuous supply of sand. During transport events the environmental conditions, such as water level, beach profile, wave characteristics and meteorological conditions should remain stable.

These conditions are met along the coastline of southwestern Australia. The morphological setting of this coastline is very much influenced by sea breeze activity during the summer and consequent wave conditions (Section 3.2).

Longshore sediment transport was measured on time scales ranging from seconds to weeks. Four different measurement techniques were used on five low-energy sandy beaches. The measuring approach is outlined in Section 3.3.1. This chapter concludes with a discussion of the use of models to estimate longshore sediment transport at the study sites (Section 3.3.2).

3.2 MORPHOLOGICAL SETTING

The data for this project were collected along the coast of southwestern Australia. The study area ranged from Mullaloo Beach in the north, to Leighton Beach in the south (Figure 3.1). The direction of the coastline is roughly North-South, with the aspect changing from $-12^\circ$ at Mullaloo to $+5^\circ$ at Leighton Beach (relative to North). The coastline is subject to mixed, mainly diurnal, microtidal conditions with a maximum spring tidal range of 0.7 m (Australian Department of the Navy Hydrographic Branch, 2000). The beaches consist of medium-sized sand with a $D_{50}$ ranging from 0.24 to 0.50 mm and have steep gradients (5-6°).
3.2.1 Sea breeze activity

Local winds are driven by the interaction of the surface with the overlying atmosphere, the simplest, most widespread and most persistent of these being the sea breeze circulation. It arises from the contrasting thermal properties of land and water surfaces along a coastline in near calm conditions (Tapper and Hurry, 1993). The lower thermal conductivity of land means that it heats and cools more rapidly than the sea surface. The more rapid heating of the land during the daytime results in the development of a temperature gradient across the coast, leading to ascent of air over the land and descent over the sea, and hence an atmospheric pressure gradient which in turn initiates an airflow from sea to land, the sea breeze. At the same time, there is a compensation return flow aloft. At night the situation is reversed and the flow is from the colder land to the warmer sea, as a land breeze. This is generally less well formed than the sea breeze (Henderson-Sellers and Robinson, 1986).

Masselink and Pattiaratchi (2001a) described the sea breeze climate of Perth, using wind data collected at Perth Airport (about 20 km inland) from 1948-1997. They demonstrated that the sea breeze activity has a seasonal variation. In the summer months, more than 20 sea breezes are experienced per month, with average speeds of 6-7 m s\(^{-1}\), while in winter only 10-15 sea breezes occur per month, with speeds of around 5 m s\(^{-1}\). Each year there is an average of 197 sea breezes with a mean wind speed of 5.7 m s\(^{-1}\). The direction of the sea breeze is from the WSW throughout the year, with a slightly more southerly direction (240°) during summer than during winter (250°). Along the coastline, sea breeze velocities are 1.4 times stronger and blow from a more southerly direction (200°) than inland. On Rottnest Island, 20 km offshore, the winds during the sea breeze are 1.7 times stronger than inland, but from the same direction as along the coast.

The onset of the sea breeze is often well defined and indicated by an abrupt increase in wind speed and shift in wind direction around mid-afternoon. The cessation of the sea breeze is less clear, because after approximately 18:00 hrs wind conditions gradually return to pre-breeze conditions. Pattiaratchi et al. (1997) assume that the mean duration of the sea breeze is 6 hours.
Figure 3.1: Map of the study area. Bathymetry is in metres. Contour lines at 10, 20 and 30 metres below mean sea level.
During calm conditions, a typical sea breeze would blow perpendicular to the shoreline. This is in contrast to the sea breeze in southwestern Australia, which has a shore-parallel nature as a result of the superposition of the local sea breeze system on the regional weather pattern (Pattiaratchi et al., 1997). In the summer, the Australian continent is generally under the influence of an easterly wind regime. The easterlies contain a shore-parallel, low-pressure trough, which lies generally inland of the west coast, but shows day-to-day variations in position (Kepert and Smith, 1992).

The location of the trough influences both the intensity and direction of the sea breeze (Pattiaratchi et al., 1997). When this trough is located offshore, then the sea breeze, if it develops, will be weak and will arrive in the late afternoon. On the other hand, when the trough is inland, a vigorous sea breeze develops comparatively early in the day (Kepert and Smith, 1992). Due to a combination of pressure gradient flow, owing to onshore differential heating and Coriolis force, the sea breeze system in Western Australia is southwesterly (Kepert and Smith, 1992). The combination of the sea breeze pressure system (southwesterly air flow) and the synoptic pressure (southeasterly air flow) results in a southerly sea breeze flowing parallel to the shoreline. When the location of the trough is such that the synoptic pattern induces southerly winds, the sea breeze enhances the southerly winds. Hence, the synoptic conditions enhance the sea breeze system in this region, resulting in very strong sea breezes during the summer months.

Pattiaratchi et al. (1997) concluded that the coastline of Perth is subject to one of the most energetic and consistent sea breeze systems in the world. The sea breeze system is expected to greatly influence coastal processes within the low wave energy, microtidal environments of southwestern Australia. As the sea breeze prevails for many months of the year, the cumulative effect of its winds on coastal processes can be considerable (Masselink and Pattiaratchi, 1998b).

### 3.2.2 Wave climate and nearshore processes

The offshore wave climate (measured in 48 m water depth) is characterised by a mean significant wave height $H_{\text{sig}}$ of 2.0 m and a spectral mean wave period $T_m$ of 8.8 s (low to moderate wave energy). However, considerable annual variation in the wave conditions is experienced because of a distinct seasonality in the regional wind regime. During
summer, south to southwesterly, local, daily sea breezes generate moderate seas ($H_{1/3}$ 1 to 2 m; $T_m <8$ s). While during winter, northwesterly storms associated with mid-latitude depressions result in distantly generated swell and locally generated storm waves ($H_{1/3}$ 1.5 to 2.5 m; $T_m >8$ s). However, a background swell with $H_{1/3}$ around 0.5 m, generated in the Indian and Southern Oceans, is persistent all year round. Closer to shore, the waves are refracted and diffracted by a chain of reefs and islands, and attenuated by friction across the inner continental shelf. As a result, inshore wave heights are generally 40-60% less than corresponding offshore wave heights (Lemm et al., 1999; Pattiaratchi et al., 1997).

The directions of locally generated waves generally follow the winds, prevailing from the southwest during summer and the northwest during winter. Hence in the nearshore zone, the addition of these locally-generated waves to the background swell results in an increase in longshore current velocities, suspended sediment concentrations and longshore sediment transport rates (Pattiaratchi et al., 1997). From an analysis of cyclonic charts, Silvester (1961, cited in Masselink and Pattiaratchi, 2001b) concluded that an oscillatory north-south motion of sand occurs during the year along the Perth coast with a resultant northerly bias. Masselink and Pattiaratchi (2001b) analysed the alongshore wind component as an alternative approach to estimating the alongshore sediment transport patterns. Their analysis indicated that, although the net alongshore wind component in summer is clearly from the south, the winter component does not show a predominant direction. Masselink and Pattiaratchi (2001b) concluded that directional wave and current data are required to determine whether the Perth coast is characterised by a seasonal reversal in the littoral drift direction.

Each summer sea breeze clearly generates a pulse of obliquely-incident wind-wave energy from the southwest, resulting in northward longshore currents and sediment transport (Pattiaratchi et al., 1997; Masselink and Pattiaratchi, 1998a, 1998b). Because the sea breeze is a very regular phenomenon in the summer, the cumulative effect of all these sea breezes is substantial. Pattiaratchi et al. (1997) estimated that the net northward littoral drift during the summer months due to sea breeze activity amounts to 150,000 m$^3$. Thus the littoral drift caused by summer sea breezes is of fundamental importance to the overall sediment budget of the coast (Masselink and Pattiaratchi, 2001a; and Pattiaratchi et al., 1997).
### 3.2.3 Influence of sea breezes on nearshore processes

An experiment conducted at City Beach in southwestern Australia in 1992 highlighted the importance of sea breeze activity in affecting surf zone processes (Pattiaratchi et al., 1997, Masselink and Pattiaratchi, 1998b). The resulting data are discussed below. Prior to the onset of the sea breeze, offshore, easterly winds with speeds less than 5 m s$^{-1}$ prevail (Figure 3.2). The wind then turns southerly, blowing parallel to the coastline, with a strong sea breeze starting at 14:45 hrs. Its velocity rapidly increases to 10 m s$^{-1}$ and remains approximately constant until 20:00 hrs.

The onset of the sea breeze induces almost immediate changes in the nearshore hydrodynamics, as recorded in a mean water depth of 1.5 m, 20 m from the shoreline. Prior to the sea breeze, small-amplitude waves with root-mean-square wave heights ($H_{rms}$) of 0.3 m and zero-upcrossing periods ($T_z$) of 7-8 s prevail (Figure 3.3A & B). During the sea breeze, the incident wave height increases progressively, reaching 0.5 m at the end of the field survey. The wave period decreases and assumes a constant value of 4 s within one hour of the start of the sea breeze.

These hydrodynamic changes are principally attributed to the progressive addition of obliquely incident, locally generated wind waves to the shore-normal, background swell wave field. This can be demonstrated using a three-dimensional time-frequency plot based on the energy spectra of the waves (Figure 3.4). The background swell is present in the form of a linear ridge around frequency 0.1 Hz and its first harmonic. The peak period associated with the swell-wave energy is 11 s and remains relatively stable during the sea breeze. Wind waves generated by the sea breeze are first noticeable at 15:00 hrs.
15 min after the onset of the sea breeze. In time, the wind wave period increases from 3 s to a maximum of 5 s. The spectral energy of the wind waves also increases throughout the afternoon, reflecting the increasing wave heights (Figure 3.3A). The wave climate during the sea breeze can be described as bimodal, with peaks at the wind- and swell-wave frequencies.

The wind and swell waves are not only characterised by different wave periods, the wave angles are also different (Masselink and Pattiaratchi, 1998a). Wave angles were calculated for different wave frequencies, identified as swell- \( f = 0.05-0.15 \text{ Hz} \), wind- \( f = 0.15-0.5 \text{ Hz} \) and incident- \( f = 0.05-0.5 \text{ Hz} \) waves. The zero angle of incidence is defined as waves with crests parallel to the beach. The incident-wave angle is 6° prior to the sea breeze, which is similar to the angle of the swell-waves. The incident-wave angle increases to 18° during the sea breeze, and falls back to 6° at 4:00 hrs. The swell-wave angle remains around 6° over the entire sea breeze cycle. The wind-wave angle reaches values of 30° during the sea breeze and gradually decreases to 5° after the sea breeze. Therefore, during the sea breeze, the change in incident-wave angle is caused by the wind waves only.

![Figure 3.3](image-url)
The sea breeze does also affect the cross- and longshore current velocities. Previous to
the sea breeze, mean cross-shore currents are negligible (<0.05 m s⁻¹) and mean
longshore currents flow in the northward direction with velocities less than 0.1 m s⁻¹. At
the start of the sea breeze, offshore-directed currents in the surf zone rapidly increase in
strength to 0.16 m s⁻¹ and then fluctuate around 0.12 m s⁻¹ (Figure 3.3C). The northerly
longshore current progressively increases in strength up to 1 m s⁻¹ (Figure 3.3D).

As expected, the changes in hydrodynamic conditions influence sediment stirring and
entrainment. During the sea breeze, the amount of suspended sediment in the water
increases six-fold. Most importantly, longshore sediment transport during the sea breeze
activity is two orders of magnitude larger than when the sea breeze is not blowing
(Figure 3.5) (Masselink and Pattiaratchi, 1998b).

Both the wave angles and the time-frequency plot of water surface elevation (Figure 3.4)
show the clear distinction between the swell and wind waves. This bimodal wave climate
is typical for the coast of southwestern Australia. The continuously present swell waves
have a stable wave period and a small wave angle. The wind waves, on the other hand,
are highly dependent on the strength, direction and duration of the sea breeze. Generally, the wind waves are characterised by relatively small wave heights and small wave periods. The prevailing direction of the wind waves is southwesterly and the waves generate longshore currents directed northward.

![Figure 3.5: Vertically averaged longshore suspended sediment flux in kg m\(^{-1}\) s\(^{-1}\). The vertical dashed line indicates the start of the sea breeze (Masselink and Pattiaratchi, 1998b).](image)

The arrival of strong sea breezes is consistent and predictable. Additionally, when the sea breeze is not blowing, quiescent conditions prevail. The sea breezes therefore cause punctuated littoral drift events alternated with periods of insignificant longshore transport. These conditions are ideal for the investigation of longshore transport processes.

### 3.3 Measuring approach and transport estimation

#### 3.3.1 Measuring approach

In this study, longshore sediment transport was investigated on time scales ranging from seconds to weeks, for various low-energy sandy beaches. Data were recorded at five different beaches in southwestern Australia, using four different methodologies (Table 3.1 and Figure 3.1). The general measuring approach is described here, while more in-depth discussion of the methodologies can be found at the start of Chapters 4, 5 and 6.
At Brighton Beach three different methodologies were applied simultaneously (Table 3.1). At the smallest scale, three hydrodynamic frames were used to monitor nearshore processes during a sea breeze cycle. Each frame comprised a pressure sensor to measure waves and water depth, a current meter to monitor the flow field and two or three optical backscatter sensors to measure suspended sediment concentrations. The frames were located in an array across the littoral zone, the locations being lower swash zone, surf zone and breaker zone. In addition, the directional wave characteristics were measured just outside the surf zone.

The second methodology involved the placement of vertical arrays of portable streamer traps along the cross-shore profile. Typically, the streamer traps were deployed at similar locations to the hydrodynamic frames, to enable comparisons of the transport data. Ten measurements at half-hourly intervals were made during the sea breeze.

A tracer experiment at Brighton Beach was carried out at the same time as the sensor and streamer trap measurements. Three different fluorescent colours of tracer sand were injected at similar cross-shore locations to the hydrodynamic frames. The advection velocity of the tracer was derived through two different integration methods, the spatial- and the time-integration method. Reproducing similar experiments on three other beaches further tested the reliability of the tracer method. These other field experiments were conducted at South Leighton, Mullaloo and North Leighton beach (Table 3.1). Comparing the experiences in the field and the laboratory gave some insight into the problems and complications associated with tracer studies, while the resulting transport measurements provided data over a variation of hydrodynamic conditions. The tracer-methodologies are further explained in Chapter 5B.

In addition to the one-day field experiments, the long-term accumulation of sediment in front of a groyne at City Beach was monitored for a period of five months, bracketing the sea breeze season of summer (Table 3.1). A measurement grid consisting of 11 transects at a 50 m spacing was established and surveyed on a weekly basis using a theodolite and graduated staff. The survey data were used to derive weekly littoral drift rates using a mass balance approach. For 20 days during these five months of monitoring, directional wave data were collected at 5 m water depth at Floreat Beach, 1.1 km north of the area of the impoundment study (Figure 3.1).
Table 3.1: Overview of longshore transport measurements performed during this study.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Sensors</th>
<th>Streamer traps</th>
<th>Tracer</th>
<th>Impoundment</th>
</tr>
</thead>
<tbody>
<tr>
<td>City Beach</td>
<td>Oct '00 – Mar '01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15 surveys</td>
</tr>
<tr>
<td>Brighton Beach</td>
<td>10.01.01</td>
<td>3 cross-shore</td>
<td>10 deployments</td>
<td>2 methods (TIM &amp; SIM)</td>
<td>-</td>
</tr>
<tr>
<td>South Leighton</td>
<td>18.01.02</td>
<td>-</td>
<td>-</td>
<td>2 methods (TIM &amp; SIM)</td>
<td>-</td>
</tr>
<tr>
<td>Mullaloo Beach</td>
<td>25.01.02</td>
<td>-</td>
<td>-</td>
<td>2 methods (TIM &amp; SIM)</td>
<td>-</td>
</tr>
<tr>
<td>North Leighton</td>
<td>12.02.02</td>
<td>-</td>
<td>-</td>
<td>2 methods (TIM &amp; SIM)</td>
<td>-</td>
</tr>
</tbody>
</table>

During each experiment, directional wave data were collected just offshore of the breakerline and were analysed using the Maximum Entropy Method (Benoit, 1992) in the DIWASP Matlab® routine (DIWASP, 2003). The wave data were used to determine significant wave heights, peak wave periods and wave angles of the incident-, swell- and wind-waves. Spectral analysis enabled the construction of a time series of the water surface elevation and the determination of the distribution of wave energy and average statistics for each wave frequency by converting the time series into a wave spectrum. The variance of the data was described with respect to the frequency of the signal. This was essentially a transformation from time-domain to the frequency-domain by using a mathematical tool known as the Fast Fourier Transform (FFT). One representation of the directional spectrum was to consider how the energy was distributed in frequency, $f$, and direction, $\theta$ or $\alpha$ (Figure 3.6). This representation gave information on the direction in which the wave energy was moving. During this project the wave frequencies were identified as swell- ($f=0.05$-$0.15$ Hz), wind- ($f=0.15$-$0.35$ Hz) and incident- ($f=0.05$-$0.35$ Hz) wave frequencies.

The peak wave period, $T_p$, corresponds to the spectral peak frequency, which is the frequency at which the spectral density has a maximum. The significant wave period, $T_{sig}$, is related to the zero ($M_0$) and first ($M_1$) moment of the spectrum as:

$$T_{sig} = \frac{M_0}{M_1}$$  (3.1)
The significant wave height, $H_{\text{sig}}$, is the average height of the one-third highest waves and approximately corresponds to visual estimates of wave heights. In coastal engineering literature it is the preferred wave height descriptor (Aagaard and Masselink, 1999) and can be related to the zero moment of the spectrum ($M_0$) as:

$$H_{\text{sig}} = 4.004 \sqrt{M_0}$$

(3.2)

In order to determine the significant wave angle, $\alpha_{\text{sig}}$, a method similar to the calculation of $T_{\text{sig}}$ was used, whereby the $M_0$ and $M_1$ are calculated for each frequency-bin (instead of for each angle-bin). For a more thorough explanation of the calculation of wave parameters refer to Hegge and Masselink (1996) or CERC (2002).

In addition to nearshore data collected during the field studies, inshore wave data and meteorological data for the entire period of study were obtained. The inshore wave data were collected by a wave rider buoy in 17 m water depth in the Cottesloe deep channel (Figure 3.1) and were kindly provided by the Department of Transport, Fremantle,
Western Australia. The Commonwealth Bureau of Meteorology provided data on wind speed and direction at Swanbourne Beach.

3.3.2 Application of longshore transport models

There are several transport models available to estimate the amount of longshore littoral drift. The use of these transport models was discussed in Section 2.4. The three models used in this project are those discussed by CERC (1984), Inman and Bagnold (1963) and Kamphuis (1991b).

Using the 'CERC'-equation the longshore volume transport is estimated using the combination of Equation 2.2 and Equation 2.7, as:

$$Q_{\text{CERC}} = \frac{K}{16\sqrt{\gamma}} \frac{\rho g^{3/2} H_b^{5/2} \sin 2\alpha}{(\rho_s - \rho) g (1 - p)}$$  \hspace{1cm} (3.3)

The estimate of 'Inman and Bagnold', using Equations 2.2 and 2.15, reads:

$$Q_{\text{I&B}} = \frac{K'}{4} \left( \frac{\rho g H_b^2}{\gamma} \right) \frac{\bar{v}_j}{(\rho_s - \rho) g (1 - p)}$$  \hspace{1cm} (3.4)

or if the longshore velocity is estimated from wave breaker values, using Equation 2.17:

$$Q_{\text{I&B, estimate}} = \frac{2.7K'}{16\sqrt{\gamma}} \frac{\rho g^{3/2} H_b^{5/2} \sin 2\alpha}{(\rho_s - \rho) g (1 - p)}$$  \hspace{1cm} (3.5)

The 'Kamphuis' formula according to Equation 2.19 is:

$$Q_{\text{Kamphuis}} = 2.03 \times 10^{-3} H_s^2 T_p^{1.5} \tan \beta^{0.75} D_s^{-0.25} \sin^{0.6} (2\alpha_b)$$  \hspace{1cm} (3.6)

At the most fundamental level, longshore transport in the nearshore zone is caused by a combination of two processes: the agitation of sediment by incident wave motion and the entrainment of sediment by a longshore current. The bimodal wave climate during sea breezes along the coast of southwestern Australia imposes complications when trying to
use this approach. The stirring of sediment is caused by a combination of both swell and wind waves, while the longshore current that transports the agitated sediment is induced mainly by the obliquely-incident wind waves. Swell waves are almost parallel to the coast and do not induce a longshore current. The problem arises when deciding on which values of the wave parameters to use as input parameters to the above equations, since the combined contribution of wind and swell waves is presumably greater than their sum when acting alone because of the interaction between them (Boon et al., 1996). Several different combinations of input parameters were tested, resulting in six different estimates of transport rates with which to compare the transport measurements (Table 3.2).

In the Inman and Bagnold (1963) equation (Section 2.4.4) $H_b$ represents the incident significant wave height at the breaker line and the $v_l$ is the longshore current measured near the water surface in the mid-surf zone, Equation 3.4 (Model 1 in Table 3.2). Where $v_l$ cannot be measured, it can be estimated using a wave height and wave angle of the wind waves, which results in Equation 3.5 (Model 2 in Table 3.2).

In the equations of CERC (1984) and Kamphuis (1991b) the separation between wave stirring factor and transporting factor is not made. This makes it harder to suggest a solution when experiencing a bimodal wave field, as it is unknown which of the wave parameters (height, period and angle) should be used as the equations’ input parameters. In this project two different sets of input values were used.

The first set used combined values of both swell and wind waves, which resulted in an input of the incident significant wave height at breaking $H_s,\text{incident}$, the incident peak wave period $T_p,\text{incident}$ and significant angle of wave approach $\alpha_s,\text{incident}$ to compute longshore transport. This model was referred to as ‘-incident’ (Models 3 & 5 in Table 3.2).

The second set assumed that the wave angle of swell waves was zero and considered the transport by the wind waves only. The input parameters were the significant wind-wave height, wind peak wave period and significant wind-wave angle. This was referred to as ‘-wind’ (Models 4 & 6 in Table 3.2).
### Table 3.2: Overview of the transport models used.

<table>
<thead>
<tr>
<th>Longshore transport model</th>
<th>Equation</th>
<th>Input wave parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Inman and Bagnold -incident</td>
<td>3.4</td>
<td>(H_s,<em>{\text{incident}}; V</em>{l,\text{measured}})</td>
</tr>
<tr>
<td>2 Inman and Bagnold -estimated</td>
<td>3.5</td>
<td>(H_s,<em>{\text{incident}}; H_s,</em>{\text{wind}}; \alpha_s,_{\text{wind}})</td>
</tr>
<tr>
<td>3 CERC -incident</td>
<td>3.3</td>
<td>(H_s,<em>{\text{incident}}; \alpha_s,</em>{\text{incident}})</td>
</tr>
<tr>
<td>4 CERC -wind</td>
<td>3.3</td>
<td>(H_s,<em>{\text{wind}}; \alpha_s,</em>{\text{wind}})</td>
</tr>
<tr>
<td>5 Kamphuis -incident</td>
<td>3.6</td>
<td>(H_s,<em>{\text{incident}}; T_p,</em>{\text{incident}}; \alpha_s,_{\text{incident}})</td>
</tr>
<tr>
<td>6 Kamphuis -wind</td>
<td>3.6</td>
<td>(H_s,<em>{\text{wind}}; T_p,</em>{\text{wind}}; \alpha_s,_{\text{wind}})</td>
</tr>
</tbody>
</table>
CHAPTER 4: IMPOUNDMENT STUDY - LONGSHORE TRANSPORT ON LARGE TEMPORAL AND SPATIAL SCALES

4.1 INTRODUCTION

This chapter considers longshore sediment transport at the largest temporal and spatial scales using an impoundment study (refer to Figure 1.1). This study was carried out at City Beach (Figure 3.1), where the amount of sand blocked by a shore-normal groyne was monitored by conducting weekly beach surveys during a five-month period. These successive surveys provided data on changes in beach morphology, beach width and beach volume, whereby the volume changes were used as an indicator of littoral drift rates. These measured drift rates were supplemented with data on the wind climate, wave breaking conditions and transport estimates derived from several littoral drift equations.

4.2 METHODOLOGY

4.2.1 Impoundment study

The long-term impoundment study involved measurement of the amount of sediment trapped in front of a permanent shore-normal groyne. Along the coast of Southwestern Australia, the prevailing southerly sea breezes during summer induce longshore sediment transport towards the north. The littoral drift results in deposition of sand at the updrift side of the groyne (Figure 4.1) resulting in saturation of the groynes at the end of summer (Figure 4.2).

The impoundment study was carried out during the summer sea breeze season from October 2000 until March 2001 on City Beach (Figure 3.1). Eleven transects with a spacing of 50 m were established perpendicular to the shoreline, at the updrift side of the groyne, with the study area extending from the groyne itself to some distance outside the adjusted shoreline (Figure 4.1). Each transect was connected to temporary benchmarks, the height of which was established relative to the Australian Height Datum (AHD-level) as a close approximation of mean sea level. Weekly surveys were conducted with beach
profiles extending into the water to a depth of circa -1.5 m AHD. A theodolite and levelling staff were used to measure the differences in height at each transect.

![Diagram of shoreline configuration](image)

**Figure 4.1:** General shoreline configuration of the study area (modified from CERC (1984)).

![Study area photo](image)

**Figure 4.2:** Study area of the impoundment experiment. Top of the photo represents south (Photography by Werner Bartel).

The successive surveys provided data on the volume of sand eroded or accreted in the study area. The region subjected to significant volume changes is referred to as the 'active zone' and can be defined by landward and seaward limits. The landward limit was simply taken as the edge of the dunes. The seaward limit represents the closure depth and is located at the seaward edge of the littoral zone where changes in the bed level are insignificant. The seaward limit needs to be accurately defined to minimise a combination of errors arising from: (1) not including a sufficient offshore distance to
cover the complete active zone; and (2) including a too large offshore distance, such that a small bias in elevation can result in significant errors (Dean et al., 1987). According to the model developed by Hallermeier (1981), and using the significant wave record during the five months of study, this closure depth was situated at -4.9 m AHD and -2.8 m AHD for the incident and wind waves respectively. These depths exceed the maximum depths of the beach surveys, as it was virtually unworkable to conduct accurate morphological measurements in water depths exceeding 1.5 m. However, inspection of the measured profiles suggested a common convergence depth for most of the profiles at -1.44 m AHD with most profile change occurring above -1 m AHD. Therefore all profile data were made to converge at -1.44 m AHD (Figure 4.3).

![Figure 4.3: (A) Original and (B) adjusted profiles 50 m updrift of the groyne.](image)

For each measured profile the beach width and volume were determined. The width of the beach can be used as a measure of beach erosion or accretion, assuming the beach extends as a result of accretional events, and shortens as a result of erosional events. The width of the beach was defined as the distance between the edge of the dune and the intersection of the beach profile with mean sea level (MSL) at \( z = 0 \) m AHD (Figure 4.4). Transect-volume was calculated between the landward (edge of the dune) and the convergence depth (\( z = -1.44 \) m AHD), in units of cubic meters per meter beach width. Data from the weekly surveys were used to calculate digital elevation models of the study area. Therefore the longshore and cross-shore coordinates of the measured beach profiles were interpolated into a grid with 1 m spacing, after which an elevation surface was passed through the data points using a triangle-based linear interpolation (‘meshgrid’ and ‘griddata’-routines in Matlab®).
Both cross-shore and longshore transport processes contribute to the total volume change, and to derive littoral drift rates from beach volumetric changes it is necessary to distinguish between the two contributions. Volume change caused by processes other than longshore sediment transport was estimated using the volume change measured at the two profiles located furthest from the groyne. During the first half of the study these profiles were situated outside the area of groyne-influence and it was assumed that the changes recorded by these profiles could be solely attributed to cross-shore sediment transport and that volume changes of the beach at these locations were directly related to onshore and offshore sediment transport processes. It was further assumed that sediment volume changes induced by cross-shore transport were uniform along the entire study area. Inside the groyne-adjusted area, volume changes are caused both by longshore and cross-shore transport. Volume changes caused by longshore transport were subsequently computed by determining the total volumetric change in the groyne-adjusted area and subtracting the cross-shore contribution derived from the volumetric changes measured outside the groyne-adjusted area, a method previously applied by Bodge and Dean (1987).

![Figure 4.4: Definition of the beach width, as the distance between the edge of the dunes and MSL (indicated by dotted vertical lines). The shaded area represents the beach volume. The beach profile in this example is Transect 1 on Day 146 (23rd February 2001).](image)

### 4.2.2 Collection and analysis of hydrodynamic data

An insight into the influence of sea breezes on the hydrodynamic conditions of the study site can be achieved by using a combination of wind and wave data. For 20 days during the five months of beach monitoring, directional wave data were collected at 5 m water depth at Floreat Beach, 1.1 km north of the area of the impoundment study (Figure 3.1).
Using refraction and shoaling equations on these wave data provided breaker wave values of wave height, period and angle (Figure 4.5).

Since the beach monitoring during the impoundment study lasted 5 months instead of 20 days, additional data was used to estimate breaker wave data during the whole study period. Using inshore wave data and wind data, and relating these to the 20 days of breaker wave data by using regression models, provided the means to estimate breaker wave characteristics at the impoundment area during the entire study period (Figure 4.5). The inshore wave data were available from a Waverider Buoy located in 17 m water depth, west of Cottesloe (Figure 3.1). The data consisted of values of significant wave height and peak wave period of total, swell and wind waves. Half-hourly coastal wind data collected at Swanbourne beach, 4.5 km south of the study area (Figure 3.1), were used to determine the sea breeze climate.

Wave refraction and shoaling equations were applied to the 20 days of directional wave data in order to determine the breaker wave values. Snell's law was used, assuming that the energy dissipation prior to breaking could be neglected and that the bottom contours were parallel to the coast. The wave breaker values depend on the breaker index \( \gamma_b \) (non-dimensional), which relates to the beach slope and deep-water wave steepness (Battjes, 1974; and Komar, 1998) according to:
\[ \gamma_b = 1.20 \xi_{\infty}^{0.27} = 1.20 \left( \frac{\tan \beta}{\sqrt{H_{\infty}/L_{\infty}}} \right)^{0.27} = 1.20 \left( \frac{\tan \beta}{\sqrt{2\pi H_{\infty}/gT^2}} \right)^{0.27} \] (4.1)

where \( \xi_{\infty} \) = deep-water Iribarren number (-); \( \tan \beta \) = beach slope (-); \( H_{\infty} \) = deep-water significant wave height (m); \( L_{\infty} \) = deep-water wave length (m); and \( T \) = wave period (s). Each wave experiences the same beach slope, but the deep-water wave steepness is variable and this influences the breaker index. Assuming typical deep-water wave conditions were measured by the Waverider Buoy in 17 m water depth, the different breaker indices were calculated and used to determine the breaker values of the wave height and wave angle (Table 4.1).

<table>
<thead>
<tr>
<th>Wave Parameter</th>
<th>Swell Waves</th>
<th>Wind Waves</th>
<th>Incident Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_{\infty} ) (m)</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>( T_{\infty} ) (s)</td>
<td>11.5</td>
<td>3.7</td>
<td>5.4</td>
</tr>
<tr>
<td>( \tan \beta ) (-)</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>( \xi_{\infty} ) (-)</td>
<td>0.61</td>
<td>0.17</td>
<td>0.21</td>
</tr>
<tr>
<td>( \gamma_b ) (-)</td>
<td>1.05</td>
<td>0.74</td>
<td>0.79</td>
</tr>
</tbody>
</table>

4.3 RESULTS FROM THE IMPOUNDMENT STUDY

4.3.1 Beach morphology

During the beach surveys, changes in beach morphology and the shape of the beach profiles were monitored (Figure 4.6). Data from the weekly surveys were used to calculate digital elevation models of the study area, indicating a general increase in beach width and sediment volume over the survey period (Figure 4.7). The first survey was carried out on 28th October 2000 (Day 28) and the last on 9th March 2001 (Day 160). The date of survey will be referred to as the day since the 1st October 2000.

At the start of the monitoring period, the profiles were relatively flat, with a small beach berm and clear berm crest at the profiles located up to 150 m from the groyne (Transects 1-3). During the monitoring period, an upward and seaward growth of the beach berm was recorded. The average height of the berm crest was 1.0 m relative to AHD at Day 34 and 4 months later was an average of 1.7 m AHD (Day 160). During this
development the slope of the beach face (from berm crest to mean sea level) remained relatively stable. As the berm grew higher and built seaward it produced a landward-sloping berm. Towards the end of the monitoring period, the highest swashes were able to run down this landward inclined berm towards the middle of the beach. According to residents of the area, in some years enough water collects here to create a static pool.

Figure 4.6: Beach profiles measured at Day 34 (solid thin line), Day 62 (dotted line), Day 97 (dashed line) and Day 160 (solid bold line). The circles indicate the berm crest location.

The growth of the berm is the result of a combination of the wave climate and the sediment supply. According to Bascom (1953) berm growth is caused by the uprush of the largest waves whose swash run-up extends completely over the crest and deposits sand on the top of the berm. Pattiaratchi et al. (1997) and Masselink and Pattiaratchi (1998a, 1998b) suggest that along the coast of southwestern Australia, this growth takes place before and after a summer sea breeze when the swell waves break by plunging and surge up the beach face. While during the sea breezes, the wind waves break by plunging/spilling and erode the beach face. Such a daily cycle of beach erosion and
accretion is analogous to the storm cycle of beach change (Komar, 1998). In general the offshore and onshore sediment transport are balanced on a daily basis, but at the study area there is also an ample supply of sediment that is impounded by the groyne which is available for onshore movement by the swell waves and can be used in the development of the berm. During winter, the berm disappears when the moderate seas generated by the sea breezes play a minor role. Instead winter storms and the associated distantly generated swell and locally generated storm waves cause erosion and flattening of the beach face.

As pointed out by Masselink and Pattiaratchi (2001b) the wind and wave conditions along the coast are characterised by a seasonal reversal in the prevailing directions. The littoral drift is directed northwards during summer (driven by sea breezes) and southwards during winter (forced by storms). Similar to the study site, beaches situated south of coastal structures, natural headlands or rocky outcrops become wider due to the accumulation of sediment against the obstacle, during summer. These beaches will subsequently erode in winter when the longshore sediment transport is toward the south. These findings indicate that for the Perth coastline, the beach cycle is not attributed to variations in the incident wave energy level, which would cause a cross-shore sediment exchange between the sub-aerial beach and surf zone, resulting in wide, non-barred beaches in summer and narrow, barred beach in winter (Davis and Fox, 1972).
Figure 4.7: Elevation model relative to mean sea level. The top of each plot represents north, the rectangle indicates the location and size of the groyne, the right-hand black line represents the foot of the dunes and the left black line represents mean sea level (0 m AHD).
4.3.2 Beach width

Changes in beach width (distance between foot of the dunes and mean sea level) are different for each transect and not constant during the whole measurement period (Figure 4.8). In the beginning, until day 48, the beach width remained relatively constant, indicating little longshore transport coming from the south. From day 48 the transects located close the groyne start to get wider (e.g., transect 1 and transect 4 in Figure 4.8) while the transects located further away increase in width at a later time (e.g., transect 11 from day 90 onwards). This illustrates how the area of groyne-influence increases in the updrift direction while the impoundment of longshore transported material continues. From day 117 onwards there is only limited increase in beach width of the study area. The shoreline of transects 1-3 extends seaward of the saturated groyne, as a result the northward transported sand mainly bypasses the groyne and this inhibits further significant changes in beach width. The periods with most extension occurred between days 48–55, 69–76, 90–97 and 104–117 (indicated by 1-4 on grey bars in Figure 4.8).

![Figure 4.8: Change of the beach width (m) relative to the first measurements (Day 28). The grey bars indicate the periods with the most extension of the beach.](image-url)
Generally, the spatial difference in the width-change depends on the distance to the groyne; there is more extension closer to the groyne than further away, e.g. transect 1 versus transect 11 (Table 4.2). These findings correspond well with the research of beach width change along the Perth metropolitan coastline, undertaken by Masselink and Pattiaratchi (2001b). They suggested a 50 m amplitude of width-change close to obstacles such as groynes and further illustrated that beach morphology along the coastline of Perth exhibits a distinct seasonality whereby the changes of beach width were mainly caused by the seasonal changes in littoral drift direction.

Table 4.2: Change in beach width during a period of 18 weeks.

<table>
<thead>
<tr>
<th>Profile number</th>
<th>Updrift distance from groyne (m)</th>
<th>Beach width (m) Day 34</th>
<th>Beach width (m) Day 160</th>
<th>Change (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>45</td>
<td>93</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>56</td>
<td>98</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>50</td>
<td>92</td>
<td>42</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>55</td>
<td>94</td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
<td>59</td>
<td>91</td>
<td>32</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>63</td>
<td>89</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>350</td>
<td>60</td>
<td>84</td>
<td>24</td>
</tr>
<tr>
<td>8</td>
<td>400</td>
<td>57</td>
<td>77</td>
<td>21</td>
</tr>
<tr>
<td>9</td>
<td>450</td>
<td>56</td>
<td>73</td>
<td>18</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>53</td>
<td>69</td>
<td>16</td>
</tr>
<tr>
<td>11</td>
<td>550</td>
<td>51</td>
<td>64</td>
<td>13</td>
</tr>
</tbody>
</table>

Unsurprisingly the increase in beach width coincides with beach volume increase (Figure 4.9). The changes in width and volume were calculated relative to the first measurement (day 28) and as a result some of the measured changes are negative since beach erosion was recorded at the start of the monitoring period. The beach volume was calculated over the area ranging from the foot of the dunes to the point of profile convergence at \( z = -1.44 \) m AHD. All profiles display a similar relationship, with the data of profile 1 located in the top-right corner of the figure, indicating the profile situated closest to the groyne which experienced the largest increase in both beach width and volume. At transect 5 the profile on day 28 was relatively linear and more convex upwards during the following measurements. Therefore the beach volume change relative to the width on day 28 was largest for this transect and the data plots 'above' the data points of other transects.
According to Sonu and James (1973), the relationship between beach width and beach volume can be indicative of the shape of the beach. Taking into account the area between the shoreline and the point of maximum horizontal wave run-up, for a given beach width, the beach volume was found to increase when the beach profile transforms from concave upward to linear to convex upward shape. Inspection of the beach profiles of this study indicates that all profiles have a relatively convex upward shape.

4.3.3 Beach volume

Data from the beach surveys were used to obtain elevation models of the beach (Figure 4.7) from which elevation changes can be derived (Figure 4.10). At the start of the measuring period, change is small, but from day 76 onwards there is a clear increase in beach volume near the groyne. Over time the area of volume-increase lengthens further southward, in a wedge-like shape. From day 90 onwards this ‘wedge’ has extended to reach the southern limit of the area of survey profiles (transects 10 and 11), indicating that by this time the study area was too small to account for all groyne-influenced volume changes. This illustrates how the area of groyne-influence increases with time.
Figure 4.10: Change of elevation relative to the first survey (Day 28). The top of each plot represents north, the rectangle indicates the location and size of the groyne, the right-hand black line represents the foot of the dunes and the left black line represents mean sea level (0 m AHD).
After the total beach volume for each survey and the volume change between surveys had been calculated, the total volume change was subdivided into segments caused by either cross-shore or longshore transport, as discussed in Section 4.2.1 (Table 4.3, Figure 4.11). This subdivision was possible until day 90, using the volume change of transects 10 and 11 as indicators of the cross-shore transport rate. The cross-shore volume change broadly shows erosion at the start of the measurement period and accretion from day 62 to day 90. A period with considerable erosion is situated between days 28–34, while most accretion was experienced between days 48–55. The volume change caused by longshore transport indicates accretion during the entire measurement period. Most accretion was found between days 48–55 and 69–76.

<table>
<thead>
<tr>
<th>Day</th>
<th>Total Volume (m³)</th>
<th>Total Volume change (m³ day⁻¹)</th>
<th>Cross shore (m³ day⁻¹)</th>
<th>Longshore (m³ day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>144686</td>
<td>-1605 -268</td>
<td>-236 88</td>
<td>-31 12</td>
</tr>
<tr>
<td>34</td>
<td>143081</td>
<td>1329 190</td>
<td>15 8</td>
<td>175 92</td>
</tr>
<tr>
<td>41</td>
<td>144410</td>
<td>73 10</td>
<td>-5 -50</td>
<td>15 150</td>
</tr>
<tr>
<td>48</td>
<td>144483</td>
<td>6308 901</td>
<td>476 53</td>
<td>425 47</td>
</tr>
<tr>
<td>55</td>
<td>150791</td>
<td>990 141</td>
<td>-24 -17</td>
<td>166 117</td>
</tr>
<tr>
<td>62</td>
<td>151781</td>
<td>2043 292</td>
<td>251 86</td>
<td>41 14</td>
</tr>
<tr>
<td>69</td>
<td>153824</td>
<td>7197 1028</td>
<td>70 7</td>
<td>958 93</td>
</tr>
<tr>
<td>76</td>
<td>161021</td>
<td>2851 204</td>
<td>67 33</td>
<td>136 67</td>
</tr>
<tr>
<td>90</td>
<td>163872</td>
<td>6449 921</td>
<td></td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>170321</td>
<td>3095 442</td>
<td></td>
<td></td>
</tr>
<tr>
<td>104</td>
<td>173416</td>
<td>8281 637</td>
<td></td>
<td></td>
</tr>
<tr>
<td>117</td>
<td>181697</td>
<td>1081 72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>132</td>
<td>182778</td>
<td>1895 135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>146</td>
<td>184673</td>
<td>485 35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>185158</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4: Impoundment study

The total beach volume decreased at the start of the summer period, between days 28 and 34 (Table 4.3). From day 48 onwards the total beach volume increased substantially until day 117, after which the total beach volume remained relatively constant. Based on both visual observations and volume measurements it was concluded that the groyne was saturated after day 117, after which a large proportion of the littoral drift was considered to bypass the groyne and therefore the volume change no longer reflects the longshore sediment transport rate. Data from day 117 onwards was not considered in further analysis. Prior to day 117 at least part of the littoral drift must have been bypassing the groyne, the amount of which is hard to quantify. This needs to be considered during further data interpretation. There are four periods of major increase in total volume. The depositional event between days 69–76 was mainly caused by accretion due to longshore transport (93 %), while the first event, days 48–55, is caused by both cross-shore and longshore transport.

The four periods of major volume increase coincide with the periods of largest increase in beach width (compare Figure 4.8 and Figure 4.11). The shape of the curve representing the change in beach width of Transect I is identical to the curve of total volume change. Similarly, the trend of Transect II is reflected in the trend of the cross-shore component. This appears reasonable, since the beach change close to the groyne is caused by both longshore and cross-shore transport processes, while outside the area of groyne-influence, at Transects 10 and 11, the change is caused by solely cross-shore transport. Additionally, the periods during which the beach width extends the most and
the volume increases the most coincide, which suggests that the beach width can be used as an indicator of beach accretion.

The total volume changes until day 90 are considered reasonably accurate given the measurements undertaken and accordingly can be regarded as the upper limit to the actual longshore transport rate. It was assumed the volume changes measured at profiles furthest from the groyne (transects 10 and 11) were solely caused by cross-shore sediment transport before day 90, as these were outside the area upon which the groyne showed an impact. Accordingly, this cross-shore transport could be assumed to be representative of the whole study area. The volume change as a result of longshore transport was thus derived as the difference between the total and cross-shore volume changes. Therefore, the best estimate of longshore sediment transport is expected to be between these limits for the total and the longshore volume change during the period days 48–90 and is represented by an envelope in Figure 4.12. From day 90 until groyne saturation (day 117) most of the longshore transported sand is expected to be included in the volume changes of the study area. After day 117 a large amount of sediment is expected to by-pass the groyne, and volume changes are no longer accurate indicators of transport rates.

![Figure 4.12: Envelope of the longshore transport rate.](image-url)
4.4 WIND CLIMATE AND WAVE BREAKING CONDITIONS

4.4.1 Directional wave data

Directional wave data at the study area were measured for a 20-day period, after which breaker wave data were derived from refraction and shoaling equations. Together with the coastal wind data, this gives an insight into the influence of sea breezes on the hydrodynamic conditions of the study site.

Generally, during a sea breeze the wind speed increases, this daily cycle being recognised during the first week of measurements (days 112–118 in Figure 4.13A). A similar diurnal variation, as a direct result of the sea-breeze activity, is recorded in the wind-wave angle (Figure 4.13B) and in the wind-wave height (Figure 4.13C). The swell-wave height changes independently of the sea breeze activity (Figure 4.13D) and is influenced by lower-frequency synoptic weather patterns, such as the passage of mid-latitude depressions (Masselink and Pattiaratchi, 2001a). Throughout the measurement period, background swell was constantly present with a dominant frequency of 0.08 Hz, while the higher-frequency wind-wave energy was only present in the wave spectrum during (and for some time after) a sea breeze (Figure 4.13E). Temporal variability in the breaker height of the swell and wind waves reflects their different causative mechanisms.

In the directional wave spectrum, the constantly present, shore-normal, background swell is characterised by a high, narrow peak, whereby the spectral energy is concentrated around low wave angles (5 degrees) and frequency 0.1 Hz (Figure 4.14 and Figure 4.15). During the sea breeze, obliquely-incident wind waves are added to the spectrum, while the swell waves remain relatively stable. The wind waves are recognised by a lower, wider peak in spectral density, located around frequencies 0.2–0.3 Hz and with wave angles in the region of 20 degrees. The directional wave spectra do illustrate the characteristic bimodal wave climate present during the sea breezes.
Figure 4.13: Summary of wind and wave conditions near the study site: (A) Wind speed; (B) Breaker angle of wind waves; (C) Significant breaker height of wind waves; (D) Significant breaker height of swell waves; and (E) Normalised wave spectrum with contourlines representing normalised spectral variance levels of 0.02, 0.04, 0.08 and 0.16.

Figure 4.14: Directional wave spectra before (at 11:00 hrs) and during (at 17:00 hrs) a sea breeze on 2nd February 2001 (Day 125).
A parameter of major influence on the longshore sediment transport rate is the longshore flux of wave energy ($P$ in N s$^{-1}$, Equation 2.6). The spectral distribution of $P$ can be calculated, since this parameter is directly proportional to the wave height (related to the spectral density, $E$) and wave angle ($\alpha_{\text{sig}}$) (Figure 4.15). If either $E$ or $\alpha_{\text{sig}}$ approaches zero, the resulting $P$ will be very small. The swell waves might contain a large amount of energy (relatively large wave height) but are characterised by low wave angles, therefore the longshore energy flux of the swell waves is small. Wind waves, on the contrary, are characterised by a medium wave height and large wave angles, which results in a large longshore flux of wave energy. Clearly the differences in both the shape and location of the swell and wind-peak in the directional wave spectrum have far-reaching consequences for the exerted longshore energy flux. During a sea breeze, the total amount of longshore energy flux exerted by the wind waves is higher than that of the swell waves and as a result longshore sediment transport during sea breezes is mainly driven by the wind waves.

![Figure 4.15: Spectral density (A & B), significant wave angle (C & D) and longshore energy flux factor (E & F) before (left column) and during (right column) a sea breeze.](image)
4.4.2 Regression models

Linear regression models were used to relate 20-days of breaker wave data to the inshore wave data and wind data. The breaker wave height of the swell ($H_{b,\text{swell}}$), wind ($H_{b,\text{wind}}$) and incident ($H_{b,\text{incident}}$) waves (derived from the directional wave data) were related to the inshore wave height of swell ($H_{o,\text{swell}}$), wind ($H_{o,\text{wind}}$) and incident ($H_{o,\text{incident}}$) waves respectively (Figure 4.16A and Table 4.4). The peak wave period of the swell ($T_{b,\text{swell}}$) and incident ($T_{b,\text{incident}}$) waves could be related to the inshore peak wave periods of swell ($T_{o,\text{swell}}$) and incident ($T_{o,\text{incident}}$) waves respectively. Unfortunately, the peak period of the wind waves measured inshore ($T_{o,\text{wind}}$) is not correlated to wave breaking equivalent ($T_{b,\text{wind}}$) since the variations in $T_{o,\text{wind}}$ were much larger. Therefore, the peak period of the wind waves was related to the longshore wind component derived from the meteorological data (Table 4.4).

The timeseries of the inshore wave angles is much less variable than the breaker wave angles, therefore other data sources were used to derive wave angles for the time of impoundment study. The breaker wave angle of the incident ($\alpha_{\text{incident}}$) and wind waves ($\alpha_{\text{wind}}$) could be related to the longshore wind component derived from the wind data (Table 4.4 and Figure 4.16B). Wind characteristics are traditionally represented as a vector, where the length denotes the wind speed and the direction denotes the wind direction, and accordingly the cross-shore and longshore wind components were derived from this vector. Swell waves were found to be unaffected by the local winds and their angle could not be related to any of the wind components. Therefore the mean swell-wave angle of the directional wave data was used, being 2.7 degrees (Table 4.4). The significance of each regression was tested using the square of the correlation coefficient ($r^2$), thus an estimate of the proportion of the variation that was explained by the regression. The $r^2$ values were significant at the 95% level for the regression equations stated in Table 4.4.
Chapter 4: Impoundment study

Figure 4.16: Linear regression of (A) breaker versus offshore wind-wave height ($N = 498; r^2 = 0.70$); and (B) breaker wind-wave angle versus longshore wind component ($N = 498, r^2 = 0.57$).

<table>
<thead>
<tr>
<th>Breaker Parameter</th>
<th>Linear Regression</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{b,\text{swell}}$ (m)</td>
<td>$0.15 + 0.79 H_{\omega,\text{swell}}$</td>
<td>0.76</td>
</tr>
<tr>
<td>$H_{b,\text{wind}}$ (m)</td>
<td>$-0.008 + 0.78 H_{\omega,\text{wind}}$</td>
<td>0.79</td>
</tr>
<tr>
<td>$H_{b,\text{incident}}$ (m)</td>
<td>$0.08 + 0.74 H_{\omega,\text{incident}}$</td>
<td>0.75</td>
</tr>
<tr>
<td>$T_{b,\text{swell}}$ (s)</td>
<td>$1.89 + 0.87 T_{\omega,\text{swell}}$</td>
<td>0.52</td>
</tr>
<tr>
<td>$T_{b,\text{wind}}$ (s)</td>
<td>$5.76 - 0.21$ Longshore Wind Component</td>
<td>0.29</td>
</tr>
<tr>
<td>$T_{b,\text{incident}}$ (s)</td>
<td>$3.33 + 0.72 T_{\omega,\text{incident}}$</td>
<td>0.43</td>
</tr>
<tr>
<td>$\alpha_{\text{swell}}$ (deg)</td>
<td>$2.7$</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha_{\text{wind}}$ (deg)</td>
<td>$1.48 + 1.91$ Longshore Wind Component</td>
<td>0.47</td>
</tr>
<tr>
<td>$\alpha_{\text{incident}}$ (deg)</td>
<td>$3.53 + 1.51$ Longshore Wind Component</td>
<td>0.37</td>
</tr>
</tbody>
</table>

4.5 LONGSHORE SEDIMENT TRANSPORT

4.5.1 Transport related to hydrodynamic conditions

The application of the regression models on the inshore wave data, as indicated in Table 4.4, resulted in a time series for the wave conditions during the entire impoundment study (Table 4.5 and Figure 4.17). The next step is to relate the time series of wind and wave conditions to the measured transport rates of the impoundment study.

At the start of the impoundment study, from day 28 until day 48, the transport rates were low (Table 4.3). During this period the sea breeze activity was minimal as indicated by the low wind speed, longshore wind component, wind wave angle ($\alpha_{\text{wind}}$) and significant
Similarly, it can be expected that the four periods of largest longshore transport rates were related to the weeks characterised by strong daily sea breezes. During the monitoring period, the number of sea breezes varied between 3 and 7 per week. Daily breezes were recorded between days 62 and 76, where there was a diurnal variation in wind speed, wind direction, cross-shore wind component and longshore wind component (Figure 4.17A–D). As a result, the longshore sediment transport can be expected to peak during this period. This was the case during the second week, between days 69 and 76, where the highest rates of total and longshore transport were measured, while the cross-shore transport was minimal (shaded period 2 in Figure 4.17, Table 4.3).

However, similar meteorological conditions were experienced in the previous week (days 62–69), where longshore transport rates were 20 times smaller. Accordingly, the longshore transport rate is noted as not being directly proportional to the number and strength of sea breezes. This can be the result of the linear regression method by which the breaker wave data have been derived. If the relations were better described by non-linear equations, the individual predictions are prone to errors.

### Table 4.5: Average wind and wave parameters during each survey Interval. Bold numbers indicate periods of major volume increase.

<table>
<thead>
<tr>
<th>Day</th>
<th>wind speed (m s⁻¹)</th>
<th>cross. comp. (m s⁻¹)</th>
<th>long. comp. (m s⁻¹)</th>
<th>α_{wind} (deg)</th>
<th>T_{p,wind} (s)</th>
<th>H_{wind} (m)</th>
<th>T_{p,swell} (s)</th>
<th>H_{swell} (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28-34</td>
<td>5.8</td>
<td>0.7</td>
<td>3.0</td>
<td>7.2</td>
<td>5.1</td>
<td>0.54</td>
<td>13.0</td>
<td>0.68</td>
</tr>
<tr>
<td>34-41</td>
<td>5.5</td>
<td>2.8</td>
<td>1.9</td>
<td>5.1</td>
<td>5.4</td>
<td>0.65</td>
<td>13.5</td>
<td>0.73</td>
</tr>
<tr>
<td>41-48</td>
<td>5.4</td>
<td>-0.7</td>
<td>1.1</td>
<td>3.5</td>
<td>5.5</td>
<td>0.44</td>
<td>12.8</td>
<td>0.53</td>
</tr>
<tr>
<td>48-55</td>
<td>5.9</td>
<td>-1.4</td>
<td>2.7</td>
<td>6.6</td>
<td>5.2</td>
<td>0.45</td>
<td>14.4</td>
<td>0.49</td>
</tr>
<tr>
<td>55-62</td>
<td>6.0</td>
<td>2.5</td>
<td>3.7</td>
<td>8.6</td>
<td>5.0</td>
<td>0.64</td>
<td>12.5</td>
<td>0.69</td>
</tr>
<tr>
<td>62-69</td>
<td>6.4</td>
<td>0.0</td>
<td>5.0</td>
<td>11.0</td>
<td>4.7</td>
<td>0.64</td>
<td>12.7</td>
<td>0.60</td>
</tr>
<tr>
<td>69-76</td>
<td>6.0</td>
<td>-0.5</td>
<td>4.5</td>
<td>10.1</td>
<td>4.8</td>
<td>0.57</td>
<td>13.1</td>
<td>0.58</td>
</tr>
<tr>
<td>76-90</td>
<td>6.2</td>
<td>0.5</td>
<td>3.7</td>
<td>8.6</td>
<td>5.0</td>
<td>0.58</td>
<td>12.7</td>
<td>0.53</td>
</tr>
<tr>
<td>90-97</td>
<td>6.2</td>
<td>2.3</td>
<td>5.1</td>
<td>11.2</td>
<td>4.7</td>
<td>0.63</td>
<td>13.1</td>
<td>0.57</td>
</tr>
<tr>
<td>97-104</td>
<td>5.1</td>
<td>0.9</td>
<td>3.3</td>
<td>7.8</td>
<td>5.1</td>
<td>0.54</td>
<td>13.1</td>
<td>0.60</td>
</tr>
<tr>
<td>104-117</td>
<td>5.9</td>
<td>1.4</td>
<td>4.1</td>
<td>9.4</td>
<td>4.9</td>
<td>0.57</td>
<td>13.3</td>
<td>0.56</td>
</tr>
</tbody>
</table>

The timeseries of wave conditions give no clear indication of which parameter(s) mainly induces or changes the longshore sediment transport (Figure 4.17), nor do the average conditions for each sampling interval of the impoundment study (Table 4.5). The influences of breaker wave parameters on the longshore sediment transport rates are difficult to describe. There might be other factors that have a significant influence on the longshore transport rate, for example the sediment supply, characteristics of the background swell, tidal levels or the influence of mid-latitude depressions (storms).
Isolating these factors and their influence is not a straightforward procedure, and lies beyond the scope of this study. Accordingly, the direct influence of the sea breezes and separate wave parameters on the impounded material is not further investigated.

Figure 4.17: Timeseries of nearshore data. Indicated are wind speed and direction (A & B), cross-shore and longshore wind component (C & D), breaker angle, peak period and breaker height of wind waves (E, F & G), peak period and breaker height of swell waves (H & I). The shaded areas indicate periods of major accretion.
As a result of the large temporal interval of beach surveys there is a smoothing of the variations in the transport signal. In order to indicate the forcing of this transport, the hydrodynamic conditions that are measured on a small time-scale need to be reduced to an average over the temporal scale of the impoundment measurements. Because of the high variability of the hydrodynamic conditions, one cannot assign a single meaningful parameter to characterise the wave environment over the long-term measurement interval of an impoundment study, as pointed out by Bodge and Kraus (1991). It is the extreme events, such as strong sea breezes or storms, that cause the largest transport rates, but the effects of an isolated event cannot be identified. As a result, there is no relationship between the weekly transport rates determined from the beach surveys and the average value of the high-frequency wind and wave data. This illustrates a drawback of the impoundment study, where large-scale survey data is compared with small-scale wave measurements.

4.5.2 Transport models

Time series of wave parameters were used as input values for longshore transport equations, as indicated in Table 3.2. Comparing the wave spectrum with the estimated longshore sediment transport gives insight in which wave characteristics drive the transport models (Figure 4.18). Of the five days displayed, days 116–118 are characterised by strong sea breezes while during days 119–120 the sea breeze is weaker and the swell wave energy more prominent (Figure 4.18A). These changes in the wave characteristics are reflected in the transport rate predictions (Figure 4.18B). Generally, the ‘CERC -incident’ predicts the highest transport rates, with slightly lower rates predicted by the ‘Inman and Bagnold -estimated’ equation. The ‘CERC -wind’ closely follows the ‘Inman and Bagnold -estimated’ equation if the swell wave energy is low (days 116–118) but predicts lower rates when the swell waves are more energetic (days 119–120). This illustrates how according to the ‘CERC -wind’ the major part of the longshore sediment flux, during a sea breeze, is caused by the wind waves. During low swell-wave energy combined with strong sea breeze activity, the two Kamphuis models predict low transport rates (days 116–118). During more pronounced swell-wave activity there is a strong increase in the transport according to ‘Kamphuis -incident’ (rates similar to ‘CERC -incident’), while ‘Kamphuis -wind’ is unaffected and remains low.
It is of interest to investigate how the equation of Kamphuis (1991b) responds to changes in the bimodal wave field. The variable input-parameters in the Kamphuis equation are the significant wave height \( H_{\text{sig}} \), peak wave period \( T_p \) and the breaker angle \( \alpha \). Since the study area is characterised by a bimodal wave field, the incident wave conditions are influenced by the most energetic of the wind and swell-wave characteristics. On day 117 the swell waves are small and during the sea breeze the incident wave parameters are similar to the characteristics of the wind waves \( H_{\text{sig}} = 0.85 \text{ m}, \ T_p = 4.2 \text{ s}, \ \alpha = 17 \text{ deg} \). During day 118, the characteristics of the sea breeze and the resulting wind waves are similar to those measured during the previous day, while the swell waves are more energetic. This is reflected in the incident wave parameters, that are \( H_{\text{sig}} = 0.96 \text{ m}, \ T_p = 12.5 \text{ s}, \ \alpha = 14 \text{ deg} \), of which the shift from the peak period of the wind waves to the larger swell peak period is of major importance. Since in the Kamphuis-equation the \( T_p \) is used to the power 1.5, this large difference in the peak wave period results in a transport-estimate a factor 5 higher. The longshore sediment transport rate according to the Kamphuis model is unaffected by small changes in the low \( T_p \) characteristic of the wind waves. Therefore, even though the ‘Kamphuis -wind’ model was expected to account for
longshore transport caused by wind-waves during sea breezes, the predicted transport rates were unaffected by variations in wind wave parameters and the model is expected to under-estimate the actual rate of longshore sediment transport. The ‘Kamphuis -incident’ model is strongly influenced by the presence of swell waves, and its associated large $T_p$.

Using the correlation between the 20 days of inshore wave data and the offshore wave-rider buoy, wave breaker data could be derived and the transport could be estimated during the entire period of the impoundment study (Table 4.6, Figure 4.19). The upper and lower limits of the impoundment transport represent respectively total and longshore transport rates. Note that not all transport models in Table 3.2 could be applied since data on mid-surf longshore current velocities were not available. As expected, the longshore transport according to the ‘Kamphuis -wind’ model is constantly the lowest and does under-predict the rates of the impoundment study. The transport rates according to the remaining four equations are comparable, but over-predict. They all predict the lowest transport rates during days 48-55, intermediate rates for days 76-90, 97-104 and 104-117, and high rates during days 62-69, 69-76 and 90-97. The periods of high transport rates are characterised by strong sea breezes, which is reflected by a large average longshore wind component (Table 4.5). The low transport rates between days 48-55 can be the result of the low sea breeze activity (small longshore wind component) in combination with the low swell wave height.

Table 4.6: Beach volume change (m$^3$ hour$^{-1}$) during a 10-week period, starting at day 48 (17th November 2000) until day 117 (25th February 2001).

<table>
<thead>
<tr>
<th>Transport volume (m$^3$ hour$^{-1}$)</th>
<th>Days</th>
<th>48-</th>
<th>55-</th>
<th>62-</th>
<th>69-</th>
<th>76-</th>
<th>90-</th>
<th>97-</th>
<th>104-</th>
<th>117</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impoundment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lower limit</td>
<td></td>
<td>17.7</td>
<td>6.9</td>
<td>1.7</td>
<td>39.9</td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>upper limit</td>
<td></td>
<td>37.5</td>
<td>5.9</td>
<td>12.2</td>
<td>42.8</td>
<td>8.5</td>
<td>38.4</td>
<td>18.4</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>Transport equation:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inman and Bagnold - estimated</td>
<td></td>
<td>23.2</td>
<td>57.3</td>
<td>72.4</td>
<td>59.3</td>
<td>51.4</td>
<td>63.8</td>
<td>42.5</td>
<td>50.4</td>
<td></td>
</tr>
<tr>
<td>CERC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- incident</td>
<td></td>
<td>35.0</td>
<td>85.6</td>
<td>95.8</td>
<td>81.2</td>
<td>70.6</td>
<td>87.0</td>
<td>61.5</td>
<td>68.6</td>
<td></td>
</tr>
<tr>
<td>- wind</td>
<td></td>
<td>16.8</td>
<td>38.3</td>
<td>57.7</td>
<td>44.0</td>
<td>39.9</td>
<td>46.5</td>
<td>31.7</td>
<td>39.5</td>
<td></td>
</tr>
<tr>
<td>Kamphuis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- incident</td>
<td></td>
<td>30.9</td>
<td>57.9</td>
<td>54.2</td>
<td>54.6</td>
<td>44.8</td>
<td>60.0</td>
<td>43.3</td>
<td>42.7</td>
<td></td>
</tr>
<tr>
<td>- wind</td>
<td></td>
<td>3.7</td>
<td>7.8</td>
<td>8.9</td>
<td>7.8</td>
<td>6.8</td>
<td>8.3</td>
<td>5.9</td>
<td>6.9</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4: Impoundment study

4.6 DISCUSSION

The results of the impoundment study were based on weekly surveys of 11 profiles at 50 m spacing during a five-month period. Several insecurities are associated with the use of such a study, and these will be discussed. An inaccuracy in the survey measurements, for example as a result of a misreading, does influence the data of a single transect. But since the average error in the readings lies around zero, the measurements have been repeated every week, and the overall trend of change in the complete study area over a large time-scale is of importance, such inaccuracies are not material enough to affect the findings of this study.

Another possible cause of inaccurate volume measurements is the definition of the closure depth. As discussed in Section 4.2.1, the used closure depth of -1.44 m AHD is less deep than suggested by the model of Hallermeier (1981). If the assumed closure depth was too small and did not include a sufficient offshore distance and depth to cover the complete active zone, then the envelope of beach change would be too small which results in an under-estimation of the volume change and the resulting transport rates. It is difficult to quantify this possible under-estimation, since no profile data are available to a sufficient depth. Further sources of potential errors are associated with the derivation of the cross-shore transport rates. Until day 90, it was assumed transects 10 and 11 were located outside the area affected by the impoundment and volume changes measured at
these transects were presumably solely caused by cross-shore sediment transport. This cross-shore transport was regarded as uniform for the whole study area. After day 90, the transects 10 and 11 were located inside the area of groyne-influence, and measured changes at these transects were the result of both cross-shore and longshore sediment transport and the total volume change was no longer divided in cross-shore and longshore components. Transects 10 and 11 could have been influenced by longshore transport during the entire period of study and as a result the longshore component would be underestimated. Another issue that could result in an under-estimation of both the total and longshore transport rates is the assumption that the effect of the shore-normal groyne is a total impoundment of sediment transported in a northerly direction. In reality, a fraction of the longshore sediment transport will by-pass the groyne, and this fraction will increase when more sediment is accreted at the updrift side of the groyne. As a result of this sand bypassing the measured changes in beach volume will not account for the entire transport volume. Moreover, from day 90 onwards the area influenced by the impoundment of sediment is larger than the area of study and not all volume changes were accounted for. Therefore total and longshore transport rates derived from an impoundment study are considered under-estimations.

In summary, several insecurities are associated with the use of an impoundment study. Given the time-scale of measurement, survey errors are regarded immaterial. But the definition of closure depth, calculation of the cross-shore transport component, incomplete impoundment by the groyne and the size of the study area can all result in an under-estimation of both the total and longshore sediment transport rates. Therefore, the measured sediment transport rates are conservative estimates of the actual rates.

Several longshore transport equations were applied using wave breaker parameters, derived from inshore wave data and coastal wind data, by means of regression models. The use of regression models was preferred to running a refraction model for three reasons. Firstly, directional inshore wave data were not available. Secondly, the nearshore bathymetry was complicated as a result of rocky outcrops of aeolinite limestone which form submarine to emergent ridges (Searle and Semeniuk, 1985). Finally, the differences between inshore and breaker wave characteristics were more related to variations in wind speed and fetch length, than wave transformation processes (Masselink and Pattiaratchi, 2001a). Nevertheless, when ignoring the general insecurities
Chapter 4: Impoundment study

of transport equations, the transport predictions can only be as accurate as the input parameters used.

When comparing the results of the transport equations with the impoundment data, it appears that, except for ‘Kamphuis –wind’, all transport equations do significantly over-predict the measured littoral drift rates (Figure 4.19). Moreover, the peak transport periods identified by the impoundment study and the transport equations do not correspond. A similar problem appeared when comparing the large-scale impoundment data with small-scale wave parameters (Section 4.5.1). As a result of the scale differences, it is difficult to conclude whether the transport equations used are capable of accurately predicting longshore sediment transport rates. More insight should be achieved when comparing smaller-scale littoral drift measurements (e.g., tracer studies) with wave parameters and transport equations.

Survey measurements were executed for five months, starting on 28th October 2000. Significant volume changes were measured for 69 days, from 17th November (start of the sea breeze season) until 25th January (saturation of the groyne). During this period the total sediment transport was ~37,000 m³ and a total of 53 sea breezes was recorded. Therefore when assuming the measured northward transport was solely the result of sea breeze activity, the littoral drift during a single sea breeze can be estimated at ~700 m³. Given the previous discussion, this amount represents a tentative estimate of the actual northward transport rate. An investigation of 49 years of wind data by Masselink and Pattiaratchi (2001a) led to the conclusion that each year an average of 197 sea breezes is experienced along the coast of Southwestern Australia. Assuming the sea breezes experienced during the impoundment study represent average conditions, it can be concluded that the yearly northward littoral drift caused by sea breezes is ~138,000 m³. This large amount demonstrates that the sea breezes have a dramatic impact on the littoral drift rates.

Yearly northward transport rates of close to the value of 80,000 m³ were estimated by Pattiaratchi et al. (1997) who based their predictions on seasonal beach profiles obtained at Trigg Beach (7 km north of the impoundment area) where sand is trapped by a natural island and reef (Figure 4.20). Again, this transport value could be an under-estimation of the actual rate, since not all transported sand is expected to be impounded at Trigg beach. The source of the transported material is not clear, but it is probably the result of erosion.
of a very thin layer of the beachface over a large distance. During winter, northwesterly storms transport this sand southwards (Masselink and Pattiaratchi, 2001b). Accordingly, it appears that the study area is characterised by a cycle of sediment movements in which the system of summer sea breezes plays an important role.

Figure 4.20: Trigg Beach. Top of the photo represents north (Photography by Ian Eliot).

4.7 SUMMARY

- During summer an upward and seaward growth of the beach berm was recorded. The average height of the berm increased from 1.0 to 1.7 m AHD during 18 weeks, while the slope of the beach face remained stable.
- Beach width can be used as an indicator of beach accretion, since periods of major beach width extension coincide with large volume increases.
- The bimodal wave climate is the result of a combination of wind and swell waves, whereby the former is influenced by the sea breeze and the latter by lower-frequency synoptic weather patterns.
- Longshore sediment transport during sea breezes is mainly the result of the high amount of longshore energy flux exerted by the wind waves. This is well reflected by the equations of Inman and Bagnold (1963) and CERC (1984). The Kamphuis
(1991b) equation is regarded unsuitable for use in combination with the bi-model wave field.

- Impounded volumes are not directly proportional to average values of neither high-frequency wind and wave data nor the number and strength of sea breezes.

- Insecurities associated with the use of an impoundment study all result in an underestimation of both the total and longshore sediment transport rate. These include the definition of closure depth, calculation of the cross-shore transport component, incomplete impoundment by the groyne and the size of the study area. Therefore, the measured sediment transport rates are conservative estimates of the actual rates.

- The littoral drift during a single sea breeze is as ~700 m³. Yearly northward littoral drift caused by sea breezes is estimated at ~138,000 m³.
5A.1 INTRODUCTION

Longshore sediment transport can be measured over a number of temporal and spatial scales and the use of tracers is appropriate for the investigation of medium scale longshore transport. Investigating longshore transport rates using tracer material is complicated by the underlying theories and the different possible measurement strategies. These are discussed in Part A of this chapter, after which the results from four field experiments are presented in Part B.

5A.2 TRACER THEORIES

The sediment response to the action of waves and currents is complex and not fully understood. On a moderate time-scale, if wave and current conditions are relatively constant and the sand motion consists of uniform advection, the velocity of sediment and littoral transport rates can be determined using tracer sand. Sand tracers are tagged material with similar hydrodynamic properties to the natural beach sediments (Komar, 1998).

Sediment can be transported in three ways.

- Advection is the downstream transport of tracers associated with the average flow in the transport system.
- Diffusion is the spreading of the tracers due to small-scale random motions, both molecular and turbulent, in the transport system.
- Dispersion is the spreading of the tracers by the combined effect of diffusion and non-uniform advective velocity in the transport system.

The assumption behind the use of tracer theory is that advection dominates over diffusion and dispersion. A concentration-weighted mean velocity must be calculated in order to estimate the true advection rate of tracer (Inman, et al., 1980; and Madsen, 1989). Additionally it is generally assumed that tracers do not change the characteristics of the transport system and also that the tracers behave in the transport system in a similar manner to the native material whose transport rate is to be determined (Madsen, 1989).
Furthermore, no tracers can leave or enter the transport system and the transport system must be steady and uniform.

It has not yet been resolved as to whether or not the longshore sediment transport system invalidates the assumptions behind the use of tracer methodologies, or to what extent such assumptions would need to be modified. Nevertheless, the use of sand tracer is the best available methodology for the determination of longshore sediment transport rates over medium time and spatial scales (transport during a couple of hours over hundreds of metres distance), and has been used in the past for calibrating sediment transport models.

5A.2.1 Two-layer model of tracer behaviour

Tracer experiments and calculations are interpreted using a two-layer model of sediment transport under the combined action of waves and currents. After the tracer sand is introduced into the nearshore, the tracer moves as a relatively thin active layer of sand with some average advection velocity over a second passive sand layer (Figure 5A.1). The thickness of the active layer has been variously defined as the depth of activity, depth of disturbance or the depth of mixing. As pointed out by Kraus et al. (1982) and Sherman et al. (1994), these terms have different characteristics; the mixing depth is measured on a time scale of hours (e.g., during a tracer experiment) and is not affected by changes in the sand level due to variations in wave or tidal conditions or to the migration of large-scale bedforms. The disturbance depth and depth of activity are assessed during longer periods (e.g., tidal cycles) and represent the maximum depth of disturbance by waves.

During a tracer experiment, information on the longshore advection velocity, $v_a$, the depth of mixing, $b$, and the width, $w$, over which transport takes place is gained from tracer concentration in core samples taken in situ at set times and distances following injection. These three parameters are needed for the calculation of longshore transport (e.g., Inman et al., 1980; Kraus et al., 1982).

The two-layer model is applicable to a medium time scale of tens of minutes to a few hours (Kraus et al., 1981). For shorter time periods (seconds) sand transport will have a local and heterogeneous character, necessitating a micro-scale model. For longer periods (days to years) the thickness of the active layer and the advection velocity are non-steady.
functions of time, and thus call for an integrating model to account for time variations in the transport. The experimental time scale used here, is long enough to achieve a homogeneously mixed active layer with equilibrium values of mixing depth and advection velocity, but short enough to cover a period of quasi-stationary wave and current conditions.

Figure 5A.1: Schematic overview of the active layer of longshore moving sediment (after Komar, 1990).

The cross-shore width of the mobile bed to be studied is confined between the runup limit of the swash zone (x = 0) and an offshore distance where longshore transport is zero during the time of the experiment (x = w). Hydrodynamics vary across the surf zone and therefore the advection velocity ($v_a$ in m s$^{-1}$) of sediment movement and the depth of sediment mixing ($b$ in m), will vary as a function of the cross-shore location (x). The local longshore transport rate, $q(x)$, or the volumetric transport rate per unit width of the surf zone in m$^2$ s$^{-1}$, is then computed by multiplying the tracer advection velocity by the mixing depth:

$$q(x) = v_a(x)b(x)$$ (5A.1)

The total volume of longshore transport, $Q$, (in m$^3$ s$^{-1}$) is then obtained by summing Equation 5A.1 across the width over which transport takes place ($\Delta x$), from $x = 0$ to $x = w$, as:
For computations of theoretical transport rates the littoral drift can also be expressed as immersed-weight (dry weight minus buoyancy) sediment transport rates $I_i$ in N s$^{-1}$:

$$I_i = (\rho_s - \rho) g (1 - p) Q$$  \hspace{1cm} (5A.3)

where $\rho_s$ = mass density of quartz sand (2650 kg m$^{-3}$); $\rho$ = mass density of seawater (1025 kg m$^{-3}$); $g$ = acceleration due to gravity (9.81 m s$^{-2}$); and $p$ = sand porosity (0.4).

This approach to derive longshore transport rates using tracer sand is significantly different from that used in most previous investigations (e.g., Komar and Inman, 1970; Inman et al., 1980; Kraus et al., 1982; Ciavola et al., 1997b; Nordstrom et al., 2003). Equation 5A.2 allows for variation in $v_a$ and $b$ across the nearshore zone, whereas most previous tracer studies assume that one or both of these variables is constant. The present approach is physically more correct and has the added advantage of addressing the cross-shore variation in longshore transport rate.

Although tracer experiments are conceptually simple, there are several fundamental problems associated with the sand motion. Among these are:

- Calculation of the advection velocity;
- Definition of the depth of mixing;
- On-offshore distributions of the depth of mixing and sand advection velocity;
- Time for equilibration of tracer injected into the surf zone with the ambient bed; and
- Tracer recovery rate.

### 5A.2.2 Advection velocity

The methodology used to determine the longshore advection velocity depends on the applied sampling strategy. The main strategies include the Spatial Integration Method (SIM), the Time Integration Method (TIM) and the Continuous Injection Method (CIM). When using the SIM, tracer is injected as a point or line-source after which sampling takes place in a spatial grid at set times after tracer injection (Figure 5A.2). The TIM uses the same type of injection, but sampling takes place along a cross-shore line at set times...
Chapter 5A: Fluorescent tracer

(Figure 5A.2). The CIM is characterised by a continuous injection of a set mass of tracer and monitoring its passage at a cross-shore line by sampling at set times. Both the SIM and TIM were used in the present study.

<table>
<thead>
<tr>
<th>SPATIAL INTEGRATION METHOD</th>
<th>TEMPORAL INTEGRATION METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMPLE A SPATIAL GRID AT FIXED TIME</td>
<td>SAMPLE AT FIXED STATIONS AT A SET TIME INTERVAL</td>
</tr>
<tr>
<td><img src="image" alt="Spatial Integration Method Diagram" /></td>
<td><img src="image" alt="Temporal Integration Method Diagram" /></td>
</tr>
</tbody>
</table>

-INJECT SAMPLE-
$t_0, y_0$ - $-\infty < y_i < \infty$

INJECT SAMPLE
$t_0, y_0$ - $0 < t_i < \infty$

LONGSHORE

Figure 5A.2: Spatial and temporal grids for monitoring sand-tracer motion, where $t_0$ = time of tracer injection, $y_0$ = longshore coordinate of tracer injection, $t_i$ = elapsed time since injection, $y_i$ = longshore coordinate of sampling (after Inman et al., 1980).

Using the Spatial Integration Method (SIM) the two-dimensional distribution of a cloud of tracers is monitored in the longshore distance, $y$. At time $t_0$ a known quantity of tracers is introduced into the surf zone at line $y = 0$ and at later times, $t_i$, the study area is sampled in a spatial grid (Figure 5A.2). The spatial limits of the sampling grid in the longshore direction are chosen in such a way that all tracers are accounted for. Which means tracer concentration $c = 0$ for $-\infty < y < \infty$. Counting of the tracer grains in the sample cores results in a two-dimensional distribution of the tracer concentration, which can be displayed in a contour plot (Figure 5A.3).

Once the two-dimensional distribution of the tracer concentration is determined in longshore distance, $y$, the average tracer advection velocity can be determined. Following White and Inman (1989a), the equation reads:

\[
    v_a(x) = \frac{\sum_y c(x,y) \frac{y}{t_i}}{\sum_y c(x,y)}
\]

(5A.4)
where \( c \) = tracer concentration in a core at a location defined by cross-shore and longshore coordinates \( x \) and \( y \); and \( t_i = \) elapsed time between tracer injection and sampling. The sum is over all \( y \) for the spatial grid. This velocity is an average over the entire longshore grid, but applies to one cross-shore location, \( x \).

Another method is the Time Integration Method (TIM) where the distribution of a cloud of tracers is monitored along a cross-shore line, \( x \), over the time, \( t_i \). A known quantity of tracers is released in the transport system at \( y = 0 \) at \( t_i = 0 \). The variation with time of tracer concentration is monitored by repeated sampling along a single cross-shore line at downstream distance \( y = y_i \). (Figure 5A.2). The requirement of advection dominating diffusion and dispersion means that the sampling line should be located sufficiently far downstream from the injection site for the tracers to have become completely mixed in the transport system. The temporal grid sampling should start at the time of tracer injection and continue until all the tracer has passed the sampling line, \( y_i \). Which means \( c = 0 \) for \( 0 < t_i < \infty \).

Figure 5A.3: Example of a contour plot (from Komar, 1990)
The advection velocity is determined from an expression similar to Equation 5A.4, but
this velocity is an average over the entire time of sampling which applies to one cross-
shore location (White and Inman, 1989a). The calculation uses the sum over all \( t_i \) for the
temporal grid, as:

\[
v_a(x) = \frac{\sum_{i} c(x,t) \frac{y_i}{t_i}}{\sum_{i} c(x,t)}
\]

(5A.5)

Both Equation 5A.4 and Equation 5A.5 result in a cross-shore distribution of the
advection velocity. The average velocity for the entire cross-shore zone can be obtained
from a weighting of the local velocities by the width of their representative section of the
surf zone, \( \Delta x \), as:

\[
\bar{v}_a = \frac{\sum_x v_a(x) \Delta x(x)}{\sum_x \Delta x(x)}
\]

(5A.6)

Strictly speaking, Equation 5A.4 and Equation 5A.5 are only applicable if the tracer is
injected along a line, however, it may also be applied for point injections if the tracer is
rapidly mixed across the nearshore zone.

Both the SIM and TIM have some prerequisites. The tracers have to be introduced
directly into the system at \( t_i = 0 \). The correct advection velocity can only be determined
from samples taken within the transport system while the active transport takes place.
Accordingly, sampling on the dry bed of an intertidal zone following a tracer injection
during high tide is insufficient. Additionally, the core samples have to be taken to a depth
greater than the maximum depth of tracer penetration.

The ability to perform consecutive determinations of \( v_a \) does provide means of assessing
the degree to which diffusion, dispersion, unsteadiness of the transport system and
sampling errors have influenced the result. Thus, if several estimates of \( v_a \) are obtained
and show a relatively small variability, one may be reasonably confident in the accuracy
of the value of \( v_a \) obtained.
5A.2.3 Tracer recovery rate

In order to make an accurate estimate of the transport velocity of sediment, the motion of most of the mass of tracer must be measured. This can be tested by estimating the recovered amount of tracer sand and comparing this with the amount injected (White and Inman, 1989a). When using the SIM the concentration of tracer in a particular sample is assumed representative of the concentration in the surrounding region. The regional concentrations are then summed over the entire sampling grid in both longshore and cross-shore direction and expressed as the mass of recovered tracer grains:

$$M_{SIM} = \frac{p \rho_s}{F} \sum_x \sum_y c(x, y) b(x) \Delta x(x) \Delta y(y) \quad (5A.7)$$

where $M_{SIM}$ = mass of recovered material (kg); and $F$ = number of tracer grains per unit mass (grains kg$^{-1}$). The factor $F$ can be derived from a grain size measure (e.g., $D_{50}$) assuming perfect spheres and standard porosity or $F$ can be estimated by counting the number of sediment grains in several small (c. 0.1 g) random sediment samples, determining the average weight of a sediment grain and converting this to the number of grains per kilogram.

A similar equation can be applied to the data of a TIM-experiment. The tracer concentration is assumed to represent a cross-shore section during a specific time interval. The sum of these concentration values results in the total number of grains (expressed in grains/kg) that passed the whole sampling line from the start until the finish of the TIM-experiment. The factor $(p \rho_s)/F$ is used to express $M_{TIM}$ as the mass of recovered material, as:

$$M_{TIM} = \frac{p \rho_s}{F} \sum_x \sum_t c(x, t) b(x) \Delta x(x) \Delta t(t) \frac{y}{t} \quad (5A.8)$$

Both Equation 5A.7 and Equation 5A.8 can only be used if the core samples penetrate the bed until at least the mixing depth of tracer.
5A.2.4 Mixing depth

The definition of the depth of tracer mixing must be considered carefully because the transport rate is directly proportional to it (see Equation 5A.2). According to Komar (1998), the measurement of the thickness $b$ is the most uncertain parameter in the use of sand tracers. Measurements of the depth of mixing in the field can be done using plugholes filled up with coloured sand, tracer distribution in beach cores and depth-of-disturbance rods. The measurement of the mixing depth must be carried out under conditions of no net accretion or erosion, as the accretion or erosion of the bed would lead to an increase or decrease in the measured mixing depth (Kraus et al., 1982; Ciavola et al., 1997b).

Usually the mixing depth is determined from the tracer concentration profiles in sample cores. For steady waves, a developing profile is expected to have a maximum tracer concentration in the surface layer and a decreasing concentration with depth. At equilibrium, the tracer should be uniformly distributed from the surface to some maximum depth. In reality the wave-induced flow, the pressure field and the turbulence are not steady and as a result profiles commonly exhibit one or more concentration gradients with depth, indicating either the occurrence of different mixing events or local erosion or accretion. Also, if the reservoir of tracer is exhausted, ambient sand will replace tracer in the upper layer and an irregular profile will result.

The problem of estimating the effective mixing depth is exacerbated by the lack of an agreed objective definition of the mixing depth. Several procedures can be used to estimate the mixing depth, of which five methods will be reviewed.

- Mixing depth can be defined as a maximum depth to which tracer is found (Komar and Inman, 1970; Gaughan, 1978). This definition gives an inappropriate weight to the few grains near the bottom of the cores and thus cannot be regarded as realistic because tracer can be accidentally buried.

- Crickmore (1967) devised a concentration-weighted procedure for mixing depths in rivers. Crickmore noted that this procedure gave intuitively reasonable results for cores with decreasing or uniform concentration with depth. This method emphasizes the depth where the major portion of the tracer is located.
The second improved method of Crickmore (1967) modifies irregular concentration gradients before analysis. Specifically, if the concentration in a given segment was smaller than that in the segment immediately below it was set to the concentration in the lower segment. For uniform and decreasing concentration with depth both methods of Crickmore are equivalent.

Inman et al. (1980) proposed a depth-weighted definition, which gives additional weight to the tracer at greater depths. In some cases this form of depth-weighting yields reasonable results. However, this definition has the undesirable effect that for irregular profiles the estimated mixing depth can be calculated as greater than the greatest depth to which tracer is buried.

Kraus et al. (1981, 1982) developed a definition with a variable cut-off percentage. In this procedure a mixing depth is calculated which includes a specified percentage of the total tracer grains found in the core. The mixing was found to be uniform to at least the depth containing 80% of the tracer. The material at greater depths was less frequently mixed vertically and thus probably spent a considerably smaller fraction of time moving laterally and contributing to longshore transport, hence Kraus defined a cut-off value of 80%.

As a result of the different methodologies, the depth of mixing used is a matter of definition. Kraus (1985) applied the described five definitions to various concentration profiles for comparison. The behaviour of both the maximum tracer depth and depth-weighted depth was spurious. The empirically based 80% cut-off depth gave equivalent to superior results to the arbitrary concentration-weighted depths. It was concluded by Kraus et al. (1982) that the cut-off percentage is the preferable method, and that the use of this approach would result in the most objective solutions. The 80% cut-off depth has since been used in several studies (e.g., Ciavola et al., 1997a; Ferreira et al., 1998) but other definitions are still in use (e.g., maximum burial depth by Sherman et al., 1994) complicating the evaluation of different study results. For the current study, the results of the maximum depth of tracer burial, cut-off at a minimum concentration of 0.5 grains/gram and cut-off percentage of 80% were compared.

Several studies have suggested some degree of dependency between the mixing depth and parameters such as the grain size, the Shields number or the wave-height at wave breaking. It has been suggested by King (1951) that the mixing depth should increase in some manner with the sediment grain size. Sunamura and Kraus (1985) reanalysed the
data of Kraus et al. (1982) in an attempt to describe this relationship. The model used was based on the shear stress exerted by waves on the bottom. The Shields parameter emerged as the important governing quantity and a predictive equation was proposed in which the average mixing depth in the surf zone was given as a linear function of the Shields parameter, thus:

$$\frac{b}{D} = 81.4(\Psi_b - \Psi_c) \quad (5A.9)$$

where, \(b\) = average depth of sediment mixing; \(D\) = grain size of the sediment; \(\Psi_b\) = Shields parameter at the wave breaking point; and \(\Psi_c\) = critical Shields number of oscillatory flow, which can be obtained graphically (Soulsby, 1997).

Sunamura and Kraus (1985) went on to indicate, by use of some simple assumptions, that the mixing depth should be directly proportional to \(H_b\). This empirical equation describes the correlation between mixing depth and breaking wave height on a gentle sloping non-barred beach (Kraus et al., 1982; Kraus 1985), as:

$$b = 0.027H_b \quad (5A.10)$$

where, \(b\) = average sand mixing depth (m); and \(H_b\) = significant wave height at breaking point (m). As steep and gently sloping beaches have a different hydrodynamic behaviour the Equation 5A.10 is inapplicable on steep beaches. Ciavola et al. (1997a) obtained a slightly different empirical relationship using data on steep mesotidal beaches with plunging waves:

$$b = 0.27H_b \quad (5A.11)$$

The constant for this equation is an order of magnitude larger than in Equation 5A.10 and is applicable to beaches with a steep beach face (\(\tan \beta > 0.08\)) under plunging wave action. It should be cautioned that Equations 5A.9, 5A.10 and 5A.11 are applicable only where the wave breaking-induced bottom stress is the principle cause of sediment mixing. Other factors could be equally or more important, for example scouring and mixing under plunging breakers, turbulence caused by the collision of runup and
rundown in the swash zone. All factors together produce larger values than predicted by the above equations.

The change of mixing depth with beach slope does indicate the mixing depth is a function of the morphodynamic beach state. Generally, gentle beaches show a bimodal distribution of the mixing depth, with maximum values near the breaker line and at the relatively shallow shoreline (e.g., King, 1951; Inman et al., 1980; Kraus, 1985). On steep gradient beaches, the profile of mixing was found to be unimodal, with a maximum in the area where the waves break and a minimum in the swash zone (Ciavola et al., 1997a; b). This suggests that the spatial variation of the mixing depth reflects the distribution and relative intensity of wave processes across the beach profile and that there might be a typical cross-shore distribution with one or more peaks in the mixing depth depending on the beach type (Anfuso et al., 2000). As it is yet unclear which parameters influence the cross-shore distribution of the mixing depth, some caution should be exercised in this respect until further research clears the complexity of the matter.

It is important to note that the equations discussed in this section do not describe the changes in mixing depth across the nearshore zone. Since the cross-shore distribution of the longshore sediment transport depends on beach type (refer to Section 2.3.3) a similar dependency can be expected for both the mixing depth and the advection velocity. Not including this variation during longshore transport calculations can be potentially dangerous as it ignores the different modes of sediment movement at specific locations and the nature of the turbulent mixing force. At the breaker line, breaking waves can cause mechanical scouring, thereby suspending sediment in high concentrations and mixing it to relatively large depths in the bed. A similar process is expected to take place in the zone where the returning backwash meets the incoming bore. Therefore, it can be considered essential to obtain samples of the depth of mixing and advection velocity from all regions in the surf zone in order to determine site-specific values.

5A.3 PREVIOUS EXPERIMENTS USING TRACER SAND

The following section will present a review of the different methodologies for the use of tracer. Tracer experiments are not new, Kidson and Carr (1971) report on experiments undertaken in the early twentieth century. Some of the attempts at tracing sediment
movement have included the use of artificial material such as pulverized coal, broken brick and magnetic concrete or grains dyed non-fluorescent hues (Ingle, 1966; Kidson and Carr, 1971; and King, 1951). Although the above techniques yielded varying degrees of success it was only in the 1960s, when serious development of the technique took place, when the use of radioactive and fluorescent tracers brought greater precision to coastal studies.

5A.3.1 Radioactive and fluorescent tracers

Sediments of clay to cobble size have been traced successfully using radio-isotopes, the methods of which have been reviewed and discussed in detail by Ingle (1966). Some of these studies involved glass containing (or coated with) an activated isotope (Cummins and Ingram, 1965) whereas others employed natural grains to which a radioactive isotope had been attached by surface absorption, surface plating or insertion into drilled holes. In addition, naturally occurring radioactive minerals in beach sands have been used to trace the movement of sand from the source area.

Kidson and Carr (1971) wrote an exhaustive review of tracer methodologies, including radioactive tagging and fluorescent markers. They concluded that the most suitable method for marking and tracing all sizes of beach material was the use of radioactive isotopes. Radioactive tracers are particularly useful in environments with controlled access, free of public interference and consequently have been more often used offshore than on beaches. However, because artificial materials (e.g. glass) containing isotopes are seldom hydrodynamically equivalent to natural sand grains, not to mention their relatively high cost and the fear of health hazards, this technique cannot always be considered (Teleki, 1966). Although the radioactive methods offer the best and only method of tagging grains finer than coarse silt, movement of coarser sediment can be traced most practically by marking with fluorescent colours.

Although the recovery of fluorescent tracers is necessary for observation and evaluation, they are significantly easier to use than irradiated material, as they do not require special precautions in their handling. Additionally, samples do not have to be analysed immediately following collection, as deterioration of emission rate is not a factor with fluorescent tracing material. Thus, it is possible to store samples for analysis at a later date. The main advantages of fluorescent tracers remain, however, in the variety of
colours in which they can be prepared, enabling simultaneous research of several variables in the field, in their relatively simple means of preparation, in their proven economy, and in their availability in large quantities (Teleki, 1966).

The simultaneous application of more than one tracer colour has been used to differentiate zones of transport rate and direction, or to relate transport mechanisms to different grain sizes. For example Kraus et al. (1982) and Kraus (1985) tagged sand with four fluorescent colours, and injected the tracer on a line crossing the surf zone, using different colours for different cross-shore locations. Munoz-Perez et al. (1999) employed two tracer colours. One colour was injected on the submerged beach below still-water level, the other colour was injected on the intertidal zone. In this way the on-offshore distributions of the longshore sand advection velocity and transport rate could be investigated. Differential transport can be investigated by marking different sand populations using different colours (e.g., Boon, 1968; Blackley and Heathershaw, 1982).

5A.3.2 Methodologies using fluorescent tracer sand

The injection method of tracer sands depends on the type of experiment, the number of colours used, the tidal range and the energetic conditions of the surf zone. Injection can take place in a single trench on the shoreface during low tide, either by raking the tracer sand in to a depth of about 3 cm (Boon, 1968) or by digging a shallow trench (Komar and Inman, 1970; Ciavola, et al., 1996; 1997a, 1997b; 1998, 1999a). Voulgaris, et al. (1998) covered the trench with 0.5 cm of natural sand. When the beach is characterised by morphological features (e.g. a system of ridges and runnels) a tracer study can be used to monitor the movement of its features. For example, Michel and Howa (1999) injected tracer on a ridge crest, and followed the movement over five consecutive tidal cycles.

Other authors did inject in a (broken) cross-shore line and treated it as a line source during further analysis. Boon (1969) injected tracer sand at 4 points along a transect between the swash and the surf zone, however for calculations, it was considered all grains entered the system at one point: the middle of the cross-shore injection line. Knoth and Nummedal (1977) injected tracer during low tide levels, by spreading it on the beach face just landward of the advancing swash in a one-metre wide band perpendicular to the beach. Injection in the surf zone took place by placing plastic bags on the sand bed to approximate a line source, the bags were emptied simultaneously at the time of injection.
Injection by using core samplers “in reverse” gave the same results (Inman et al., 1980; Kraus et al., 1982; and Kraus, 1985). Duane and James (1980) adopted a similar approach whereby injection took place at six points along a shore-normal profile, thus simulating a line source. A quasi-continuous procedure was followed, whereby tracer was injected intermittently at a rate of 27.3 kg every five minutes.

Certain authors (e.g. Knoth and Nummedal, 1977; Kraus et al., 1982; and Kraus, 1985) chose to soak the tracer in a solution of water and liquid detergent prior to release close to the bed surface. This sought to avoid floatation of the tracer after injection, as floating particles are situated in an unrealistic transporting environment and would be carried at abnormally high velocity until settling (Ingle, 1966).

The means of recovery of sediment have taken a number of different forms, including surface samples, grab samples and core samples. Ingle (1966) undertook a series of tracer experiments where surface samples were taken using paperboards covered in Vaseline that were pressed onto the sand surface. Badr and Lotfy (1999) collected surface samples by pressing a bentonite-coated wooden board onto the sea bottom, core samples then being used to determine the thickness of the mobile bed layer.

Numerous authors developed devices that can take grab samples of the top layer of a bed. Inman et al. (1980) and Zampol and Waldorf (1989) employed a technique where samples were collected using a scissors-type box which collected only the first two centimetres of the surface layer. Duane and James (1980) collected samples using a hand-held scoop built on broad runners that would penetrate the sand column no more than 1 cm. Core samples can also be taken in situ using hand-held wedge-shaped PVC tubes, sometimes split lengthwise, or a special coring device (Boon, 1968; 1969; Ciavola, et al., 1996; 1997a; 1997b; 1998; 1999a; Knoth and Nummedal, 1977; Kraus, et al., 1982; Kraus, 1985; and Munoz-Perez, et al., 1999).

Meaningful results have been obtained by tracer studies only when the volume samples extended to the depth of burial of the sand tracer. Sticky cards and grab samples have been used to sample the top layer of sand, however such sampling yielded results that were not representative of the entire distribution of tracer and therefore only core samples appear suitable for quantitative purposes.
Chapter 5A: Fluorescent tracer

The core samples need to be segmented before further analysis, using either a constant interval or a depth related to the mixing depth. Ciavola et al. (1996; 1997a; b; 1998; 1999a) used PVC tubes that were split lengthwise, hence it was possible to split the core samples at vertical intervals in the field. Boon (1968) divided the cores in the laboratory. The cores were cut into two halves, the sediment surface was impregnated with liquid jelly and heated. This formed an external crust, and sub-samples at 2.5 cm interval were collected.

Other researchers let the depth of the sub-samples depend on the estimated mixing depth. Boon (1969) computed the mobile layer thickness using profile data acquired between successive high tides. The mixing depth was found to be 1.3 cm, and consequently in the laboratory the top 1.3 cm of each core was removed for further analysis. Kraus et al. (1982) and Kraus (1985) finely segmented certain cores in 1- or 2-cm lengths to determine the mixing depth. The remainder were treated as grab samples in the analysis. Before counting the fluorescent grains, the sub-samples were washed and dried. For some experiments the samples were sieved into different size fractions (Komar and Inman, 1970; and Munoz-Perez, et al., 1999).

Counting of the number of fluorescent grains is done by exposing the samples to an ultraviolet light source in a completely darkened room (e.g. Boon, 1968; 1969; Ciavola, et al., 1996; 1997a; 1998; 1999a). Inman et al. (1980) spread 10 gram sub-samples to a single grain layer thickness on a counting grid. The tracer concentration was expressed as number per unit volume (tagged grains per centimetre in the bed) (Kraus et al., 1982; Kraus, 1985) or as number of marked grains per 100 g of sample (Knoth and Nummedal, 1977; Munoz-Perez, et al., 1999).

One of the main disadvantages of manual grain counting is it requires considerable time and manpower. Devices have been constructed to count the numbers of tagged grains in beach-sand samples. Teleki (1966) and Farinato and Kraus (1980) devised a spectrofluorimetric method for determining tracer concentrations. The sand samples were washed with a solvent able to dissolve the resin and the paint covering the grains. The fluorescence of the effluent was then measured using a spectrophotometer: the measured intensity was proportional to the number of tagged grains, the solution transmission and the uniformity of the paint cover. The calibration of the intensity coefficient versus the number of marked grains per gram had to be undertaken according to the degree of
marking, the grain size distribution, the chemical properties of the solvent and of the resin. Kraus et al. (1982) used the spectrofluorimetric method and managed to build up a large database using data from eight different field experiments undertaken on Japanese beaches using sands of different colours. The method improved the time efficiency of the analysis, however, some of the underlying assumptions are difficult to accept. For the method to work, all sand grains should be almost equi-dimensional. Certainly in the case of a unimodal, well-sorted sand that can be true, but the method loses significance as sorting becomes worse. Also, it is assumed that the paint cover of the grains is uniform, which is unlikely.

5A.4 SUMMARY

- The use of sand tracer is the best available methodology for the determination of longshore sediment transport rates over medium temporal and spatial scales, and has been used in the past for calibrating sediment transport models.
- As a result of the lack of an agreed objective calculation procedure, the mixing depth is a matter of definition, complicating the evaluation of different study results. It was concluded by Kraus et al. (1982) that the 80 % cut-off percentage is the preferable method, and this procedure has since been used in several but not all studies.
- Generally, gentle beaches show a small mixing depth characterised by a bimodal distribution, with maximum values near the breaker line and the relatively shallow shoreline. On steep gradient beaches, the profile of mixing has been found to be unimodal, with a maximum in the area where the waves break and a minimum in the swash zone. There might be a typical cross-shore distribution with one or more peaks in the mixing depth depending on the beach type, but some caution should be exercised in this respect until further research clears the complexity of the matter.
- Cross-shore distributions of the mixing depth, the advection velocity and the longshore sediment transport rate depend on beach type. Therefore, it can be considered essential to determine site-specific values, e.g. by using the method of White and Inman (1989a). Unfortunately, most previous tracer studies use a physically less correct strategy assuming that at least one of these variables is constant.
Chapter 5B: Fluorescent tracer

CHAPTER 5B: FLUORESCENT TRACER -
LONGSHORE TRANSPORT ON MEDIUM
TEMPORAL AND SPATIAL SCALES

5B.1 INTRODUCTION
Part B describes the results from four studies using sand tracers to investigate the longshore sediment transport on medium temporal and spatial scales (refer to Figure 1.1). The field experiments involved marking the natural beach material with fluorescent paint, injecting the tracer sand across the surf zone and following its spatial and temporal pattern of movement. The resulting cross-shore distributions of the mixing depth and advection velocities were used to derive longshore sediment transport rates. These measurements were compared with transport predictions based on wave breaking and surf-zone conditions.

5B.2 METHODOLOGY

5B.2.1 Study area
Results will be reported from four experiments, one performed in 2001 on Brighton beach (refer to Section 5B.3), and three performed in 2002 on South Leighton, North Leighton and Mullaloo beaches (refer to Section 5B.4) (Figure 3.1). The results of the Brighton beach measurements are more extensively discussed as the instrumentation was most comprehensive, the sea breeze was the strongest and simultaneous transport measurements using OBS-sensors and streamer sediment traps were performed (for results see Chapter 6).

5B.2.2 Collection and analysis of hydrodynamic data
The general experimental arrangement of the multicolour tracer experiments is shown in Figure 5B.1. The hydrodynamic data were collected using a cross-shore array of hydrodynamic frames. The frame locations were just outside the surf zone (wave shoaling area), the outer surf zone, the mid-surf zone and the lower swash zone. The type of sensors differed slightly for each frame, but at each location the data resulted in information on the water surface elevation, cross-shore and longshore current velocities.
Data were sampled at 2 Hz and were logged on the instrument itself or transferred via a cable to shore-based personal computers.

The pressure sensors were calibrated in a tank where varying water depth and voltage output were recorded. The nearly linear response curves were used to obtain water depths from the field data, including corrections for water temperature and salinity. The current meters were calibrated using factory specifications.

5B.2.3 Collection and analysis of tracer data

Sand was collected from the upper swash at the proposed field site, was washed to remove salt, and then tagged with a water-based fluorescent paint. For these experiments, paint in the colours red, yellow and blue was used. The tagged sand was dried, any lumps were removed and the remainder was stored in bags.

On the day of the experiment, the tagged sand was pre-soaked in a solution of seawater and detergent to wet all the grains before injection (Figure 5B.2). The pre-soaked tracer sand was placed in plastic bags, each of which contained approximately 15 kg of material. Tracer was injected in the lower swash, mid-surf zone and in the outer surf zone, whereby a different colour was used at each location (Figure 5B.1). Injection was made by a group of people, each person carrying a bag into the surf zone to the injection location where the group simultaneously ripped open the bags of tracer close to the bed (Figure 5B.2). The duration of injecting all three tracer colours was two minutes. During the Brighton beach experiment (conducted on 10.01.01) 80 kg of tracer sand was injected in both the lower swash and mid-surf zone, and 120 kg was injected in the outer surf zone. During the experiments at South Leighton, North Leighton and Mullaloo beaches (conducted in the year 2002) calmer conditions were experienced and therefore less tracer sand was used; typically 50 kg of each colour at each cross-shore location.

The fact that sand collected at the beach face was painted and used as tracer sand, effectively resulted in non-native sand being used for tracer injection in the surf zone. During the tracer experiment there was no cross-shore graduation in grain sizes at the South Leighton, Mullaloo and North Leighton beaches. For the Brighton beach experiment, the mean sediment size of tracer sand was 0.5 mm, which was similar to the beachface sediment, but 15 % finer than the surf zone sediment. It was assumed this
slight difference in grain size did not affect the transport processes because of the turbulent nature of the surf zone, especially during the sea breezes.

Figure 5B.1: Schematic overview of a typical multi colour tracer experiment, with injection sites, reference markers, sample locations and the position of hydrodynamic measurements.

To derive longshore transport rates from the movement of sand tracer, both the Spatial Integration Method (SIM) and the Temporal Integration Method (TIM) were used. The location and timing of the samples was based on the results of a pilot study carried out at Brighton Beach on 30.12.00. To assist with locating the sampling points, a rectangular arrangement of reference markers was used, consisting of stakes driven into the sand (Figure 5B.1). For the SIM, six cross-shore transects were established at \( y = -10, 0, 50, 100, 150 \) and \( 200 \) m, where \( y = 0 \) represents the tracer injection line. Along each transect, core samples were collected at the upper swash, lower swash, inner surf, mid-surf and outer surf zone (Figure 5B.1). The grid was sampled one and two hours after tracer injection and it took less than 15 minutes to sample the entire grid. Such a relatively short duration for the tracer experiment was selected because conditions during the sea breeze are highly variable and some degree of stability was desirable. For the TIM, sampling was repeated at a fixed longshore distance from the injection site. Samples were collected every 15 minutes along the \( y = 50 \) m transect, over a two-hour period following tracer
Figure 5B.2: Bags of tracer sand (top left); pre-soaking of tracer sand (top right); and injection of tracer at the lower swash (bottom left and right).

Figure 5B.3: Hand-operated extruder, comprising of a vertically-mounted hydraulic jack with an extended body which accommodates the sample tube.
injection. Each time six samples were taken along this cross-shore line, the locations being: upper swash, lower swash, inner surf, mid-surf, outer surf and offshore of the breaker line.

All core samples were taken by manually pushing a 30 cm long plastic tube with a diameter of 36 mm into the bed. After the samples were taken, the top and bottom of the tubes were sealed and the core samples were stored and transported to the laboratory. It was ensured that the tubes remained in a vertical position to minimise disturbance of the samples. In the laboratory, a hand-operated extruder was used to remove the sand cores from the plastic tubes (Figure 5B.3). The TIM samples were extruded from the plastic tubes, cut into 1 cm layers, oven-dried and weighed.

Significant effort was spent on developing an automated system with which to count the fluorescent grains under ultraviolet light. Unfortunately, this was not possible as a result of the natural white colour of the beach sand, the inability of the digital camera to filter the ultraviolet light, and the similarity in reflectance of the yellow and blue tagged grains. Therefore, the fluorescent tracer grains were hand-counted under ultraviolet light and the tracer concentration was expressed as the number of fluorescent grains per gram sample.

The mixing depth has to be carefully derived from the tracer concentration profiles because the transport rate is directly proportional to it. The problem of estimating the mixing depth is the lack of satisfactory procedure for objectively defining the mixing depth. Three definitions of the mixing depth were applied on the data and the results were compared, the definitions being:

- maximum depth of tracer burial as implemented by Komar and Inman (1970),
- cut-off percentage of 80 % as employed by Kraus et al. (1981, 1982), and
- cut-off concentration of 0.5 grains/gram.

For the 45 TIM-cores and for each tracer colour, the mixing depth $b$ was determined from the tracer concentration profile using the three definitions. As many profiles contained more than one concentration gradient, including some layers without tracer grains, the maximum depth and 80 % cut-off methods gave extra weight to grains near the bottom of the cores. The mixing depth according to the maximum depth method was on average 15 cm, which was approximately 6 cm deeper than the average 80 % cut-off mixing depth and 8 cm deeper than the 0.5 grains/gram cut-off mixing depth. As a result
the longshore transport rate according to the maximum depth method would be 67\% larger than according to the 80\% cut-off method. This emphasises the importance of an objective definition of the mixing depth that can be widely used.

As three different tracer colours were injected, it was possible to retrieve more than one colour in some sub-samples, allowing for comparisons of the mixing depth of different colours in one core. It is assumed that the tracer grains are transported in equilibrium with the native sediment by the time they reach the sampling line located 50 m downstream of the injection sites. When more than one tracer colour was present in a core, the mixing depth of the different colours should be similar and the standard deviation should be small. The results of the maximum depth and 80\% cut-off mixing depth showed high standard deviations caused by relatively high variation in the low concentration of the samples. Hence, it is unreliable to use these methods for estimating the mixing depth. Instead, the mixing depth was defined as the depth where the concentration dropped below 0.5 grains per gram sample. The resulting mixing depth gave more consistent results than using the maximum depth of tracer burial as employed by Komar and Inman (1970) or using an 80\% cut-off such as implemented by Kraus et al. (1982).

For each of the cross-shore sampling locations, the results for the different time steps were averaged to give the cross-shore distribution in mixing depth $b(x)$ according to the TIM-samples. The data were manually inspected and mixing depth was set to zero if only some tracer grains were retrieved and the concentration remained below 0.5 grains/gram in the entire core. Due to negligible to zero tracer concentrations in the cores taken offshore of the breaker line, the mixing depth in this region was set to 0 cm at all times. The mixing depth at the maximum swash uprush was also set to 0 cm. If a core contained multiple tracer colours a single mixing depth was calculated as the average mixing depth of the different colours, and the standard deviation was determined. The average cross-shore distribution of the mixing depth during the 120 minutes of sampling was also determined.

The cores for the SIM were not sliced into small increments, but bulk samples were taken of the whole mixing depth, which depended on the cross-shore location from where the core was taken as determined from the TIM-samples. Using bulk samples, rather than increments or slices presupposes that the tracer concentration is uniformly distributed
with depth. Prior to the analysis of the tracer dispersal, the tracer concentrations were converted to grains per kg and were standardised by multiplying by the factor 100/M, where M is the mass of injected tracer for each of the tracer colours.

Once the two-dimensional distribution of the tracer concentration was determined, in longshore distance, \( y \), using the SIM and in time since injection, \( t \), using the TIM, the tracer advection velocity was determined using Equation 5A.4 and Equation 5A.5, respectively. For the spatial grid, the summation is over all \( y \)'s and \( t \) represents the time between tracer injection and sampling (one and two hours). For the temporal grid, the summation is over all \( t \)'s and \( y \) represents the alongshore distance between tracer injection and sampling (\( y = 50 \) m). The local longshore transport rate \( q(x) \) (in \( m^2 s^{-1} \)) is computed using the cross-shore distribution of both the mixing depth and the advection velocity (Equation 5A.1). The total longshore transport rate \( Q \) (in \( m^3 s^{-1} \)) is obtained according to Equation 5A.2. Sediment transport rates were computed for each of the three tracer colours and also for the bulk tracer population, allowing for four separate estimates of the transport rate.

To assess the reliability of the estimated longshore transport rates, tracer recovery for both SIM and TIM were determined using the method of White and Inman (1989a) as outlined by Equation 5A.7 and 5A.8. The number of tracer grains per unit mass, \( F \), was estimated by counting the number of sediment grains in several small (c. 0.1 g) random samples, determining the average weight of a sediment grain and converting this to the number of grains per kg. This method is more correct than converting the average grains size (\( D_{50} \)) into an average grain weight assuming spherical grains, because the latter method is biased toward the larger grains in the size population and yields a much smaller number of grains per kg.
5B.3 RESULTS OF THE EXPERIMENT AT BRIGHTON BEACH IN 2001

5B.3.1 Wind climate and wave breaking conditions

A field study was conducted from 5th to 12th January 2001 on Brighton beach located along the coastline of Southwestern Australia (Figure 3.1). The tracer experiment discussed in this section took place on 10th January from 13:00 to 15:00 hrs and was conducted simultaneously with the streamer trap and OBS measurements that are discussed in Chapter 6.

The weather, tide and wave conditions experienced during the field study were typical of summer conditions along the Perth metropolitan coastline (Figure 5B.4). Wind data were obtained from Swanbourne beach, located 7 km south of the study area, and water level and wave data were measured using a wave sensor deployed just outside the surf zone of Brighton beach. Throughout the measurement period, background swell was present with a dominant frequency of 0.08 Hz. The swell was initially quite energetic, with a significant wave height exceeding 1 m, but progressively decreased to 0.5 m. Weak sea breezes were experienced on 8th and 11th January and strong sea breezes on 9th and 10th January, as indicated by an increase in wave height and decrease in wave period. During the strong sea breezes the significant wave height doubled from 0.5 to 1 m. The wave spectra show that during a sea breeze a mixture of wind and swell waves are present. The frequency of the wind waves progressively decreases during each of the sea breezes and the wind-wave energy merges with the swell energy in the evening at the end of the sea breeze.

The tracer experiment was conducted during the strong sea breeze of 10th January, typical of Southwestern Australia (shaded area in Figure 5B.4). Wind speeds during the tracer experiment were around 6 m s\(^{-1}\) and the direction was consistently south-southwesterly and thus was blowing slightly onshore (Table 5B.1).
Breaking wave conditions were derived from self-logging sensors deployed outside the surf zone in the wave shoaling area, at a water depth of 3-3.5 m (location 7 in Figure 5B.5). The water surface elevation was measured with a pressure sensor and three-dimensional current velocities were recorded using an acoustic current meter. Data were sampled at 2 Hz and the sensor was programmed to collect 20 minutes of data every hour. The wave directional spectrum was computed using the extended maximum entropy method (Hashimoto, 1997). Linear wave theory was used to account for the frequency-dependent depth attenuation of the wave signal. For the incident, swell and wind wave the significant wave height $H_{sig}$, peak and significant wave period $T_p$ and $T_{sig}$, and an energy-weighted mean wave angle $\alpha$ were derived. Using linear wave theory, each of these representative waves was refracted to a water depth of 1.5 times the
significant incident-wave height measured at the location of the offshore rig. The conditions at this depth were considered breaking wave conditions.

Table 5B.1: Overview of the average wind, wave and current conditions during the tracer experiment. Wave data was collected near the breaker line, wind data collected at Swanbourne Beach.

<table>
<thead>
<tr>
<th></th>
<th>10.01.01 Brighton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (m s(^{-1}))</td>
<td>5.7</td>
</tr>
<tr>
<td>Wind direction (degrees)</td>
<td>212</td>
</tr>
<tr>
<td>Beach slope (tan/(\theta))</td>
<td>0.06</td>
</tr>
<tr>
<td>Grain size, (D_{50}) ((\mu)m)</td>
<td>500</td>
</tr>
<tr>
<td>Longshore current, mid-surf (m s(^{-1}))</td>
<td>0.84</td>
</tr>
<tr>
<td>Breaker wave height (m)</td>
<td></td>
</tr>
<tr>
<td>incident</td>
<td>0.85</td>
</tr>
<tr>
<td>swell</td>
<td>0.54</td>
</tr>
<tr>
<td>wind</td>
<td>0.73</td>
</tr>
<tr>
<td>Peak wave period (s)</td>
<td></td>
</tr>
<tr>
<td>incident</td>
<td>4.1</td>
</tr>
<tr>
<td>swell</td>
<td>12.5</td>
</tr>
<tr>
<td>wind</td>
<td>3.6</td>
</tr>
<tr>
<td>Wave angle (degrees)*</td>
<td></td>
</tr>
<tr>
<td>incident</td>
<td>16.6</td>
</tr>
<tr>
<td>swell</td>
<td>0</td>
</tr>
<tr>
<td>wind</td>
<td>22.3</td>
</tr>
</tbody>
</table>

* Relative to shore-normal

The tracer experiment was conducted when the tide was rising (Figure 5B.4B). At the breaker line, the incident significant wave height was around 0.9 m (Table 5B.1). The swell wave energy was low (Figure 5B.4E) and the significant height of the swell waves was ~0.5 m, whilst the wind waves were around ~0.7 m in height. Throughout the tracer experiment, the swell waves were parallel-incident. In contrast, the wind waves were obliquely-incident, with wave angles of 22°. The wave angle associated with the combined wave field (swell and wind waves) during the experiment was 17°.

The longshore current velocity was derived from a bi-directional electromagnetic current (EMCM) meter attached to a hydrodynamic frame located in the mid-surf zone (location 4 in Figure 5B.5). This instrument was mounted at a nominal distance of 0.2 m above the bed, hard-wired to the beach and data were logged continuously at 2 Hz frequency on a personal computer. Every effort was made during the experiment to maintain the instrument elevation at the original level, which required frequent adjustments during data collection.
5B.3.2 Nearshore morphology

Beach sediments were medium to coarse, well-sorted, predominantly quartzose sand, with significant amounts of carbonate material mixed in. The median sediment size, $D_{50}$, and fall velocity, $w_f$, of the sediments in the swash zone were 0.5 mm and 0.07 m s$^{-1}$, respectively. Surf zone sediments were somewhat coarser ($D_{50} = 0.6$ mm and $w_f = 0.08$ m s$^{-1}$), whereas sediments in the wave shoaling area were considerably finer ($D_{50} = 0.3$ mm and $w_f = 0.04$ m s$^{-1}$).

The cross-shore profile was surveyed from the beach to the wave shoaling area during quiet wave conditions before the onset of the sea breeze (Figure 5B.5). Due to vigorous wave action and strong currents, measurements of the bed level and bedforms in the surf and shoaling zone could not be made during the sea breeze. Therefore, during the tracer experiment only the swash zone was repeatedly surveyed. Profiles measured at the start of the tracer experiment ($t = 0$ minutes), one hour and two hours after the start are represented. The cross-shore distance is measured relative to the average position of the runup limit during the tracer experiment. The beach was characterised by a subaerial berm and a moderately steep foreshore ($\tan \beta = 0.06$) whereby the swash zone measured a steeper slope than the surf zone. The upper swash (location 1 in Figure 5B.5) experienced 0.1 m accretion during the first hour of the tracer experiment and 0.1 m erosion during the second hour. The lower swash (location 2) experienced erosion during the whole tracer experiment; 0.06 m and 0.08 m in the first and second hour, respectively. No
information was available regarding erosional or depositional events in the surf and shoaling region. Nevertheless, the erosion and accretion measured in the swash zone are an indication of cross-shore sediment transport during the tracer experiment. This will have an influence on the direction of tracer transport, which as a result could be bi-directional, with transport paths in both longshore and cross-shore directions.

Bedforms were not measured in the surf and shoaling zone, but observations were made during repeated sampling at several cross-shore locations. The swash zone had a planar surface. In the turbulent inner surf zone, the sediment was very loosely packed and formed a hummocky surface. These features decreased in size in the direction of the outer surf, to change into a densely packed, flat bed at the breaker line. Offshore of the breaker line, small asymmetric bed features existed. The size of the bedforms in the inner surf zone was not measured but literature suggests that the irregularities consist largely of sets of troughs or depressions, 1-2 m across and 10-50 cm deep, elongate parallel to the shoreline and separated by broad, flat “ridges” (e.g., Clifton et al., 1971; and Gallagher, 2003).

5B.3.3 Mixing depth

As discussed in Section 5.2.1, a tracer experiment is based on the assumption that a thin active layer of sand moves with some average advection velocity over a second passive sand layer. The thickness of the active layer represents the mixing depth, which was determined from the TIM-samples taken in a cross-shore line located 50 m downdrift of the tracer injection line (locations 1-6 in Figure 5B.5). A total of 45 cores were sliced in centimetre layers and the number of tracer grains was counted in 770 sub-samples. Tracer concentration profiles showed most of the tagged sand to be typically contained in the upper 6 cm of a core, but frequently some grains were found down to 15 cm deep.

The cross-shore distribution of the mixing depth during the 120 minutes of sampling was also determined (Figure 5B.6). The average cross-shore distribution of the mixing depth displayed a maximum of 12.6 cm in the mid-surf zone where energetic breaker conditions prevailed and large, irregular bedforms were present on the bed. A second peak was located at the upper swash, with a mixing depth of 7.8 cm. The mid-surf and upper swash zone were also characterised by the highest standard deviations of 3.8 cm and 3.9 cm, respectively. The minimum mixing depth, of 2 cm, was found in the lower
swash, with also the lowest standard deviation of 1.2 cm. Repeated surveys (Figure 5B.5) did indicate the lower swash zone experienced 16 cm erosion during the tracer experiment which reduced the mixing depth. The average mixing depth across the nearshore zone is 7 cm and compares well with other investigations conducted on relatively steep beaches under similar wave conditions (Ciavola et al., 1997a).

The subplots in Figure 5B.6 display the changes in the cross-shore distribution of the mixing depth over a 15-minute interval. The cross-shore distribution is very similar to the average distribution at all times. All distributions showed a peak in the surf zone, although after 30 minutes the peak was located in the inner surf, and not in the mid-surf zone, as was the case for all other sampling times. All but the one distribution, at \( t = 15 \) minutes, displayed a clear peak in the swash zone. Comparing the shape of the average cross-shore distribution with the time specific distribution, it appeared that after 45 minutes the cross-shore change in mixing depth reached its typical distribution, with a peak in the upper swash and mid-surf zone.

The hummocky bed of the inner surf zone was characterised by sets of ridges and depression up to 50 cm deep (refer to Section 5B.3.2). Because of the size of these features the exact sample location would have a considerable influence on the mixing depth. Ideally, core samples were consistently taken on the top of the ridges or in the depressions, yet in the field that was hard to ascertain. This might have caused the variations in mixing depth as measured in the surf zone (Figure 5B.6) and thus single values must be treated with caution.
Figure 5B.6: Temporal changes of the cross-shore distribution of the mixing depth at $y = 50$ m. The thick line with solid circles indicates the mixing depth at the time indicated in the figure. The thin line with open triangles represents the average distribution over the two-hour period, with error bars indicating +/- one standard deviation. The shaded areas represent the swash zone and the area offshore of the breaker line.
The changes in mixing depth over time are further investigated in Figure 5B.7. The time since tracer injection is plotted on the x-axis, with each subplot representing a different sampling location. The results of the sampling offshore of the breaker line are not shown as the mixing depth is zero at all times, indicating no tracer has moved offshore of the breaker line. The upper swash displayed an increase in mixing depth during the whole 120 minutes of sampling, this increase with time was shown less clearly in both the inner surf and mid-surf. The outer surf showed some variation in mixing depth, but overall the mixing depth remained relatively constant. The thick line with the solid circles indicates the mixing depth at each location. Values are the averages for the three different tracer colours and error bars indicate +/- one standard deviation.

Figure 5B.7: The changes in mixing depth over time at y = 50 m, for five sample locations. The thick line with the solid circles indicates the mixing depth at each location. Values are the averages for the three different tracer colours and error bars indicate +/- one standard deviation.
and mid-surf zone. The mixing depth at the lower swash showed little variation and the values were always relatively low. During the first 60 min of the experiment, the mixing depth at both the mid-surf and outer surf zone varied, while during the second hour the mixing depth stabilised which might indicate that an equilibrium value for the mixing depth has been reached. Using the information on the changes of mixing depth with time and location (Figure 5B.6 and Figure 5B.7) it can be concluded that there exists a large spatial variability in the mixing depth, with values up to 15 cm. Therefore, a location-dependent depth should be used during transport calculations. During this study, the SIM results after one hour were computed using the average mixing depth computed over the first hour, whereas the TIM results and the SIM results after two hours were determined using the average mixing depth computed over the 2-hour tracer experiment (Table 5B.2 and Figure 5B.8).

Table 5B.2: Cross-shore distribution of the mixing depth during equilibrium transport, based on the values during the first hour and both hours of the tracer experiment.

<table>
<thead>
<tr>
<th>Cross-shore distance</th>
<th>Mixing depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>first hour</td>
</tr>
<tr>
<td>Maximum uprush</td>
<td>0.00</td>
</tr>
<tr>
<td>Upper swash</td>
<td>0.04</td>
</tr>
<tr>
<td>Lower swash</td>
<td>0.01</td>
</tr>
<tr>
<td>Inner surf zone</td>
<td>0.07</td>
</tr>
<tr>
<td>Mid-surf zone</td>
<td>0.10</td>
</tr>
<tr>
<td>Outer surf zone</td>
<td>0.06</td>
</tr>
<tr>
<td>Offshore breakers</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 5B.8: Cross-shore distribution of the mixing depth, at y = 50 m. Based on the mixing depth during the first hour of the tracer experiment (thick line with solid circles) and the 2-hour experiment (thin line with open triangles).

5B.3.4 Spatial Integration Method

Sampling according to the Spatial Integration Method (SIM) was performed 60 and 120 minutes after tracer injection in a sampling grid extending 200 m longshore and
37 m cross-shore. For each core the tracer concentration was determined from a bulk sample that included the entirety of the mixing depth. Due to negligible to zero tracer concentrations offshore of the breaker line the concentration in this region was set to 0 grains/gram at all times. The tracer concentration was also set to zero at the location of maximum swash uprush.

The spatial distribution of the tracer concentration after 60 and 120 minutes for each of the tracer injection locations is shown in Figure 5B.9 and Figure 5B.10. The prevailing sediment transport is toward the north (top of the diagrams). In the 10 cores taken updrift (south) of the injection line, a total of four tracer grains were retrieved, resulting in concentrations smaller than the cut-off limit. During the first hour, tracer injected in the surf zone travelled around 100 m in downstream direction, while the tracer injected in the lower swash zone moved on average 50 m (Figure 5B.9). During the second hour, some tracer seems to have moved by about the same distance as during the first hour, but most of the tracer did not move at all, suggesting tracer burial occurred during the second hour. As a result the tracer distribution after 120 minutes is similar to that after 60 minutes. Furthermore, a significant amount of tracer sand travelled out of the sampling area at the downstream end, especially after 2 hours, indicating that the sampling grid was too small.

Superimposed on the longshore tracer movement is a cross-shore advection of the tracer. This results in a splitting up of all three tracer populations into an upper swash and an outer surf zone sub-population, with very low tracer concentrations around the lower swash zone (x = 15-20 m). Repeated beach surveys show that the lower swash zone was characterised by erosion during the tracer experiment (Figure 5B.5), inhibiting the deposition of tracer sand and resulting in low tracer concentrations. The cross-shore distribution of tracer sand reveals that sediment eroded in the lower swash zone either moved onshore toward the upper beachface or offshore toward the breaker line, driven by the wave/swash and bed return flow, respectively. However, sediment exchange does occur between the surf and swash zone, which is reflected by the retrieval of tracer sand across the whole nearshore zone (swash and surf zone) regardless of the tracer injection location.
5B.3.5 Temporal Integration Method

The same samples as discussed in the section on the variation in mixing depth were used during the TIM as an indicator of pulses in tracer migration. By using the mixing depth as defined in Table 5B.2 and Figure 5B.8 it was possible to determine the tracer concentration across the surf zone at $y = 50$ m during different sampling times resulting in a temporal concentration variation (Figure 5B.11). Similar to the SIM results, the tracer moves as two separate sub-populations: the mid- to upper swash zone and the mid-
to outer surf zone. In accordance with other tracer investigations using the TIM (e.g. Kraus et al., 1982), the tracer concentration over time is characterised by more than one peak, making the results uncertain and difficult to interpret (Komar, 1998). A very large proportion of the tracer appears to have passed the sample line within the first 30 minutes, but even after the first hour the tracer flux is still significant.

The highest concentration of tracer injected in the lower swash zone passed the sampling line after 15 minutes at the inner and mid-surf zone (Figure 5B.11A). A second slower moving peak with lower tracer concentrations was monitored in the inner swash around 105 minutes. These results do correspond with the results 60 minutes after tracer injection of the SIM (Figure 5B.9A). Using the SIM a fast moving tracer cloud was found around the breaker line 100 m downstream of the injection line. It can be assumed this tracer passed the sampling line of the TIM around 15 minutes after injection. The slower moving tracer in the inner swash was also recorded in both integration methods.

For the tracer injected in the mid-surf zone, the highest peak was monitored after 15 minutes in the outer surf zone (Figure 5B.11B), as with the tracer injected in the lower swash. Two other peaks with lower concentration were measured at the same location after 45 and 75 minutes. These pulses in tracer migration indicate the transport processes were not stable caused, for example, by pulses in the actual advection velocity or temporal burial of tracer sand. The pulses made it difficult to link the peak reported
100 m downstream 60 minutes after injection when using the SIM to the results of the TIM.

For the tracer injected at the breaker line results show a high concentration in the outer surf zone during the two hours of monitoring (Figure 5B.11C). The notable differences in transport directions of tracer injected at different cross-shore locations indicate that multi-colour tracer injections are a useful tool in the identification of both cross- and longshore sediment pathways.

5B.3.6 Tracer advection velocity and longshore transport rate

The tracer dispersal results (SIM and TIM) were used to obtain tracer advection velocities using Equation 5A.4 and Equation 5A.5 (upper panels in Figure 5B.12). The advection velocities were combined with the mixing depth to yield an estimate of the longshore transport rate using Equation 5A.1 (lower panels in Figure 5B.12). For the surf zone, the SIM results after 60 minutes and the TIM results are very similar, but the SIM results after 120 minutes yield tracer advection velocities and longshore transport rates that are lower. The swash zone results for both SIM experiments are similar while the TIM suggests higher advection velocities and transport volumes. The results are remarkably consistent for the different tracers, despite the distinctly different injection locations. The tracer advection velocities are 1.5–3 cm s⁻¹ (2–4% of the mid-surf longshore current velocity) and do not vary much across the nearshore. They are faster than reported by Kraus et al. (1982) who found that the advection velocity of the tracer is 1–2% of the longshore current velocity. Due to the spatial variation in the mixing depth, the distribution in the longshore transport rate is characterised by maxima at the upper swash zone and mid-surf zone. Longshore transport rates are 0.2–2.9 × 10⁻³ m³ s⁻¹ per unit meter beach width.

Total immersed-weight longshore transport I, and tracer recovery rates (computed using Equations 5A.2, 5A.3, 5A.7 and 5A.8) are listed in Table 5B.3. Even though tracer recovery rates have been mentioned in previous studies, there has been little discussion of the influence of recovery rates on the reliability of the transport estimations (e.g., Inman et al., 1980; Kraus et al., 1981; Sherman et al., 1994; and Voulgaris et al., 1998). Both Kraus et al. (1981) and Sherman et al. (1994) indicated that small recovery percentages might be the result of the largest tracer concentrations being situated in
between the sampling points. As a result a large part of the tracer is not accounted for while it resides still in the sampling area. Another assumption is that the recovery rate decreases when more tracer grains leave the area of monitoring at the downdrift side. The average tracer recovery rate as reported in the above mentioned studies is 48%, which compares well with the bulk recovery percentage of the TIM at Brighton beach (53%). The recovery rates during both SIM experiments were around 20%. A high recovery percentage indicates that a large part of the injected tracer is accounted for, giving confidence in the transport estimates. Consistency in advection velocities and recovery percentages for the different tracer injections is reflected in the similarity in transport rate estimates, therefore it is appropriate to combine the results and use the bulk estimate of the longshore transport.

Figure 5B.12: Cross-shore distribution of tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach, obtained using the SIM after 60 minutes (left panels), the SIM after 120 minutes (middle panels) and the TIM (right panels). The solid, dashed and dotted thin lines represent the results for the tracer released in the lower swash, mid-surf and outer surf zone, respectively. The thick solid line with black circles represents the result obtained by combining the three tracers. The shaded areas represent the swash zone (left) and the area offshore of the breaker line (right).
Table 5B.3: Total immersed-weight longshore transport ($I$) and tracer recovery rates.

<table>
<thead>
<tr>
<th>Injection location</th>
<th>Lower swash</th>
<th>Mid-surf</th>
<th>Outer-surf</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton Beach (10.01.01)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIM 60 min $I$ (N s$^{-1}$)</td>
<td>366</td>
<td>379</td>
<td>548</td>
<td>408</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>18</td>
<td>15</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>SIM 120 min $I$ (N s$^{-1}$)</td>
<td>246</td>
<td>290</td>
<td>336</td>
<td>262</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>22</td>
<td>19</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>TIM 120 min $I$ (N s$^{-1}$)</td>
<td>570</td>
<td>534</td>
<td>591</td>
<td>549</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>42</td>
<td>83</td>
<td>33</td>
<td>53</td>
</tr>
</tbody>
</table>

5B.4 RESULTS FROM THREE TRACER EXPERIMENTS IN 2002

5B.4.1 Wind climate and wave breaking conditions

A year after the previously discussed tracer experiment, three more experiments were undertaken using a similar methodology. The sites were South Leighton beach (18.01.02), Mullaloo beach (25.01.02) and North Leighton beach (12.02.02) (Figure 3.1). The results of these experiments will be discussed in the following section, using the same structure as in Section 5B.3.

Table 5B.4: Overview of the average environmental conditions during three tracer experiments in 2002.

<table>
<thead>
<tr>
<th>Wind speed (m s$^{-1}$)</th>
<th>Wind direction (degrees)</th>
<th>Beach slope (tan$\beta$)</th>
<th>Grain size, $D_{50}$ ($\mu$m)</th>
<th>Longshore current, mid-surf (m s$^{-1}$)</th>
<th>Breaker wave height (m)</th>
<th>Peak wave period (s)</th>
<th>Wave angle (degrees)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Leighton 18.01.02</td>
<td>7.0</td>
<td>205</td>
<td>0.10</td>
<td>287</td>
<td>0.35</td>
<td>8.8</td>
<td>5.9</td>
</tr>
<tr>
<td>Mullaloo 25.01.02</td>
<td>7.5</td>
<td>190</td>
<td>0.09</td>
<td>246</td>
<td>0.18</td>
<td>10.8</td>
<td>2.7</td>
</tr>
<tr>
<td>North Leighton 12.02.02</td>
<td>7.0</td>
<td>220</td>
<td>0.07</td>
<td>241</td>
<td>0.59</td>
<td>10.6</td>
<td>7.8</td>
</tr>
</tbody>
</table>

The tracer experiments all took place under sea breeze conditions, with the average wind speed being 7.0, 7.5 and 7.0 m/s during respectively the South Leighton, Mullaloo and
Chapter 5B: Fluorescent tracer

North Leighton beach experiments (Table 5B.4). The average wind directions were south-southwesterly to southwesterly.

Hydrodynamic measurements were made during each tracer experiment (Table 5B.4). Unfortunately for South Leighton and Mullaloo beach, breaking wave data were available for respectively only the first 30 and 60 minutes of the tracer experiment. Generally, the North Leighton experiment was the most energetic, which is reflected by the high values of mid-surf longshore current velocities, breaker wave heights and wave angles. During the South Leighton experiment, the wind waves were more energetic than the swell waves \((H_{\text{sig.wind}} > H_{\text{sig.swell}})\) and as a result the incident peak wave period was smaller compared to peak periods during the other experiments.

5B.4.2 Nearshore morphology

Beach sediments were medium to coarse, well-sorted, predominantly quartzose sand, with significant amounts of carbonate material mixed in. The median grain size and fall velocity of the sediment of the three study areas are similar. The swash zone sediments were slightly coarser \((D_{50} = 0.3-0.4 \text{ mm and } w_s = 0.04-0.05 \text{ m s}^{-1})\) than the sediments in the surf zone and wave shoaling area \((D_{50} = 0.2-0.3 \text{ mm and } w_s = 0.03-0.04 \text{ m s}^{-1})\).

The cross-shore profile was repeatedly surveyed during each tracer experiment (Figure 5B.13). The cross-shore distance was measured relative to the position of the swash runup limit during the tracer experiment. Profiles measured at the start of the tracer experiment \((t = 0 \text{ minutes})\), one hour and two hours after the start are represented. All three beaches were characterised by a steep foreshore exposed to swash action. Beach slopes \((\tan \beta)\) of the swash zone were 0.10, 0.09 and 0.07 for respectively the 18.01.02, 25.01.02 and 12.02.02 experiments. The area between the lower swash and mid-surf zone was relatively flat, with a step around mid-surf zone which caused the final plunge of waves as they break for the last time before surging up the beach face. The beach face was surveyed every 15 minutes during each tracer experiment. During the 18.01.02 experiment at South Leighton Beach the changes were minimal. During the experiment at Mullaloo Beach (25.01.02) up to 15 cm erosion was measured in the swash zone, and the same amount of accretion in the mid surf zone. North Leighton Beach (12.02.02) experienced up to 15 cm erosion in the inner surf zone. Measurements further offshore indicated accretion, but not enough data were available to estimate the amount.
Figure 5B.13: Cross-shore profiles and zones during the three tracer experiments in the year 2002. The horizontal dashed line represents mean sea level. Indicated are locations of hydrodynamic frames (sites 2 to 5), tracer injection (2, 3, 4) and tracer samples (1 to 5).
5B.4.3 Mixing depth

Cores used to analyse the mixing depth were taken in a cross-shore line located 50 m downdrift of the tracer injection line (Figure 5B.1). These samples were also used for the TIM analysis. During all three experiments, core samples were taken at the upper swash, lower swash, mid-surf, outer-surf zone and offshore of the breaker line (Locations 1-5 in Figure 5B.13). Samples were taken every 15 minutes until 120 minutes after tracer injection. The methodology to estimate the mixing depth was the same as that used on the Brighton Beach experiment of 10.01.01 (see Section 5B.3.3).

The average cross-shore distribution of the mixing depth was investigated (Table 5B.5 and Figure 5B.14). Overall the mixing depth was lower than measured during the Brighton Beach experiment (Section 5B.3.3). The mean distribution of the mixing depth for the experiment at South Leighton beach displayed an increase from the upper limit of swash uprush until the lower swash zone (Figure 5B.14A), after which there was a slight decrease in mixing depth until the breaker line, with a sharp decrease further offshore. The Mullaloo Beach experiment was characterised by a zero mixing depth in the swash zone (Figure 5B.14B). Repeated surveys of the cross-shore profile indicated erosion in the swash zone (Figure 5B.13) preventing the sand tracer from mixing with the native sediment and resulting in low to zero mixing depths (Figure 5B.14B). This illustrates the influence of local events of erosion on the mixing depth. The mixing depth increases from the lower swash until offshore of the breaker line, where the mixing depth peaks at 5 cm. The average mixing depth of the North Leighton Beach experiment (Figure 5B.14C) shows a relatively constant mixing depth, varying between 2 and 3 cm between the upper swash and offshore of the breaker line.

<table>
<thead>
<tr>
<th>Table 5B.5: Cross-shore distribution of the mixing depth (m).</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.01.02 South Leighton</td>
</tr>
<tr>
<td>Maximum uprush</td>
</tr>
<tr>
<td>Upper swash</td>
</tr>
<tr>
<td>Lower swash</td>
</tr>
<tr>
<td>Mid surf</td>
</tr>
<tr>
<td>Breaker line</td>
</tr>
<tr>
<td>Offshore breaker</td>
</tr>
<tr>
<td>Further offshore</td>
</tr>
</tbody>
</table>
Chapter 5B: Fluorescent tracer

As for the Brighton beach experiment (Section 5.5.3), the temporal change in the mixing depth was investigated. For all experiments there was a small variation in mixing depth, up to 2 cm during the 120 minutes of monitoring. It was concluded that the mixing depth is mainly dependent on the cross-shore location, hence a location dependent depth, as shown in Figure 5B.14, will be used during transport calculations.

5B.4.4 Spatial Integration Method

Sampling according to the Spatial Integration Method (SIM) was performed 60 and 120 minutes after tracer injection and the analysis was performed as previously discussed. For each core the tracer concentration was determined from a bulk sample that included the entirety of the mixing depth as defined in Table 5B.5 and Figure 5B.14. Only the result of the 60 minute sampling will be discussed for both Leighton beach experiments (South and North); for Mullaloo beach the results of the 120 minute sampling are discussed. The spatial distribution of the tracer concentration for each of the tracer injection locations is shown in Figure 5B.15. The prevailing sediment transport is toward the north (top of the diagrams) and no tracer sand was retrieved south of the injection line.
Figure 5B.15: Spatial distribution of three different sand-tracers for three experiments in 2002: (A, B, C) one hour after injection on South Leighton beach (18.01.02), (D, E, F) two hours after injection on Mullaloo beach (25.01.02), and (G, H, I) 60 minutes after injection on North Leighton beach (12.02.02). Tracer was injected at the lower swash (A, D, G), mid-surf (B, E, H) and outer surf (C, F, I) zone, represented by solid circles at longshore distance 0 m. Sample locations are indicated by crosses. The contour lines represent tracer concentrations of 50, 100, 200, 400, 800, 1600, 3200 and 6400 grains per kg, with darker colours reflecting higher concentrations.
Chapter 5B: Fluorescent tracer

At South Leighton beach (Figure 5B.15A, B and C) the spatial distribution of the tracer sand was different for each injection location. The tracer injected in the lower swash zone was transported in two sub-populations located in the swash and outer surf zone (Figure 5B.15A). The swash-population moved with a smaller longshore velocity than the outer surf-population. The tracer sand injected in the mid-surf zone moved slightly offshore towards the outer surf zone, while a small amount of tracer was retrieved in the swash zone (Figure 5B.15B). The tracer injected in the outer surf zone generally remained in this cross-shore location while it moved in a longshore direction, with a small amount moving towards the upper swash zone (Figure 5B.15C). Compared to the experiment at Brighton beach (Figure 5B.9) there was less cross-shore dispersal and mixing of the tracer sand from different injection locations.

The data from Mullaloo beach show a similar spatial distribution for all three tracer injections (Figure 5B.15D, E and F). Most of the tracer sand was confined to the outer surf zone, while none of the tracer sand was retrieved in the swash zone. This corresponds to the findings of the survey data, which indicated erosion in the swash zone (Figure 5B.13B). The findings of both the SIM and repeated surveys point towards an offshore movement by bed return flow and redistribution of sediment from the swash zone to the outer surf zone. Similarly, during the Brighton beach experiment no tracer grains were retrieved in the zone of erosion, as sediment moved from the lower swash to the upper swash and outer surf zones.

The SIM-results for North Leighton beach do show a similar spatial distribution for all three tracer injections (Figure 5B.15G, H and I), which corresponds to the findings at Brighton beach (Figure 5B.9). There is a sediment exchange between the surf and swash zone, as indicated by surf zone-injected tracer found in the swash zone and swash zone-injected tracer found in the surf zone. Furthermore, the tracer of each injection location moves as two sub-populations as a result of two dominant cross-shore sediment pathways. The first sub-population travels longshore in the swash zone caused by wave/swash-driven transport to the top of the beach, while the second is located in the outer surf zone near the breaker line as a consequence of the bed return flow. The latter moved with a higher longshore velocity. The zone in between the two sub-populations, the inner surf zone, did experience erosion during the tracer experiment (Figure 5B.13C), which explains the lower tracer concentrations found in this region.
5B.4.5 Temporal Integration Method

The same samples as discussed in the section on the variation in mixing depth were used as an indicator of pulses in tracer migration. It was possible to determine the tracer concentration across the surf zone at several sampling times using the mixing depth as defined in Table 5B.5 and Figure 5B.14. Plots of concentration of the individual tracer injections versus time for the Temporal Integration Method are given in Figure 5B.16.

The TIM-results of the South Leighton beach (18.01.02) experiment (Figure 5B.16 A, B and C) are consistent with the SIM-results (Figure 5B.15A, B and C). The tracer injected in the lower swash zone moves as two populations in a longshore direction. These populations are located in the swash zone and the surf zone, of which the latter has a higher longshore advection velocity (Figure 5B.16 A). The tracer injected in both the mid-surf and outer surf zone, moved mainly in the outer surf zone with a similar longshore velocity. The tracer of all three injection sites showed a maximum concentration 30 minutes after injection. The results of the tracer experiment indicated a large cross-shore spreading of tracer sand injected at the lower swash, while tracer located at the outer surf zone did remain at this cross-shore position.

Results of the Mullaloo beach experiment are displayed in Figure 5B.16D, E and F. The figures all indicate two peaks in tracer concentration at the outer surf zone, the first between 30 and 60 minutes and the second peak on or after 120 minutes. The first peak corresponds to the peak measured using the SIM (Figure 5B.15D, E and F). The tracer concentration was always low for samples taken at the inner and outer swash. Therefore during this experiment there must have been significant erosion in the swash zone, with a cross-shore movement by bed-return flow of the eroded sand towards the breaker line. This corresponds with the changes of the cross-shore profile as measured by repeated surveys (Figure 5B.13C).
Figure 5B.16: Temporal concentration distribution of tracer. Figures A-C represent lower swash, mid-surf and outer surf zone injections at South Leighton beach (18.01.02) respectively. Figures D-F represent lower swash, mid-surf and outer surf zone injections at Mullaloo Beach (25.01.02). Figures G-I represent lower swash, mid-surf and outer surf zone injections at North Leighton Beach (12.02.02). Crosses indicate sample locations. The contour lines represent tracer concentrations of 50, 100, 200, 400, 800, 1600, 3200, 6400 and 12800 grains per kg, with darker colours indicating higher tracer concentrations.
The results of the North Leighton beach experiment (12.02.02) (Figure 5B.16G, H and I) displayed two to three peaks at several locations. For all three tracer injections, the first peak of tracer sand passed after 30 minutes around the breaker line. The second and highest peak passed the swash zone after 60 minutes. High tracer concentrations were also recorded near the end of the experiment between 90 and 120 minutes after tracer injection, but the actual location of the peak was hard to identify. The first and second peaks, as described above, were also captured during the SIM. The first peak is similar to the high concentration measured around 150 m and the second peak corresponds to the 50 m peak in Figure 5B.15G, H and I.

5B.4.6 Tracer advection velocity and longshore transport rate

The tracer dispersal results (SIM and TIM) were used to obtain tracer advection velocities according to Equation 5A.4 and Equation 5A.5. The advection velocities for the two Leighton beach experiments (upper panels in Figure 5B.17 and Figure 5B.19) are similar to each other and higher than those at Mullaloo beach (upper panels of Figure 5B.18), which is caused by both the absence of tracer movement in the swash zone of Mullaloo beach and the calm hydrodynamic conditions experienced during the Mullaloo experiment.

At Mullaloo beach the values based on the SIM after 120 minutes were similar to the TIM-values. For the other two experiments, the advection velocities based on the SIM after 60 minutes were higher than the TIM-based velocities. This difference might be explained by the results obtained during the Brighton beach experiment, where the longshore velocity of tracer sand slowed down rapidly during the second 60 minutes of the experiment (Section 5B.3). The tracer dispersal suggests that a large part of the tracer became buried during the second hour of the tracer experiment and was effectively removed from the longshore sediment transport system. For the SIM after 120 minutes and TIM, this immobile tracer was included in the analysis, resulting in an underestimate of the advection velocity during the second hour.
Figure 5B.17: Tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach at South Leighton beach (18.01.02). Data obtained using the SIM after 60 minutes (left panels) and the TIM (right panels). The solid, dashed and dotted thin lines represent the results for the tracer released in respectively the lower swash, mid-surf and outer surf zone. The thick solid line with black circles represents the result obtained by combining the three tracers. The shaded areas represent the swash zone (left) and the area offshore of the breaker line (right).

Figure 5B.18: Tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach at Mullaloo beach (25.01.02). Data obtained using the SIM after 120 minutes (left panels) and the TIM (right panels). The shaded areas represent the swash zone (left) and the area offshore of the breaker line (right).
Chapter 5B: Fluorescent tracer

Figure 5B.19: Tracer advection velocity and volumetric longshore sediment transport rate per unit meter beach at North Leighton beach (12.02.02). Data obtained using the SIM after 60 minutes (left panels) and the TIM (right panels). The shaded areas represent the swash zone (left) and the area offshore of the breaker line (right).

Using Equation 5A.1, the advection velocities were combined with the mixing depth to yield an estimate of the longshore transport rate per metre beach width (in m² s⁻¹) (lower panels in Figures 5B.17, 5B.18 and 5B.19). Especially for the TIM, the results are remarkably consistent for the different tracers, despite the distinctly different injection locations. Longshore transport rates are up to 1 x 10⁻³ m³ s⁻¹ per unit meter beach width.

Total immersed-weight longshore transport \( I \), and tracer recovery rates (computed using Equations 5A.3, 5A.7 and 5A.8) are listed in Table 5B.6. The average tracer recovery rates are 41 and 17 % for respectively South and North Leighton beach experiments. The consistency in advection velocities for the different tracer injections is reflected in the similarity in transport rate estimates, and it is appropriate to combine the results and use the bulk estimate of the longshore transport. Conversely, the average recovery percentage during the Mullaloo experiment was low (8 %), resulting in unreliable transport estimates compared to the other three studies. Furthermore, transport estimated using the SIM after 120 minutes at the lower swash and mid-surf zone are similar, while the tracer transport in the outer surf zone is much lower.
Table 5B.6: Total immersed-weight longshore transport rate (I) and tracer recovery percentage.

<table>
<thead>
<tr>
<th>Injection location</th>
<th>Lower swash</th>
<th>Mid-surf</th>
<th>Outer-surf</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>South Leighton (18.01.02)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIM 60 min</td>
<td>189</td>
<td>193</td>
<td>188</td>
<td>173</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>20</td>
<td>37</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>TIM 120 min</td>
<td>152</td>
<td>148</td>
<td>126</td>
<td>144</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>47</td>
<td>66</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td><strong>Mullaloo Beach (25.01.02)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIM 120 min</td>
<td>111</td>
<td>110</td>
<td>56</td>
<td>71</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>8</td>
<td>10</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>TIM 120 min</td>
<td>78</td>
<td>84</td>
<td>78</td>
<td>81</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>8</td>
<td>10</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td><strong>North Leighton (12.02.02)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIM 60 min</td>
<td>239</td>
<td>250</td>
<td>262</td>
<td>249</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>18</td>
<td>26</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>TIM 120 min</td>
<td>132</td>
<td>128</td>
<td>128</td>
<td>129</td>
</tr>
<tr>
<td>Recovery (%)</td>
<td>8</td>
<td>14</td>
<td>15</td>
<td>12</td>
</tr>
</tbody>
</table>

5B.5 LONGSHORE SEDIMENT TRANSPORT

5B.5.1 Transport according to tracer studies

The total volume of longshore sediment transport has been measured on four different beaches using fluorescent sand tracers (Table 5B.3 and Table 5B.6). Based on the previously discussed tracer distributions and advection velocities, the longshore transport rate determined using the SIM with sampling after 60 minutes is regarded the closest estimate of the actual longshore transport rate. Both the longshore transport estimates based on the SIM with sampling after 120 minutes and the TIM are considered unreliable because of tracer burial and tracer leaving the sampling area at the downdrift side during the second hour. For the Mullaloo experiment, transport values based on the SIM after 60 minutes were not available and recovery percentages were very low, therefore this data is not included in the further discussion.

The longshore transport rate was highest for Brighton Beach and the results of both Leighton Beach experiments were very similar (Table 5B.7). Of the three field sites, Brighton Beach experienced the largest incident- and wind-wave heights, the largest wave angles and the strongest longshore current velocities (Table 5B.1 and Table 5B.4). The plunging breakers caused a turbulent environment. This was reflected by the peak in the mixing depth (Figure 5B.8) and longshore transport peak (Figure 5B.12) in the mid-
surf zone. During the studies at North and South Leighton beaches the meteorological and hydrodynamic conditions were calmer, and as a result longshore transport rates were the smaller without a clearly defined transport peak.

### Table 5B.7: Total volume transport rates and the relative contribution of the swash load, according to the Spatial Integration Method after 60 minutes.

<table>
<thead>
<tr>
<th></th>
<th>Total volume transport rate (m³ s⁻¹)</th>
<th>Swash contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton beach</td>
<td>0.043</td>
<td>12</td>
</tr>
<tr>
<td>South Leighton beach</td>
<td>0.018</td>
<td>28</td>
</tr>
<tr>
<td>North Leighton beach</td>
<td>0.026</td>
<td>22</td>
</tr>
</tbody>
</table>

It is possible to make some quantitative statements regarding the relative contribution of the swash load to the total load during longshore sediment transport (Table 5B.7), using the cross-shore distribution of the transport based on the Spatial Integration Method after 60 minutes (Figure 5B.12, Figure 5B.17 and Figure 5B.19). According to these figures, the area under the curve in the left shaded area represented the transport in the swash zone, while the total longshore sediment transport was based on the area under the entire curve. It has to be noted that zero longshore transport was estimated at the swash runup limit, rather than measured. As a result the calculated swash contribution could well be an underestimation of the actual swash contribution. Bodge and Dean (1987) investigated the contribution of the swash zone longshore transport both in the laboratory and in the field and concluded that under plunging breakers the contribution is 26% increasing to 60% under collapsing breakers. Since the studied beaches experienced mainly plunging breakers, the data of this study support the findings of Bodge and Dean (1987).

### 5B.5.2 Transport models

Littoral drift rates obtained from tracer experiments at Brighton, South Leighton and North Leighton beach were compared with the estimations based on longshore transport equations (Table 5B.8). Wave and current measurements were used as input parameters in the equations, as indicated in Table 3.2. Similar to the result of the tracer experiment, using models the transport rates were the highest for Brighton beach and the lowest for the South Leighton beach experiment.
Table 5B.8: Longshore sediment transport rates during three tracer experiments.

<table>
<thead>
<tr>
<th>Tracer study</th>
<th>10.01.01 Brighton</th>
<th>18.01.02 North Leigh</th>
<th>12.02.02 North Leigh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport volume (m³ hour⁻¹)</td>
<td>153.7</td>
<td>65.2</td>
<td>94.0</td>
</tr>
</tbody>
</table>

Transport equation:

**Inman and Bagnold**
- **incident**
  - 72.4
  - 114.5
- **estimated**
  - 9.0
  - 7.2

**CERC**
- **incident**
  - 118.1
  - 101.2
- **wind**
  - 7.4
  - 6.4

**Kamphuis**
- **incident**
  - 24.5
  - 17.3
- **wind**
  - 16.6
  - 4.3

For each experiment, the lowest transport rates are predicted by the 'Kamphuis -wind' model, with rates generally around an order of magnitude smaller than the tracer measurements. During low swell-wave activity combined with strong sea breeze activity (Brighton experiment) the rates of both 'Kamphuis -incident' and 'Kamphuis -wind' are relatively similar, while during an experiment characterised by a more pronounced swell-wave activity the 'incident' transport is considerably higher than the 'wind' transport (North Leighton beach).

Transport according to the 'Inman and Bagnold -incident' model is proportional to the incident wave height and mid-surf longshore current velocity, regardless of the origin of longshore current (e.g., driven by wave, tide, wind and/or cell circulation). The models 'Inman and Bagnold -estimated' and 'CERC' are only valid in the special case of longshore currents exclusively generated by obliquely-incident waves. If the longshore current velocity is the result of not only the obliquely-incident waves but is aided by other processes, then the longshore transport rate would be under-predicted. This could be why the transport according to these models is relatively small for the Leighton beach experiments.

Generally, the hydrodynamic conditions during the Brighton beach experiment were the most energetic and as a result the longshore sediment transport rate according to the model estimates is the highest. On the other hand, South Leighton beach was the least energetic and the estimates transport rates are the lowest.
5B.6 DISCUSSION

Several factors with potential influence on the depth of mixing have been mentioned in Section 5A.2.4, including the significant wave height at wave breaking \( (H_b) \), as:

\[
b = c \cdot H_b
\]  

(5B.1)

where \( c = 0.027 \) for gentle slope non-barred beaches (Kraus et al., 1982; Kraus, 1985) and \( c = 0.27 \) for steeper beaches (\( \tan \beta > 0.08 \)) under plunging wave action (Ciavola et al., 1997a). For Brighton, South Leighton, Mullaloo and North Leighton beaches the values of \( c \), based on the average mixing depth and incident wave height, were 0.084, 0.067, 0.052 and 0.037, respectively. Even though the beach gradients of South Leighton and Mullaloo beach were larger than 0.08, and the breaker types were plunging, the relation suggested by Ciavola et al. (1997a) did over-estimate the measured mixing depths. All values found in this study are in the range between the two suggested \( c \)-values, but no clear empirical relationship between the mixing depth and significant wave height was found.

A possible relationship between beach slope and the cross-shore distribution of the mixing depth is suggested in the literature (refer to Section 5A.2.4). It appears that on gently slope beaches, the mixing depth shows a bimodal distribution, with maxima near the breaker line and the shoreline (King, 1951; Inman et al., 1980; Kraus, 1985). While on steep gradient beaches a unimodal distribution is found, with a maximum in the area where the waves break and a minimum in the swash zone (Ciavola, et al., 1997a; 1997b). The beach slopes of the field sites in this study were all in the intermediate range (\( \tan \beta \approx 0.01-0.1 \)). The most gently sloping Brighton Beach (\( \tan \beta \approx 0.06 \)) did reflect a bimodal distribution. A unimodal distribution with a slight peak near the breaker line was found on Mullaloo Beach, where the beach slope is slightly steeper (\( \tan \beta \approx 0.09 \)). The variation in mixing depth was much less for the other beaches and no clear mode was found during the experiments at South Leighton (\( \tan \beta \approx 0.1 \)) and North Leighton (\( \tan \beta \approx 0.07 \)). Even though the studied beaches had intermediate slopes, the cross-shore distribution of the mixing depth does support the findings of previous researchers.

Another potential explanation for the different mixing depths is the influence of bedforms, assuming a featureless planar bed is characterised by less sediment mixing than, for example, a rippled surface. The most remarkable bed feature during the four
Chapter 5B: Fluorescent tracer

tracer experiments was the hummocky surface in the inner surf zone of Brighton beach, where the loosely packed sediment was arranged in broad, flat ridges and depressions up to 50 cm deep. These bed features decreased in size towards the outer surf zone, while the remainder of the cross-shore zone was planar. According to this, a single peak in the mixing depth was expected at the inner surf zone whereas measurements indicated peaks at the upper swash and mid-surf zone (Figure 5B.8). During the other three tracer experiments, a flat bed surface was found across both the swash and surf zone and mixing depths were smaller than at Brighton beach (Figure 5B.14). Of the four studied beaches the hydrodynamic conditions were the most turbulent at Brighton beach resulting in both sizeable bedforms and large mixing depths. This indicates bedforms and mixing depths are related and both the result of the hydrodynamic conditions, but the size of bedforms is only a qualitative indicator of the mixing depth, as the actual depth needs to be confirmed by measurements.

The present study has indicated that the mixing depth largely depends on cross-shore position and therefore this cross-shore distribution of the mixing depth should be used in the calculation of longshore sediment transport rates. Several previous studies have instead used a single mixing depth, from for example the beach face (e.g., Komar and Inman, 1970; Munoz Perez et al., 1999). By assuming the mixing depth is constant across the swash and surf zone, information on the cross-shore distribution of transport processes is lost. It is also possible that the mixing depth as measured at a single location, for example the lower swash, is not representative of the entire zone of transport and the resulting estimate of longshore sediment transport rate is unreliable. Relationships like Equation 5B.1 should only be used to estimate the mixing depth near the breaker line. Other factors with significant influence on mixing depth are more arduous to describe by a number or equation, these include the influences of the beach slope, bedforms and local erosion or accretion on the cross-shore distribution of the mixing depth. Information on the cross-shore distribution of the mixing depth is needed in order to make reliable predictions of the longshore sediment transport rate, but an equation to accurately describe this distribution is still beyond our knowledge.

Transport components were investigated by injecting different tracer colours at several cross-shore locations. During all studies both the spatial and temporal distribution of tracer sand indicates a net diagonal movement of sediment whereby sediment is moved in alongshore as well as cross-shore direction. For the Brighton and North Leighton
Chapter 5B: Fluorescent tracer

experiments, the tracer injected at any cross-shore location mixed across the nearshore zone and moved in longshore direction as two sub-populations located in the swash and outer surf zone. In other words, co-existing, but opposing sediment pathways existed in the nearshore, from the outer surf zone to the swash zone and vice versa. The tracer at South Leighton and Mullaloo beach was mainly located in the outer surf zone. Little tracer sand was retrieved in eroding zones, for example the swash zone of Mullaloo beach.

The dispersal of the sand tracer in the cross-shore direction is ascribed to disequilibrium beach morphodynamic conditions during sea breeze activity, when there is the tendency for offshore sediment transport to prevail, resulting in nearshore bar formation (Masselink and Pattiaratchi, 2001b). Kraus et al. (1982) also conducted tracer experiments with different tracer colours injected at different nearshore locations, but reported insignificant cross-shore movement of the tracer.

Since the tracer is rapidly mixed across the nearshore zone it was valid to derive the cross-shore distribution of the longshore advection velocity by applying the equations of White and Inman (1989a) (Equations 5A.4 and 5A.5). Unfortunately this method has not been applied widely in literature and there is no frame of reference available. The cross-shore distribution of the advection velocity can be calculated from the data of any regular tracer experiment and it might be possible to re-evaluate data from existing tracer studies in order to further investigate this pattern.

At Brighton beach, a large alongshore movement of tracer was recorded at the first sampling (after 1 hour) and then very little movement took place in the second sampling (after 2 hours), in other words, the longshore transport rate appears to have decreased during the experiment. The tracer dispersal pattern strongly suggests that a large part of the tracer became buried during the second hour of the tracer experiment and was effectively removed from the longshore sediment transport system. For the SIM after 2 hours, this immobile tracer was included in the analysis, resulting in an underestimate of the sediment transport rates during the second hour. Unfortunately, sediment cores collected for the SIM were not sliced and therefore a three-dimensional analysis of the tracer concentrations, necessary to convincingly demonstrate tracer burial, could not be carried out. Beach surveys were conducted during the tracer experiment, but they did not extend seaward of the swash zone and could neither be used to demonstrate tracer burial.
The TIM cores were sliced, however, but these only suggest tracer burial at the mid surf zone. Significant erosion occurred in the lower swash zone during the tracer experiment and it is not inconceivable that offshore sediment transport in the surf zone, presumably by the bed return flow, would have resulted in sediment deposition around the wave breakpoint. In any case, the longshore transport rate determined using the SIM with sampling after 2 hours is considered unreliable.

The TIM results exhibit a series of concentration peaks, which indicate that sand moved across the 50 m line in discrete pulses. Since the longshore current did not reverse direction during the experiment, as shown by the longshore current records, the existence of pulses in tracer concentration indicates unsteady sand transport took place. These pulses are probably related to the patchy distribution of tracer on the beach, short-term burial and re-excavation of some tracer sand, minor beach topography that might affect the small-scale water circulation patterns, or may arise from low frequency oscillations in the forcing functions of waves and currents.

Comparing transport rates according to the tracer studies with the model estimates (Table 5B.8) it appears that for both methods the highest transport rates were found at Brighton beach while South Leighton beach is characterised by the lowest transport rates. For both Leighton beach experiments, the transport rates based on the tracer studies are rather similar, while the estimates according to transport equations are much lower for South Leighton than for North Leighton beach. This is the result of the slightly less energetic conditions experienced at South Leighton beach (refer to Table 5B.4).

Determining sediment transport using tracer remains difficult and despite yielding some interesting results, this study also exhibits some serious shortcomings. The main difficulty concerns the burial of tracer and the inability to detect this and account for it. Only after repeated sampling and, for example, comparing the results of the SIM after 60 and 120 minutes is it possible to get an indication of potential tracer burial. A three-dimensional analysis of tracer concentrations would have been helpful in this respect, as would other means of determining bed level change (e.g., beach surveys). Another major shortcoming is related to the sampling scheme, which in retrospect should have been denser and larger, requiring a much increased field crew. Collectively, a three-dimensional analysis of the sediment cores and a larger sampling grid would have increased efforts in determining tracer concentrations by at least one order of magnitude.
Selection of the field site and hydrodynamic conditions also warrants further consideration. On the one hand, the energetic conditions during especially the Brighton beach experiment were ideal and generated strong longshore currents and large longshore transport rates. On the other hand, the conditions were rather too energetic and changed rapidly during the course of the experiment. This resulted in beach disequilibrium (erosion/accretion), non-stationary hydrodynamic conditions and considerable difficulties in taking samples and collecting complimentary data.

The results of previous tracer studies are difficult to compare as a result of differences in the definition of mixing depth, uncertainties in measurement of both mixing depth and advection velocity, and the lack of reliable previous studies that have applied the method of White and Inman (1989a). Despite these difficulties, tracer experiment have had a determining role in relating the longshore directed wave energy flux to the longshore transport rates, in the widely-used CERC (1984)-equation (Equation 2.5) (Bruno et al., 1980; Galvin, 1987). Using 14 data points based on tracer studies, Komar and Inman (1970) suggested a proportionality coefficient of $K = 0.77$. This became the recommended value in the Shore Protection Manual (CERC, 1984) and is still in use (CERC, 2002).

5B.7 SUMMARY

- Both mixing depth and advection velocity are dependent on cross-shore position, and site-specific values should be used during longshore transport equations. An equation to accurately relate these cross-shore distributions to environmental parameters is still beyond our knowledge.
- It is important to define a widely used procedure that objectively determines the mixing depth, since varying definitions of mixing depth result in large differences in resulting transport rates. Consistent results were found when using a cut-off at a minimum concentration of 0.5 grains per gram instead of the 80% cut-off percentage implemented by Kraus et al. (1982).
- The spatial distribution of the different tracers suggests that the nearshore sediments were transported diagonally across the surf zone. The cross-shore exchange of sand tracer injected at different locations indicates that co-existing, but opposing sediment pathways exist in the nearshore, from the outer surf zone to the swash zone and vice versa.
The temporal tracer distribution (TIM) exhibits a series of concentration peaks, which indicates that sediment moves in discrete pulses. These pulses are probably related to the patchy distribution of tracer on the beach, short-term burial and re-excavation of some dyed sand, minor beach topography that might affect the small-scale water circulation patterns, or may arise from low frequency oscillations in the forcing functions of waves and currents.

Taking into account the shortcomings of tracer techniques and potential errors in the data, it is possible to quantify the relative contribution of the swash load to the total load during longshore transport as 12 to 28 %.

Generally, the sediment transport as predicted by transport models is different from the results of the fluorescent tracer studies. For each experiment, the ‘Kamphuis – wind’ model predicts the lowest transport rates, with rates generally around an order of magnitude smaller than the tracer measurements.
6.1 INTRODUCTION

This chapter describes results obtained from a field study of longshore sediment transport on the smallest temporal and spatial scale. The field experiment involved simultaneous measurements of suspended sediment transport using streamer traps and a combination of instantaneous suspended sediment sensors and current velocity sensors (Figure 1.1). These techniques resulted in point measurements of the suspended sediment flux, therefore vertical integration from the bed to the still water level was needed to calculate the local suspended load transport. Simultaneous measurements at several cross-shore locations were used to calculate total suspended longshore transport to be compared with model predictions.

6.2 METHODOLOGY

6.2.1 Study area

A field study was conducted from 5 to 12 January 2001 on Brighton Beach located along the Perth metropolitan coastline in Western Australia (Figure 3.1). The experiment discussed in this chapter was conducted during the strong sea breeze of 10th January with streamer trap measurements conducted from 13:30 to 17:30 hrs (shaded area in Figure 5B.4). Simultaneously, a tracer sand experiment was carried out, which has been discussed in Chapter 5B. An overview of the wind climate and wave breaking conditions experienced during the field experiment is given in Section 5.5.1 and the nearshore morphology is described in Section 5.5.2.

6.2.2 Collection and analysis of hydrodynamic data

A self-logging wave/current sensor was deployed outside the surf zone in the wave shoaling area throughout the field period, at a water depth of 3–3.5 m, to provide pre-breaking wave conditions (location 5 in Figure 6.1). The water surface elevation was measured with a pressure sensor and three-dimensional current velocities were recorded.
using an acoustic current meter. Data were sampled at 2 Hz and the sensor was programmed to collect 20 minutes of data every hour.

Figure 6.1: Cross-shore profile of Brighton Beach on 10th January 2001. The cross-shore distance is measured relative to the position of the runup limit from 13:00 until 15:00 hrs. The numbers indicate instrument locations, the horizontal dashed line represents mean sea level.

Hydrodynamic data collected using this ‘offshore’ sensor were complemented using a number of additional instrument frames equipped with pressure sensors, electro-magnetic current meters (EMCM), acoustic current meters and optical backscatter (OBS) sensors. These instruments were hard-wired to the beach and data were logged continuously at 2 Hz frequency on personal computers.

On 10th January the following three instrument frames were deployed:
- Lower swash station with pressure sensor, bi-directional electromagnetic current meter and OBS sensor (location 1 in Figure 6.1);
- Mid-surf zone station with pressure sensor, bi-directional electromagnetic current meter and three OBS sensors (location 3 in Figure 6.1); and
- Outer surf zone station with pressure sensor, three-dimensional acoustic current meter and three OBS sensors (location 4 in Figure 6.1).

Flow velocities were measured at a nominal distance of 0.1, 0.2 and 0.4 m above the bed, in the lower swash, mid-surf zone and outer surf zone respectively. OBS sensors were deployed to measure sediment concentrations at 0.1, 0.2 and 0.4 m from the bed at both the mid-surf and outer surf zone stations, and 0.1 m above the bed in the swash zone. Every effort was made during the experiment to maintain the instrument elevations at the original levels, which required frequent adjustments during data collection. Such
adjustments were not made in the dark and accordingly, data collected after 20:00 hrs should be treated with caution.

The pressure sensors were calibrated in a tank where varying water depth and voltage output were recorded. The nearly linear response curves were used to obtain water depths from the field data, including corrections for water temperature and salinity. The current meters were calibrated using the factory specifications. Both field and laboratory data were used to convert the OBS output voltages to suspended sediment concentrations. The offset was determined in the field as the typical minimum output during quiet conditions. The gain of the OBS sensors was determined in the laboratory using native sediment in concentrations up to 20 g l⁻¹. The correlation coefficients between the concentrations in the tank and the output voltage of the OBS were generally high ($r^2 \approx 0.94$).

The wave directional spectrum was computed from data collected by the ‘offshore’ station using the extended maximum entropy method (Hashimoto, 1997). Linear wave theory was used to account for the frequency-dependent depth attenuation of the wave signal, with an upper ‘cut-off’ at 0.35 Hz as suggested by Ruessink (1995). During this project, the wave frequencies were identified as swell ($f = 0.05$–0.15 Hz), wind ($f = 0.15$–0.35 Hz) and incident ($f = 0.05$–0.35 Hz) wave frequencies. For the incident, swell and wind waves, the significant wave height $H_{s\text{igs}}$, peak and significant wave period $T_p$ and $T_{s\text{igs}}$, and an energy-weighted mean wave angle $\alpha$ were derived. Using linear wave theory, the saturated breaking zone for irregular waves was estimated at a water depth of 1.5 times the significant incident-wave height measured at the location of the offshore instrument frame (e.g., Sallenger and Holman, 1985; Thornton and Guza, 1989). The waves were refracted to this depth and the conditions at this location were considered breaking wave conditions.

Suspended sediment fluxes were investigated by determining the mean, net and oscillatory components following Jaffe et al. (1984):

$$
\langle uc \rangle = \bar{u}c + \langle u'c' \rangle \quad \text{and} \quad \langle vc \rangle = \bar{v}c + \langle v'c' \rangle
$$

(6.1)

where $c$ = sediment concentration; $u$ = cross-shore current velocity; and $v$ = longshore current velocity. The terms $\langle uc \rangle$ and $\langle vc \rangle$ represent the net suspended sediment flux and
are obtained by averaging the product of the current velocity and the sediment concentration time series. The terms $\bar{u}c$ and $\bar{v}c$ are referred to as the mean sediment transport rate and are computed as the time-averaged velocity multiplied by the time-averaged sediment concentration. The terms $\langle u'c' \rangle$ and $\langle v'c' \rangle$ represent the oscillating sediment transport rate and may be obtained either through subtracting the mean from the net transport rate, or by integration across all frequencies of the co-spectrum between current velocity and sediment concentration. The co-spectrum was also used to investigate the contributions of the different wave frequencies to the oscillatory suspended sediment flux (Huntley and Hanes, 1987; Aagaard and Greenwood, 1994b, 1995b).

6.2.3 Collection and analysis of streamer trap data

The suspended longshore sediment transport was measured using three vertical arrays of streamer sediment traps attached to portable racks (Figure 6.2). The streamer traps were based on the design of Kraus (1987) and each consisted of a nozzle mouth, projecting 0.025 m up-current, with an opening 0.1 m wide and 0.025 m high, and a 1.5-m long sand collection component made of 100-µm polyester mono-filament sieve cloth (Brander, 1999). The number of streamer bags attached to the rack was determined by the water depth and breaker height. The configuration of the streamer traps on the racks was consistent throughout the sediment sampling runs with traps deployed at 0.04, 0.1, 0.16, 0.22, and 0.34 m above the bottom of the rack assembly. One trap had additional streamer traps at 0.52 and 0.76 m.

The racks with streamer traps were initially deployed next to the three measurement frames, namely lower swash zone, mid-surf zone and outer surf zone (locations 1, 3 and 4 in Figure 6.1). After a few hours, however, conditions at the outer surf zone position became too energetic and this rack was subsequently deployed in the inner surf zone, between the mid-surf zone and the lower swash zone position (location 2 in Figure 6.1). The racks were deployed for a period of 2 minutes with the bottom of the rack assembly touching the bed (Figure 6.3). The racks were located approximately 5 m downstream of the instrument rigs to avoid flow disturbance, potential scouring and bed disturbance induced by the frame bases. Sediment samples were collected from the streamer traps in the field and were washed, oven-dried and weighed in the laboratory. Streamer trap data were collected at 30 minute intervals from 12:30 to 17:30 hrs.
Several previous studies have focussed on the hydraulic and sand-trapping efficiencies of streamer racks (e.g., Rosati and Kraus, 1988, 1989; CERC, 1987). It was noted that the efficiency depends on location in the water column and nozzle type, with low efficiency at bed level but near unity efficiency above the bed. Since during this field study all
steamer traps were mounted a distance above the bed (0.04 m and upwards), the efficiency was assumed to be 100%.

The vertical suspended flux profiles obtained from the streamer trap deployments were characterised by an exponential shape, which can be explained by the existing understanding of profiles of sediment concentration and longshore current velocity. Several studies have shown that sediment concentration decreases exponentially away from the bed (Nielsen, 1984, 1992). The velocity profile has been found to be fairly constant throughout the water column except in the thin bottom-boundary layer (van Rijn, 1984b). The product of an exponential concentration profile and a uniform velocity profile results in the exponential flux profile. Kraus and Dean (1987) proposed the following equation to describe the sediment-flux profile in the water column:

\[ q(x, z) = q_0(x) \exp[-\alpha(z/h)] \] (6.2)

where \( q(x, z) \) = suspended flux (kg m\(^{-2}\) s\(^{-1}\)); \( x \) = offshore distance (m); \( z \) = elevation above the bed (m); \( q_0(x) \) = sediment flux at bed level (kg m\(^{-2}\) s\(^{-1}\)); \( \alpha \) = dimensionless empirical decay coefficient; and \( h \) = water depth at the streamer trap location (m).

The distribution of the suspended sediment flux over the water column is determined largely by the value of the decay coefficient \( \alpha \). The smaller \( \alpha \), the more uniform the distribution of the suspended flux over the water column and the better the sediment mixing. A larger \( \alpha \) corresponds to a greater rate of upward decrease in suspended flux, given the same dimensionless depth \( z/h \). For each streamer rack deployment, \( q_0(x) \) and \( \alpha \) were determined using least-squares analysis. For reasons of consistency, only the lowest five streamers were considered in this analysis, even if more streamers were deployed.

The vertically-integrated suspended flux \( q_{\text{tot}}(x) \) (in kg m\(^{-1}\) s\(^{-1}\)) at each of the streamer trap deployments was obtained by integrating Equation 6.2 over the local water depth from \( z = 0 \) to \( z = h \):

\[ q_{\text{tot}}(x) = \frac{q_0(x)h}{\alpha} \left[ \exp\left(-\alpha \frac{0}{h}\right) - \exp\left(-\alpha \frac{h}{h}\right) \right] = \frac{q_0(x)h}{\alpha} [1 - \exp(-\alpha)] \] (6.3)
Finally, $q_{i0}(x)$ was integrated over the width of the nearshore zone (swash and surf zone) to obtain the total longshore suspended sediment transport, $Q$ (in kg s$^{-1}$).

The cross-shore distribution of the longshore suspended sediment transport was determined from the simultaneous deployment of several streamer racks at different cross-shore locations. Since the streamer racks were deployed under changing conditions at shifting cross-shore locations, the results were not directly comparable. For example, deployments in the outer surf zone were conducted during the first part of the sea breeze under relatively calm conditions, whereas the inner surf zone deployments were carried out during the second part of the sea breeze under considerably more energetic conditions. Therefore, the vertically integrated flux $q_{i0}(x)$ at each cross-shore position was divided by the vertically integrated flux measured at mid-surf zone position in order to calculate a normalised flux. The longshore transport flux was forced to zero at the swash runup limit (based on field observations) and at some distance seaward of the breaker line. The latter was informed by the sand tracer data, discussed in Chapter 5. The average normalised flux at each location was used to describe the cross-shore distribution of the longshore sediment transport rate. The normalised total longshore transport rate was determined by integration over the width of the nearshore zone.

6.2.4 Combining suspended sediment sensor and streamer trap data

One of the shortcomings of streamer trap deployments is that they represent discontinuous data over rather short periods of time (Pilkey and Cooper, 2002). The nearshore hydro- and sediment dynamics (e.g., water level, flow velocities and sediment concentrations) vary greatly over a range of time scales and therefore one can question how well a streamer trap deployment for a duration of 2 minutes represents sediment transport during larger time scales (e.g., a sea breeze event). On the other hand, data obtained from surf zone instruments such as suspended sediment sensors and current meters are continuous and do capture the natural variability in the hydro- and sediment dynamics. However, a drawback from using surf zone instruments is that resulting data represent point measurements and may not be representative for the whole water column or the nearshore zone, unless vast numbers of instruments are available (Miller, 1999). A combination of data obtained from both streamer traps and surf zone instruments can be used to circumvent the shortcomings inherent to each measurement technique.
Therefore, in this study the discontinuous and spatially-integrated streamer trap data were combined with the continuous and local data collected with the surf zone instruments. Firstly, the vertically-integrated suspended flux $q_{tot}(x)$ derived from 2 minute streamer trap deployments was correlated with the local suspended flux $q(x,z)$ obtained from the product of longshore current velocity and suspended sediment concentration measured at the same time and location. These were based on average values of 2-minute sections of data derived from an OBS and current meter pair from the deployments at the mid-surf zone position, since a streamer trap was deployed at this location during most measurement runs and consistently good quality results were obtained.

Secondly, using the correlation equation that resulted from the least-squares analysis of the two types of suspended flux estimates, a time series of the vertically-integrated suspended flux $q_{tot}(x)$ at the mid-surf zone position was obtained. In other words, the continuous OBS and longshore current data was used to extrapolate the 2-minute streamer trap data. This approach assumes that the total suspended flux is proportional to the flux measured at a single point using an OBS and current meter pair.

The time series of the total suspended sediment transport across the nearshore zone, $Q$, was determined as the product of the $q_{tot}(x)$ at mid-surf position and the normalised cross-shore distribution of the longshore suspended sediment transport. Finally, the time series of $Q$ was smoothed using a 10-min moving average to filter out temporal variations that may not be representative of the surf zone as a whole (e.g., infragravity waves, wave groups, shear waves).

### 6.3 RESULTS

#### 6.3.1 Wind climate and wave breaking conditions

During the field experiment of 10 January 2001, the time series of wind speed and direction were typical of a southwestern Australian sea breeze cycle (Figure 6.4A). The sea breeze started blowing at 11:30 hours and the change in wind speed and direction was almost instantaneous. Wind speeds associated with the land breeze were around 4.5 m s$^{-1}$, whereas the wind speeds during the sea breeze at mid-afternoon reached a maximum of about 7 m s$^{-1}$. The wind speed recorded at the mainland coast at Swanbourne was significantly less than some distance offshore at Rottnest Island, where speeds of up to 10 m s$^{-1}$ were recorded. The direction of the sea breeze was consistently
south-southwesterly (212°), and thus was blowing slightly onshore. The wind speed started to decrease at 18:00 hrs concurrent with a change in wind direction to east-southeasterly after 20:30 hrs. The cessation of the sea breeze was more gradual than its start.

![Figure 6A](image)

**Figure 6A**: (A) Wind speed at Swanbourne (solid line) and Rottnest Island (dashed line); (B) significant breaking wave height and (C) breaking wave angle on 10th January. The breaking wave conditions were derived by refraction of wave data collected at location 5 in Figure 6.1. Solid, dashed and dotted lines in (B) and (C) represent the incident, swell and wind-wave band, respectively. The shading indicates the time of the streamer trap experiment.

The changes in the wind climate induced instantaneous changes in the incident wave field (Figure 6.4B). Prior to the sea breeze, the total significant wave height was around 0.8 metres (solid line). From the start of the sea breeze, wave height increased progressively, resulting in a height of 1.2 m towards the end of the sea breeze. The significant height of the wind waves increased from 0.4 to 1 m (dotted line), while the swell waves were unaffected by the sea breeze cycle, but increased slightly from 0.5 to 0.7 m (dashed line).

Throughout the day, the swell waves were parallel-incident with their wave angles deviating from 0° by only a few degrees (Figure 6.4C). In contrast, the wind waves were obliquely-incident, with wave angles of 25° at the start of the sea breeze. As the sea breeze continued to blow throughout the afternoon, the period and energy of the wind waves progressively increased (Figure 5B.4E), such that the wave refraction increased and the wind-wave angle decreased to 15° at the end of the sea breeze. The wave angle associated with the combined wave field (swell and wind waves) during the sea breeze was 12–15°.
6.3.2 Nearshore hydrodynamic data

The hydrodynamic conditions measured in the nearshore zone are shown in Figure 6.5. The temporal variation was the combined result of increasingly energetic conditions due to the sea breeze and a rising tide level. This complicated the interpretation of the temporal variation recorded by the instantaneous nearshore instruments. For example, from 12:00 to 16:00 hrs, the most landward instrument station was located in the lower swash zone, whereas later in the day, this station was located in the inner surf zone. Therefore, the increase in wave height (Figure 6.5B) and longshore current velocity (Figure 6.5C) at this location was noted as being as much due to a rise in water level (Figure 6.5A), as the result of the sea breeze.

![Figure 6.5: (A) Local water depth; (B) significant wave height; (C) longshore current velocity and (D) suspended sediment concentration at z = 0.4 m on 10th January. Solid, dashed and dotted lines represent the outer surf, mid-surf and lower swash zone, respectively. The grey shading indicates the time of the streamer trap experiment.](image)

In the onshore direction, there was a clear decrease in the incident wave height (Figure 6.5B). This was investigated further by comparing the spectra of the water surface elevation for the outer surf zone, the mid-surf zone and the lower swash zone (Figure 6.6). At all locations the dominant peak was situated around a period of 12 seconds (0.08 Hz) which represented the swell wave energy. The wind wave energy was located around 4–5 seconds (0.20–0.25 Hz) for the data collected at the outer surf zone, but the wind-wave energy disappeared as the waves propagated across the surf
zone. This indicates that the wind-wave energy in the surf zone is rather limited, perhaps suggesting that the energy of the wind waves is transferred to lower frequencies through bore interactions. The general decrease in the wave height in the onshore direction is due to wave dissipation by breaking.

![Wave spectra](image)

**Figure 6.6:** Wave spectra calculated from 12:30–17:30 hrs on 10th January for different locations in the surf zone. Solid, dashed and dotted lines represent respectively the outer surf, mid-surf, lower swash zone.

By contrast, the longshore current velocity increased with decreasing water depth towards the shoreline, especially in the evening (Figure 6.5C). Maximum longshore current velocities in the outer surf, mid-surf zone and lower swash zone were respectively 0.7, 1.0 and 1.3 m s\(^{-1}\). The longshore current velocities decreased as the sea breeze died down and reached insignificant levels around 21:00 hrs.

### 6.3.3 Instantaneous suspended sediment data

The temporal variation in suspended sediment concentration is difficult to interpret (Figure 6.5D). At the outer surf zone position, the sediment concentration peaked at 4 kg m\(^{-3}\) at the start of the sea breeze and progressively decreased throughout the day, despite increasing wave energy levels. This reduction in suspension levels can be the result of a tide-induced displacement of the instrument frame relative to the breaker line, from just inside the outer surf zone to just seaward of the outer surf zone. The progressive increase in the sediment concentration in the mid-surf zone throughout the day from 3 to 8 kg m\(^{-3}\) was the result of more energetic surf zone conditions due to the sea breeze. The increase after 20:00 hrs, however, was more likely the result of a decrease in the elevation of the sensors above the bed due to accretion, and is considered
suspect. Suspended sediment data collected in the lower swash zone was not included, since light saturation of the OBS sensors made the data unreliable.

Net cross-shore and longshore suspended sediment fluxes were computed using data collected in the mid-surf zone position at 0.1 m above the bed (Figure 6.7). Analysis was carried out using data segments of 20 minutes and the net fluxes were partitioned into mean and oscillatory components according to Equation 6.1. Maximum sediment fluxes occurred around 18:00 hrs and coincided with the most energetic hydrodynamic conditions (Figure 6.4 and Figure 6.5). At this time, the net cross-shore and longshore fluxes were 3 and 12 kg m\(^{-2}\) s\(^{-1}\), respectively. These values are on average a factor 10 higher than reported in literature (e.g., Aagaard, 2002; Aagaard and Greenwood, 1995b; Beach and Sternberg, 1992; Ciavola, 1999b; Davidson et al., 1993; Russell, 1993)

![Figure 6.7: (A) Cross-shore and (B) longshore suspended sediment flux measured in the mid-surf zone at 0.1 m from the bed on 10\(^{th}\) January. The net flux (solid line) is the sum of the mean flux (dashed line) and the oscillatory flux (bold line). The grey shading indicates the time of the streamer trap experiment.](image)

The net cross-shore flux was directed offshore and was dominated by the mean component associated with the bed return flow (Figure 6.7A). The oscillatory flux, which is related to the wave asymmetry, was directed onshore, but of secondary importance. These opposing mean and oscillatory transport directions can result in an approximate balance in the local net sediment transport (e.g., Aagaard et al., 2002; Greenwood et al., 1991; Kroon, 1991; Osborne et al., 1990; Osborne and Greenwood, 1992; Ruessink et al., 1998). The net longshore flux was dominated by the mean flux component, which resulted from the mean longshore current directed towards the north (Figure 6.7B). The oscillatory component, which was also northward, was rather insignificant when compared with the mean longshore flux component, but was comparable to the cross-shore oscillatory flux component. This importance of the mean longshore current as a
transport mechanism has also been indicated by, for example, Aagaard, 2002; Beach and Sternberg, 1992; and Davidson et al., 1993.

The oscillatory component of the suspended flux during the streamer trap experiment, was investigated further using the average normalised co-spectra for the cross-shore and longshore suspended sediment flux (Figure 6.8). The data were collected in the mid-surf zone, at 0.2 m above the bed for the current velocity and 0.1 m for the suspended sediment concentration. The cross-shore co-spectrum was dominated by onshore suspended sediment transport at the swell-wave frequency with some transport occurring at the infragravity frequencies (Figure 6.8A). Despite the presence of energetic wind waves in the outer surf zone (Figure 6.6), the wind waves did not appear to contribute much to the oscillatory suspended flux in the mid-surf zone, as only weak onshore sediment transport was recorded at the wind-wave frequencies. The longshore co-spectrum has similar peaks at the swell- and infragravity-wave frequencies, both indicating northward transport, but insignificant transport at wind-wave frequencies similar to the cross-shore co-spectrum (Figure 6.8B). Similar co-spectra have been reported in previous studies (e.g., Aagaard and Greenwood, 1995a; Miles et al., 2002). The source for the infragravity peak is not obvious, but may be related to wave groups (e.g., Masselink and Pattiaratchi, 2000) or shear waves associated with the longshore current (e.g., Miles et al., 2002).

Figure 6.8: Average normalised co-spectra for (A) cross-shore and (B) longshore suspended sediment transport. Co-spectra were computed over data segments of 20 minutes and normalised such that the sum of the co-spectral estimates is 1. The average co-spectrum was computed using data collected at 12:30–17:30 hrs. The dotted lines represent the average co-spectrum +/- one standard deviation.
Chapter 6: Streamer trap & OBS

transport mechanism has also been indicated by, for example, Aagaard, 2002; Beach and Sternberg, 1992; and Davidson et al., 1993.

The oscillatory component of the suspended flux during the streamer trap experiment, was investigated further using the average normalised co-spectra for the cross-shore and longshore suspended sediment flux (Figure 6.8). The data were collected in the mid-surf zone, at 0.2 m above the bed for the current velocity and 0.1 m for the suspended sediment concentration. The cross-shore co-spectrum was dominated by onshore suspended sediment transport at the swell-wave frequency with some transport occurring at the infragravity frequencies (Figure 6.8A). Despite the presence of energetic wind waves in the outer surf zone (Figure 6.6), the wind waves did not appear to contribute much to the oscillatory suspended flux in the mid-surf zone, as only weak onshore sediment transport was recorded at the wind-wave frequencies. The longshore co-spectrum has similar peaks at the swell- and infragravity-wave frequencies, both indicating northward transport, but insignificant transport at wind-wave frequencies similar to the cross-shore co-spectrum (Figure 6.8B). Similar co-spectra have been reported in previous studies (e.g., Aagaard and Greenwood, 1995a; Miles et al., 2002). The source for the infragravity peak is not obvious, but may be related to wave groups (e.g., Masselink and Pattiaratchi, 2000) or shear waves associated with the longshore current (e.g., Miles et al., 2002).

![Figure 6.8](image_url)

**Figure 6.8**: Average normalised co-spectra for (A) cross-shore and (B) longshore suspended sediment transport. Co-spectra were computed over data segments of 20 minutes and normalised such that the sum of the co-spectral estimates is 1. The average co-spectrum was computed using data collected at 12:30–17:30 hrs. The dotted lines represent the average co-spectrum +/- one standard deviation.
6.3.4 Streamer trap data

A total of 24 successful streamer trap deployments were conducted throughout the sea breeze of 10\textsuperscript{th} January 2001 (Figure 6.9). For each of the trap deployments, Equation 6.2 was fitted to the data using least-squares analysis (Table 6.1). The values of the associated squared correlation coefficient, \( r^2 \), were generally larger than 0.9 indicating that the vertical suspended flux profile was well described by an exponential function. The vertically-integrated sediment flux \( q(x) \) averaged over the sea breeze was approximately 1.5 kg m\(^{-1}\) s\(^{-1}\), but increased from less than 1 kg m\(^{-1}\) s\(^{-1}\) at the start of the sea breeze, to more than 3 kg m\(^{-1}\) s\(^{-1}\) at the end of the sea breeze (Figure 6.9).

The number of trap deployments reported here is rather modest, but the data are considered reasonably representative of the conditions experienced. The data show a wide range of \( \alpha \) values and also suggest that \( \alpha \) increases in the onshore direction, from 1 in the outer surf zone to 5 in the swash zone. This indicates that the sediment flux profile in the outer surf zone position was much better mixed than in the swash zone, with the flux profiles in the mid- and inner surf zone taking up an intermediate position. This latter result is particularly apparent in Figure 6.10, which shows the average normalised suspended flux profile at each of the nearshore locations. These profiles were normalised by dividing the sediment fluxes for each of the streamer traps in a rack by the sediment flux of the streamer trap nearest to the bottom (at \( z = 0.04 \) m).

![Figure 6.9: Temporal variation in the total suspended sediment fluxes for the different streamer trap locations.](image-url)
Table 6.1: Summary statistics for the streamer trap deployments. The values for \( h \) and \( v \) were obtained from hydrodynamic data collected at the same time and location as the streamer trap deployments. The individual values for \( q_0(x) \), \( \alpha \), \( \alpha^2 \) and \( q(x) \) were found by fitting Equation 6.2 to the data using least-squares analysis.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean ( h ) (m)</th>
<th>Mean ( v ) (m s(^{-1}))</th>
<th>Mean ( q_0(x) ) (kg m(^{-2}) s(^{-1}))</th>
<th>Mean ( \alpha ) (-)</th>
<th>Mean ( \alpha^2 ) (-)</th>
<th>Mean ( q(x) ) (kg m(^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer surf zone</td>
<td>4</td>
<td>1.25</td>
<td>0.57</td>
<td>1.67</td>
<td>0.95</td>
<td>0.54</td>
<td>0.69</td>
</tr>
<tr>
<td>Mid-surf zone</td>
<td>8</td>
<td>1.04</td>
<td>0.74</td>
<td>5.02</td>
<td>2.31</td>
<td>1.12</td>
<td>0.89</td>
</tr>
<tr>
<td>Inner surf zone</td>
<td>5</td>
<td>0.79</td>
<td>n.a.</td>
<td>3.64</td>
<td>1.65</td>
<td>0.63</td>
<td>0.92</td>
</tr>
<tr>
<td>Swash zone</td>
<td>7</td>
<td>0.36</td>
<td>0.35</td>
<td>13.43</td>
<td>4.70</td>
<td>1.36</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Figure 6.10: Average normalised suspended flux profile in: (A) outer surf zone; (B) mid-surf zone; (C) inner surf zone; and (D) swash zone. Solid lines indicate the least-squares fit of Equation 6.2 to the data and the shaded areas represent the data envelopes.

The spatial variation in the total suspended sediment fluxes is hard to describe as a result of the discontinuous measurements at especially the outer and inner surf zone (Figure 6.9). Similarly, the summary statistics for the different streamer trap locations listed in Table 6.1 are not directly comparable because the data on which they are based are not necessarily coincident. Therefore, the average cross-shore profile of the normalised suspended flux was calculated (Figure 6.11) (refer for methodology to Section 6.2.3). The cross-shore flux profile was forced to zero at the runup limit (based on field observations) and 2.5 m seaward of the breaker line (informed by sand tracer...
data, Chapter 5). The cross-shore distribution in the longshore suspended flux showed a maximum at the mid- to outer part of the surf zone, with considerably less, but still significant amounts of sediment being transported in the inner surf zone and the swash zone. According to Figure 6.11 the contribution of the swash zone to the total longshore flux is about 28%, calculated from the area underneath the curve. However, given that the boundaries in the swash zone were based on observations rather than actual measurements, this number only serves as a best estimate.

![Figure 6.11: Average cross-shore distribution of the normalised, vertically-integrated suspended sediment flux.](image)

Figure 6.11: Average cross-shore distribution of the normalised, vertically-integrated suspended sediment flux. The shaded area represents the surf zone. The total normalised flux (integration under the curve) is 20.5 m.

6.3.5 Time series of the total suspended sediment flux

The discontinuous and spatially-integrated streamer trap data were combined with the continuous and local data collected with the surf zone instruments to obtain a time series of the total suspended sediment transport, \( Q \), covering the nearshore zone (refer for methodology to Section 6.2.4). The vertically-integrated suspended flux \( q(x) \) measured at the mid-surf zone position using streamer traps was correlated with the local suspended flux \( q(x,z) \) obtained from the product of longshore current velocity and suspended sediment concentration measured at the same time and location (Figure 6.12). The correlation between these two suspended flux measures, which is dimensionally incorrect, is quite good, especially when sediment concentrations measured at 0.1 and 0.4 m from the bed are used.
A time series of the vertically-integrated suspended flux at the mid-surf zone position $q(x)$ was obtained from the longshore suspended flux data $q(x,z)$ measured at $z = 0.1$ m using $q(x) = 0.29 q(x,z)$, where 0.29 is the result of least-squares analysis (Figure 6.12A). The total suspended sediment flux, $Q$, was determined using $Q = 20.5 q(x)$, where 20.5 is the integration of the cross-shore distribution of the normalised $q(x)$ across the nearshore zone (area under the curve in Figure 6.11). Finally, the time series of $Q$ was smoothed using a 10 minute moving average to filter out temporal variations that may not be representative of the surf zone as a whole (e.g., infragravity waves, wave groups, shear waves). Figure 6.13 shows the time series of the total longshore suspended flux, $Q$, estimated by combining the streamer trap and the OBS data. Included for comparison are the mid-surf zone streamer trap deployments extrapolated to the whole nearshore zone using the cross-shore distribution in suspended sediment flux.
According to the wind record, the sea breeze started around 11:30 hrs and died down after 20:30 hrs. The total volume of longshore suspended transport during this 9-hour sea breeze period was 1006 m$^3$, which represents an average flux of 49 kg s$^{-1}$. The results show a threefold increase in the total suspended longshore transport rates, from 25 kg s$^{-1}$ during the first hour of the sea breeze (11:30-12:30 hrs) to 70 kg s$^{-1}$ during the peak of the sea breeze (17:00-18:00 hrs). The pronounced increase in longshore transport after 15:00 hrs is mainly ascribed to an intensification of the overall surf zone conditions, reflected by wave height, current velocity and suspended sediment concentrations, due to the ongoing sea breeze (Figure 6.5). Part of the increase must, however, be attributed to the tide-induced change in the relative surf zone position of the mid-surf zone instrument from a position in the middle of the surf zone to the outer surf zone. Therefore, it is possible that the total longshore suspended flux during the second part of the sea breeze was overestimated in Figure 6.13.

6.3.6 Transport models

A time series of total suspended sediment transport was derived from the combination of both streamer trap and optical backscatter sensor (OBS) measurements. Simultaneously with the suspended flux measurements, a fluorescent tracer experiment was conducted as discussed in Chapter 5B. Three transport rates were measured, of which the 'SIM' after 2 hours was assumed to represent the upper limit of the total load longshore transport rate. The transport measurements are compared with transport estimations according to several equations, whereby wave and current measurements are used as input parameters, as indicated in Table 3.2 (Figure 6.14).

Interpretation of the tracer and OBS/trap results depends on the reliability of the field observational data. The OBS/trap measurements account for the suspended sediment transport and can be seen as the lower limit of the total longshore transport rate. Additionally, due to the rising tide (over static instruments), it is expected that the suspended flux during the second part of the sea breeze was overestimated. The total longshore transport rate determined using the SIM with sampling after 2 hours can be regarded as the upper limit to the total longshore transport rate. Taking into account the potential errors in the data, it is possible to make some quantitative statements regarding the relative contribution of the suspended load to the total load during longshore
transport. During the two-hour tracer experiment, the maximum total load longshore transport rate was 116.3 m$^3$ hour$^{-1}$ and the suspended load component is estimated at 68.2 m$^3$ hour$^{-1}$, therefore the suspended load contribution is at least 59%.

![Graph showing longshore transport rates with shaded area indicating experiment time](image)

**Figure 6.14:** Predicted and measured longshore sediment transport rates. The grey shading indicates the time of the tracer experiment (13:00–15:00 hrs).

Since the models estimate the total longshore transport rates, reliable transport estimates should predict transport rates situated between the SIM after 2 hours and the suspended flux measurements. There is an excellent quantitative agreement between the rate of suspended longshore transport (OBS/trap) and the total load transport according to the ‘Inman and Bagnold’ and ‘CERC’ models, with both measurements and predictions indicating maximum longshore transport rates during 15:00–19:00 hrs (Figure 6.14 and Table 6.2).

**Table 6.2: Average volume of transported sediment during a single sea breeze from 11:30 until 20:30 hrs on Brighton Beach.**

<table>
<thead>
<tr>
<th>Sea breeze transport volume (m$^3$ hour$^{-1}$)</th>
<th>111.8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transport equations:</strong></td>
<td></td>
</tr>
<tr>
<td>OBS &amp; streamer trap</td>
<td></td>
</tr>
<tr>
<td><strong>Inman and Bagnold</strong></td>
<td></td>
</tr>
<tr>
<td>-incident</td>
<td>102.4</td>
</tr>
<tr>
<td>-estimated</td>
<td>127.4</td>
</tr>
<tr>
<td><strong>CERC</strong></td>
<td></td>
</tr>
<tr>
<td>-incident</td>
<td>131.6</td>
</tr>
<tr>
<td>-wind</td>
<td>115.1</td>
</tr>
<tr>
<td><strong>Kamphuis</strong></td>
<td></td>
</tr>
<tr>
<td>-incident</td>
<td>39.0</td>
</tr>
<tr>
<td>-wind</td>
<td>21.5</td>
</tr>
</tbody>
</table>
Characteristic of the ‘Kamphuis –incident’ model is the maximum transport rates predicted at the beginning and end of the monitoring period, with abrupt changes in transport rates around the start (12:00 hrs) and finish (19:00 hrs) of the sea breeze (Figure 6.14). These changes are a result of the definition of the peak wave-period, $T_p$, in the Kamphuis-equation. Generally, during a sea breeze, the peak in wave energy is caused by low-period wind waves, while before and after the sea breeze the swell waves contain the most energy. As a result the incident $T_p$ resembles the swell $T_p$ before and after the sea breeze, and the lower wind $T_p$ during the sea breeze. Since in the Kamphuis-equation the parameter $T_p$ is used to the power 1.5, a reduction in $T_p$ during the sea breeze can reduce the transport rate. Accordingly, the $T_p$ of incident waves is difficult to define if a site is characterised by a bimodal wave field, which reduces the applicability of the Kamphuis-equation.

With the exception of the first two hours (10:00–12:00 hrs) both ‘Kamphuis’ models consistently under-predict the suspended flux (note that the measurements after 20:00 hrs are not considered reliable). The amount of under-prediction depends on the relative contribution of the suspended load to the total load. If 59% of the longshore transport is by suspended load, the mean transport according to the ‘Kamphuis’ model under-predicts the total transport rate by an average factor 7, but the discrepancy increases as the percentage of suspended load decreases.

### 6.4 Discussion

The suspended flux profile across the water column was found to represent an exponential curve, described by Equation 6.2. The data in Table 6.1 show a wide range of $\alpha$-values and also suggests that $\alpha$ increases in the onshore direction, from 1 in the outer surf zone to 5 in the swash zone, indicating a decrease in mixing of the sediment flux profile from the outer surf zone position towards the swash zone (Figure 6.10). The cross-shore change in mixing characteristics indicates the importance of sand movement close to the bed in the swash zone and may reflect a transition from suspended transport under breakers to more sheet-flow transport under asymmetric bores and swash (Hughes et al., 1997).
According to Kraus et al. (1989) however, the exponential suspended flux profile is an almost ‘universal’ shape, regardless of location, wave climate or grain size, a theory supported by several studies that reported a rather limited range of $\alpha$-values. Rosati et al. (1991) compared streamer trap data from four different locations, including the studies discussed in Kraus et al. (1989), and found $\alpha = 2.5-3.7$. Wang (1998) conducted a large number of streamer trap deployments in a variety of low-energy beaches ranging from dissipative to reflective morphodynamic environments and found a modest dependence of $\alpha$ on the surf zone position with $\alpha = 2.9-3.2$ in the surf zone, and $\alpha = 2$ in the swash zone. The fundamental difference between the results presented in this chapter, and those presented in previous studies, is that the previous studies were conducted under less energetic conditions with smaller wave heights. Accordingly, the differences observed indicate that the cross-shore changes in suspended sediment mixing increase with higher wave heights.

The cross-shore distribution in the longshore suspended flux has a prominent peak at the mid- to outer part of the surf zone, and considerably less, but still significant amounts of sediment being transported in the inner surf zone and the swash zone (Figure 6.11). The contribution of the swash zone to the total longshore flux is about 28%, however this is founded upon a single measurement in the lower swash zone and an estimate of zero transport at the swash runup limit and could well be an underestimation of the actual swash contribution. According to the description of cross-shore profiles of low-energy beaches in Section 2.3.3, the distribution in Figure 6.11 is situated between a unimodal profile, with a transport peak in the outer surf zone, and bimodal profile, with peaks both the swash and outer surf zone. Such distribution is fairly typical of non-barred, low-energy beaches with plunging breakers (e.g., Kraus et al., 1981, 1982; Bodge and Dean, 1987; Kraus and Dean, 1987; Wang, 1998).

According to the streamer trap data, the vertically-integrated sediment flux, $q(x)$, during the sea breeze was on average 1.5 kg m$^{-1}$ s$^{-1}$, but increased from less than 1 kg m$^{-1}$ s$^{-1}$ at the start of the sea breeze, to more than 3 kg m$^{-1}$ s$^{-1}$ at the end of the sea breeze (Figure 6.9). Based on the combined streamer trap and OBS-data the average longshore suspended transport volume, $Q$, was 49 kg s$^{-1}$. The measured transport rates were approximately one order of magnitude larger than those reported in previous streamer trap studies (Ciavola et al., 1999a; Kraus and Dean, 1987; Kraus et al., 1989; Rosati et
al., 1991; Wang, 1998) and this is a reflection of the higher energy levels encountered in the present study.

The time-series of \( Q \) was displayed in Figure 6.13. Despite application of a 10-min moving average window to the data, \( Q \) fluctuates widely and can change by 10–20 kg s\(^{-1}\) within minutes, calling into question the use of short-term streamer trap deployments to estimate long-term longshore transport rates (Stutz and Pilkey, 1999). Since the correlation between the vertically-integrated streamer trap flux and the local suspended flux determined from a pair of OBS and current meters was quite strong, the simultaneous deployment of streamer traps with pairs of OBS sensors and current meters appears to be a useful technique for future studies (Figure 6.12). This correlation is also better than previous attempts at correlating these two types of suspended transport measurements (Rosati et al., 1991; Ciavola et al., 1999a).

The present study compliments previous investigations into the impact of sea breeze activity on nearshore processes along the Perth metropolitan coastline (Pattiaratchi et al., 1997; Masselink and Pattiaratchi, 1998a, 1998b, 2001b). The sea breeze discussed in the present study was characterised by wind velocities of 5–7 m s\(^{-1}\) and can be considered an average summer sea breeze along the Perth coastline. During this sea breeze (from 11:30 to 20:30 hrs) the total suspended longshore transport was 1,006 m\(^3\). On average, almost 200 sea breezes are experienced per year along the coast of Southwestern Australia (Masselink and Pattiaratchi, 2001a) therefore the measurements would add-up to a yearly northward littoral drift caused by sea breezes of 200,000 m\(^3\). Pattiaratchi et al. (1997) conducted measurements of suspended sediment fluxes during a very strong sea breeze, using a combination of current and suspended sediment sensors at a beach 2 km north of Brighton beach (Scarborough beach). They concluded that around 150,000 m\(^3\) of sand is transported northward during the summer.

6.5 SUMMARY

- The wave spectra in the surf and swash zone display a general decrease of wave height in the onshore direction (due to wave dissipation) and a limited amount of wind-wave energy, as a probable result of transferral of energy to lower frequencies through bore interactions.
The data of paired OBS and current meters recorded net cross-shore and longshore suspended fluxes of respectively 3 kg m\(^{-2}\) s\(^{-1}\) directed offshore (bed return flow) and 12 kg m\(^{-2}\) s\(^{-1}\) directed northward. Both fluxes were dominated by the mean component, the oscillatory component being of secondary importance.

The streamer trap data suggest a decrease in the mixing of the sediment flux profile from the outer surf zone towards the swash zone, which may reflect the transition from suspended transport under breakers to more sheet-flow transport under asymmetric bores and swash.

The average cross-shore distribution of the normalised suspended flux showed a maximum at the mid- to outer part of the surf zone, with the contribution of the swash zone being a tentative 28%. This distribution is typical of non-barred, low-energy beaches with plunging breaking waves.

The vertically-integrated sediment flux averaged over the sea breeze was approximately 1.5 kg m\(^{-1}\) s\(^{-1}\). This transport rate is approximately one order of magnitude larger than reported in previous streamer trap studies and this is a reflection of the higher energy levels encountered in the present study.

The time series of total longshore sediment flux derived from combined streamer trap and surf zone instruments shows a threefold increase in the transport rates during the sea breeze. The total volume transport during the 9 hour sea breeze period is estimated as approximately 1000 m\(^3\).

The simultaneous deployment of streamer traps and pairs of OBS and current meters is a useful technique for future studies which circumvents the shortcomings inherent to both measurement techniques.

The suspended load contribution to the total longshore sediment transport is at least 59%, based on fluorescent tracer studies and streamer traps combined with surf zone instruments.

There is a quantitative agreement between the timeseries of suspended longshore sediment transport and the transport estimated by the equations of Inman and Bagnold (1963) and CERC (1984). During the sea breeze, the equation of Kamphuis (1991) consistently under-predicts the measured transport rate by a factor 7. This equation is difficult to apply on this study area characterised by a bimodal wave field.
CHAPTER 7: SYNTHESIS AND CONCLUSIONS

7.1 INTRODUCTION
The longshore transport of sand is an important nearshore process that controls beach morphology. Accordingly, a qualitative and quantitative sense of longshore transport rates is essential in determining coastal evolution and the environmental impact of coastal structures and beach nourishments. The literature review of this thesis highlighted the fact that although measurements of longshore sediment transport rates have been conducted for a considerable time, the understanding of longshore sediment transport processes remains underdeveloped. Points in need of investigation are the relative contributions of bedload and suspended load to the total littoral drift rate, the cross-shore variation of longshore sediment transport and the contribution of swash processes. The applicability of conventional transport equations to predict littoral drift rates on low-energy beaches also requires further research.

The results of field studies have been presented and discussed in this thesis. During this study, longshore sediment transport rate was measured during energetic sea breeze activity, on intermediate-to-reflective sandy beaches in Southwestern Australia. Estimates of suspended load were obtained using backscatter sensors, current meters and streamer traps. Total load was determined using tracer sand and an impoundment study. The measurements were cross-compared. A review of a number of equations resulted in the selection of three widely-used transport models with which to compare the measured transport rates. In this synthesis the different transport measurements will be combined and compared with transport estimates, and findings of previous studies. In addition, implications for future research will be considered.

7.2 COMBINING THE FIELD MEASUREMENTS
The objectives of this thesis have been listed in Section 1.3. A combination of field measurements can be used to address a number of these objectives, particularly the relative contributions of bedload and suspended load to the total littoral drift, the cross-shore variation in littoral drift rate and the contribution of swash processes to the total littoral drift.
Longshore sediment transport rates were measured using different techniques on several temporal and spatial scales (Table 7.1). A direct comparison of measured transport rates is complicated by the scale differences of the measuring techniques. Thus, when comparing the different transport rates, it should be noted that:

- each methodology has inherent inaccuracies and uncertainties;
- wind climate and wave breaking conditions were different during each experiment;
- transport rates are only representative of conditions at the time and location of measurement;
- temporal scales of measurement ranged from seconds to weeks; and
- spatial scales ranged from a centimetre sized area in the water column to hundreds of metres of beach.

However, the simultaneous deployment of several techniques can be informative, since through repeated measurement trials and inter-comparison of results, the techniques can be reviewed and refined for reliability. Unfortunately, few researchers have chosen to investigate this. Furthermore, care should be taken when using shorter-term measurements to estimate longer-term volumes of longshore sediment transport. Bearing in mind that usually a few storms a year contribute to the majority of longshore transport at a site, it is critical to measure longshore transport during such conditions. Perhaps the greatest weakness in field measurements is the inability to accurately measure storm-related transport.

### Table 7.1: Measured longshore sediment transport rates.

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Transport volume (m³ hour⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBS / streamer trap</td>
<td>111.8</td>
</tr>
<tr>
<td>10.01.01 Brighton*</td>
<td></td>
</tr>
<tr>
<td>Tracer</td>
<td></td>
</tr>
<tr>
<td>10.01.01 Brighton</td>
<td>116.3</td>
</tr>
<tr>
<td>18.01.02 South Leighton</td>
<td>54.4</td>
</tr>
<tr>
<td>25.01.02 Mullaloo</td>
<td>26.6</td>
</tr>
<tr>
<td>12.02.02 North Leighton</td>
<td>48.6</td>
</tr>
<tr>
<td>Impoundment</td>
<td></td>
</tr>
<tr>
<td>lower limit**</td>
<td>14.4 (43.2***</td>
</tr>
<tr>
<td>upper limit**</td>
<td>21.4 (64.2***</td>
</tr>
</tbody>
</table>

* Based on average during sea breeze (11:30–20:30 hrs).
** Based on data from day 48 until day 90 (refer to Table 4.6).
*** Assuming daily sea breezes with duration of 8 hours.
Chapter 7: Synthesis and Conclusions

The highest transport rates were recorded at Brighton beach, by both the tracer experiment and combined OBS/streamer trap measurements. These measurements took place during a relatively strong sea breeze with very energetic hydrodynamic conditions. The intermediate transport rates during the other three tracer experiments were obtained under calmer conditions. The lowest transport rates were recorded during the impoundment study. This can be explained by the fact that these data were recorded on a weekly interval and included possible southward transport, days without sea breezes and calm nights when the longshore sediment transport would be minimal. The tracer and combined OBS/trap measurements, on the other hand, were conducted during sea breezes. Assuming daily sea breezes that last an average eight hours, the longshore sediment transport being insubstantial for the remaining 16 hours of the day, the sediment transport during sea breezes was three times the measured value. This results in lower and upper limits of 43.2 and 64.2 m$^3$ hour$^{-1}$, respectively (bracketed rates in Table 7.1). Given that the impoundment study was assumed to under-predict actual northward drift rates (refer to Section 4.6), these results closely resemble the findings of the other measurements. Even though care should be taken when comparing the results of different measurement techniques, it is clear that the scale differences are not the only issue. However, it is promising that the different methods yield similar results, especially for the measurements at Brighton beach (Table 7.1).

Both the tracer experiments and combined OBS/streamer trap deployments provide some information on the cross-shore distribution of the longshore sediment transport. During the experiment at Brighton beach, the cross-shore distribution in the longshore flux had a prominent peak at the mid- to outer part of the surf zone (Figure 5B.12 and Figure 6.11). Considerably less, but still significant amounts of sediment were transported in the lower and upper swash zone. Four different cross-shore distributions of longshore sediment transport have been described in Section 2.3.3, and this distribution is situated between a unimodal profile, with a transport peak in the outer surf zone, and a bimodal profile, with peaks in both the swash and outer surf zone. Such a distribution is fairly typical of non-barred, intermediate-to-dissipative, low-energy beaches with plunging breakers (e.g., Kraus et al., 1981, 1982; Bodge and Dean, 1987; Kraus and Dean, 1987; Wang, 1998). The longshore transport rates at North Leighton, South Leighton and Mullaloo beaches are lower and peaks in the cross-shore distribution were not as well defined as at Brighton beach.
The contribution of the swash zone to the longshore flux at Brighton beach was estimated at about 12% for the tracer experiment, and 28% for the combined OBS and streamer trap data. The tracer experiments at South and North Leighton beach indicated a swash contribution of, respectively, 28% and 22%. These percentages were similar even though the data were collected on several beaches using different measurement techniques. The swash contribution agrees with previous findings under plunging wave conditions (Bodge and Dean, 1987).

There has long been a question as to whether sand-tracer methods measure bedload transport only or total transport. Nelson and Coakley (1974) assumed that transport rates estimated from tracer experiments were principally estimates of bedload transport. Similarly, others assumed the mass of grains in suspension to be orders of magnitude smaller than the bedload mass and not of influence on the total transport rate (Inman et al., 1980; White and Inman, 1989b). This assumption was based on experiments where the suspended load was defined as sediment transported in the water column from 10 cm above the bed to the water surface, because the sampler did not function closer to the bed. Given an exponential suspended flux profile across the water column (see Section 6.3.4), the transport rate close to the bed is very important and neglecting this transport would result in an underestimation of the suspended sediment flux. In the current study, the tracer transport is assumed to represent the total load, similar to Komar (1998) and Ciavola (1999b). In the nearshore zone there is an interaction and exchange between bedload and suspended load, therefore, an individual tracer grain may spend varying portions of time in suspension, saltation, bedload or even buried beneath the bedload (Hanes, 1988). The contribution of the suspended load to the total load during the two-hour tracer experiment at Brighton beach was estimated as at least 59% (refer to Section 6.3.6).

7.3 COMPARISON OF SEA BREEZE ACTIVITY AND LONGSHORE TRANSPORT RATES

Sea breeze occurrence is dependent on latitude, and consistent, diurnal sea breeze activity is concentrated in the tropical and subtropical regions, which comprise about two-thirds of the earth’s coastline (Sonu et al., 1973). In areas where the sea breeze prevails for many months of the year, the cumulative effect of its (modest) winds on coastal processes can be a significant. Comparison of sea-breeze intensities with other regions
indicates that the sea-breeze system in southwestern Australia is one of the strongest worldwide (Table 7.2) (Pattiaratchi et al., 1997).

Table 7.2: Maximum recorded wind speed of the sea breeze at various coastal sites (from data reported by Pattiaratchi et al. (1997))

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum wind speed (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean Reef near Perth, Western Australia</td>
<td>20</td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>14</td>
</tr>
<tr>
<td>Santa Rosa Island, Florida</td>
<td>5</td>
</tr>
<tr>
<td>Monterey, California</td>
<td>7</td>
</tr>
<tr>
<td>Tokyo, Japan</td>
<td>8</td>
</tr>
<tr>
<td>Piraes near Athens, Greece</td>
<td>10</td>
</tr>
<tr>
<td>Katunayake near Colombo, Sri Lanka</td>
<td>9</td>
</tr>
</tbody>
</table>

In sheltered, low wave energy environments, sea breeze activity has a significant impact on nearshore processes and morphology, as demonstrated by this thesis and other investigations conducted on sandy beaches in southwestern Australia (Pattiaratchi et al., 1997; Masselink and Pattiaratchi, 1998a, 1998b). Each sea breeze influences the nearshore processes, creating a similar effect to that of a storm on the beach. During summer, the regular sea breezes generate wind waves and longshore currents that result in northward longshore sediment transport, which is of major importance to the long-term sediment budget and large-scale transport patterns of the coastline. As suggested by Pattiaratchi et al. (1997), this sea breeze induced transport may account for practically all the northward littoral drift that occurs along the coast of southwestern Australia. Since the sea breeze represents a prominent phenomenon along most of the Western Australian coast (Masselink and Pattiaratchi, 2001a) and other beaches worldwide, its effect on the littoral drift is expected to be widespread along this coast and other areas with strong sea breeze activity (Masselink and Pattiaratchi, 1998b).

Despite large differences in the temporal and spatial scales of the measurement techniques, the yearly northward transport rates along the Perth coastline are comparable. The littoral drift rates have been estimated as ~138,000 m³ and ~200,000 m³ by, respectively, the impoundment study and combined use of OBS sensors and streamer traps (for calculations see Sections 4.6 and 6.4). These transport rates are smaller than the northward littoral drift rates along, for example, the Gold Coast in eastern Australia (e.g., Carley et al., 1999; Boak et al., 2001), the coastal zone of Holland (van Rijn, 1997), or along Skallingen, Denmark (Aagaard et al., 1998) (Table 7.3). The sea breeze induced
longshore transport rates, however, were larger than rates reported along, for example, the U.S. Great Lakes (Table 7.3).

Table 7.3: Longshore sediment transport rates at various coastal sites (adapted from CERC (1984) and Komar (1998)).

<table>
<thead>
<tr>
<th>Location</th>
<th>Dominant transport direction</th>
<th>Net longshore transport (m³ yr⁻¹)</th>
<th>Date of record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perth, WA</td>
<td>N</td>
<td>138,000–200,000</td>
<td>2000–2002</td>
</tr>
<tr>
<td>Gold Coast, NSW</td>
<td>N</td>
<td>500,000</td>
<td></td>
</tr>
<tr>
<td>U.S.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlantic Coast</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Absecon Inlet, NJ</td>
<td>S</td>
<td>306,000</td>
<td>1935–1946</td>
</tr>
<tr>
<td>- Hillsboro Inlet, FL</td>
<td>S</td>
<td>57,000</td>
<td>1850–1908</td>
</tr>
<tr>
<td>- Atlantic Beach, NC</td>
<td>E</td>
<td>22,500</td>
<td>1850–1908</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Galveston, T</td>
<td>E</td>
<td>334,700</td>
<td>1919–1934</td>
</tr>
<tr>
<td>- Perdido Pass, AL</td>
<td>W</td>
<td>153,000</td>
<td>1934–1953</td>
</tr>
<tr>
<td>- Pinellas County, FL</td>
<td>S</td>
<td>38,000</td>
<td>1922–1950</td>
</tr>
<tr>
<td>Pacific Coast</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Oxnard Plain Shore, CA</td>
<td>S</td>
<td>765,000</td>
<td>1938–1948</td>
</tr>
<tr>
<td>- Port Hueneme, CA</td>
<td>S</td>
<td>382,000</td>
<td>1938–1948</td>
</tr>
<tr>
<td>- Anaheim Bay, CA</td>
<td>E</td>
<td>115,000</td>
<td>1937–1948</td>
</tr>
<tr>
<td>- Camp Pendleton, CA</td>
<td>S</td>
<td>76,000</td>
<td>1950–1952</td>
</tr>
<tr>
<td>Great lakes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- IL state line to Waukegan</td>
<td>S</td>
<td>69,000</td>
<td></td>
</tr>
<tr>
<td>- Waukegan to Evanston</td>
<td>S</td>
<td>44,000</td>
<td></td>
</tr>
<tr>
<td>- Kenosha, WI</td>
<td>S</td>
<td>11,000</td>
<td>1872–1909</td>
</tr>
<tr>
<td>- Milwaukee County, WI</td>
<td>S</td>
<td>6,000</td>
<td>1894–1912</td>
</tr>
<tr>
<td>Hawaii</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Waikiki Beach</td>
<td>-</td>
<td>8,000</td>
<td></td>
</tr>
<tr>
<td>Other sites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monrovia, Liberia</td>
<td>N</td>
<td>383,000</td>
<td>1946–1954</td>
</tr>
<tr>
<td>Port Said, Egypt</td>
<td>E</td>
<td>696,000</td>
<td></td>
</tr>
<tr>
<td>Port Elizabeth, South Africa</td>
<td>N</td>
<td>459,000</td>
<td></td>
</tr>
<tr>
<td>Durban, South Africa</td>
<td>N</td>
<td>293,000</td>
<td>1897–1904</td>
</tr>
<tr>
<td>Madra, India</td>
<td>N</td>
<td>566,000</td>
<td>1886–1949</td>
</tr>
<tr>
<td>Mucuripe, Brazil</td>
<td>N</td>
<td>327,000</td>
<td>1946–1950</td>
</tr>
<tr>
<td>West coast of Holland</td>
<td>N</td>
<td>500,000</td>
<td>1964–1992</td>
</tr>
<tr>
<td>Skallingen, Denmark</td>
<td>S</td>
<td>500,000–1,000,000</td>
<td></td>
</tr>
</tbody>
</table>

7.4 COMBINING THE MODEL ESTIMATES

An objective of this thesis was to analyse the applicability of conventional transport equations to predict littoral drift rates on low-energy beaches (Section 1.3). The hydrodynamic measurements made during the field experiments were used as input parameters into transport equations (Table 4.6, Table 5B.8 and Table 6.2), the two most basic models being the CERC (1984) and the Inman and Bagnold (1963) equations. Although both models have their complications and uncertainties, they are widely
applied, both because of their ease of use and the small number of input parameters needed. A more realistic equation was developed by Kamphuis (1991b) and includes the effects of sediment size and breaker type. The model fits the available laboratory and previous field data on longshore transport well and appears to be widely applicable.

Characteristic of Southwestern Australia is a bimodal wave field, the result of a combination of wind and swell waves, whereby the former is influenced by sea breezes and the latter by lower-frequency synoptic weather patterns. Littoral drift results from large amounts of longshore energy flux exerted by the wind waves. The Kamphuis (1991b) equation is regarded unsuitable for use in combination with a bi-modal wave field, as a result of the variability of the peak wave period. Despite large uncertainties associated with the measured transport rates, the ‘Inman and Bagnold’ model fits the transport rates reasonably well. Perhaps surprisingly, it appears that the least complicated model, the equation of CERC (1984), matches the measured transport rates best, especially when only considering the contribution of the wind waves (‘CERC -wind’).

The role of swell waves in affecting the longshore transport rate is limited, it is therefore of interest to investigate how the bimodal wave climate of the study site influences the longshore sediment transport. Compared to swell waves, wind waves are characterised by small wave heights, low peak wave periods and large wave angles, and wind waves break closer to the shore than swell waves. This is confirmed by field observations, which indicate an inner surf zone dominated by breaking wind waves and an outer surf zone characterised by breaking swell waves. At the location where the swell-waves break, the wave motion agitates sediments, but there is only a weak wave-induced longshore current available to advect the sediments in a longshore direction. The agitation by swell waves reduces towards to shore, and in the inner surf zone the swell energy is limited in comparison to high overall turbulence levels due to the breaking wind-waves and strong longshore currents. Accordingly, it appears that of both the swell and wind waves, mainly the latter are instrumental in causing longshore sediment transport. This may explain why the ‘CERC -wind’ model does more closely estimate the longshore sediment flux than the ‘CERC -incident’ model.

Ideally, transport models applied to sites characterised by a bimodal wave climate require input parameters that provide information about the structure of the spectrum. This information is lost in the conventional transport equations, where the wave conditions are
characterised by single parameters (e.g., $H_{\text{sig}}$, $T_p$, or $\alpha_{\text{sig}}$). In the current study and several others (e.g., Boon et al., 1996; Elfrink et al., 1998) the swell and wind waves were distinguished from the incident waves and treated separately in sediment transport calculations. Even though the transport using either swell or wind waves can be calculated, the combined effect on the total longshore sediment transport rate is expected to be larger than the sum of the separate transport rates. Moreover, it can be difficult to define input parameters, especially the peak wave period, which is used in the ‘Kamphuis’-equation (see Section 6.3.6), because the peak wave period of the incident waves is similar to the peak wave period of either the swell or wind waves, depending which one is the most energetic. Generally, the wind waves are most energetic during the sea breeze, while the swell waves are more energetic during the remainder of the day. Therefore, during the sea breeze, the incident peak wave period is around 4 s ($\sim$ peak wind wave period), instead of 13 s ($\sim$ peak swell wave period). Since $T_p$ is raised to the power 1.5 in the ‘Kamphuis’-equation, this effectively reduces the longshore sediment transport rate by a factor of 6, whereas an increase would have been intuitively expected. Clearly, for bimodal wave characteristics, the peak wave period is inadequate as input parameter in a transport equation. Therefore, the ‘Kamphuis’-equation is unsuitable for longshore transport calculation under a bimodal wave field.

During this study, the offshore limit of the saturated breaking zone was estimated at a water depth of 1.5 times the significant incident-wave height (refer to Section 6.2.2). The waves were shoaled and refracted to this depth and the conditions at this location were considered breaking wave conditions. Aagaard and Masselink (1999) and Masselink and Hegge (1995) suggested wave breaking at larger water depths, of twice the significant wave height, by using the equation as suggested by Sallenger (1985):

$$\gamma_{\text{rms}} = 3.2 \tan \beta + 0.30$$  \hspace{1cm} (7.1)

The sensitivity of the transport equations to changes in the wave breaker index ($\gamma$) has been investigated. Assuming a smaller wave breaker index, and therefore a larger water depth at wave breaking, would result in less wave shoaling and therefore lower values of the breaker wave height, less wave refraction and consequently higher wave angles. For the wave data collected during the combined OBS and streamer trap experiment, these differences would result in a decrease of $H_{\text{sig}}$ by 0.04 m and an increase of $\alpha$ by 0.84 deg. It is of interest to investigate how these changes in breaker wave parameters influence the
longshore sediment transport rates as estimated by several transport models. For the 'CERC', 'Inman and Bagnold –estimated', and 'Kamphuis' equations the influences of the decrease in $H_{sig}$ and increase in $\alpha$ are opposite and as a result, the change in transport rate is insignificant. However, for the 'Inman and Bagnold –incident' equation, when using a measured longshore current velocity, the transport rate will decrease with larger breaker depth, in this case by $\sim 10\%$. While the choice of breaker depth clearly has some effect on the calculated wave parameters, most transport models do not consider it as a factor.

At the present time, there is no well-established transport formula that takes into account all the different factors that control longshore sediment transport. Such a formula should quantify bedload and suspended load, include transport in the swash zone and incorporate a description of the morphodynamic beach state, the hydrodynamic conditions and sediment size.

### 7.5 COMPARISON WITH PREVIOUS STUDIES

To discuss the applicability of the transport equations to low-energy sandy beaches, it is important to know how the results of this study fit in with results of previous studies (Figure 7.1). A way of doing so is to plot measured immersed weight transport rates against the longshore energy flux factor, resulting in a figure similar to the diagram in the Coastal Engineering Manual (Figure III-2-4 in CERC (2002)). The measured volumetric longshore transport values ($Q$ in $m^3\text{s}^{-1}$) were converted to immersed-weight transport rates ($I_i$ in $N\text{s}^{-1}$), according to Equation 2.1. The model-estimates of longshore sediment transport based on the CERC-equation (CERC -incident, and -wind) were converted to average longshore energy flux factors ($P$ in $W\text{m}^{-1}$) using root-mean-square wave heights ($H_{rms}$). For the impoundment study, only data from days 48–90 were used. Field data from previous research included in Figure 7.1 has been limited to the longshore transport of sand-sized sediments, excluding the transport of coarser sediments such as gravel (similar to the data in Figure 2.1). The CERC-equation is the solid line in the figure using the proportionality coefficient $K_{rms} = 0.70$ (or $K_{sig} = 0.35$). The results of previous studies suggest there is considerable scatter within the data. As discussed in Section 2.4.2, this is reflected in the variations in the values of $K$. 
Figure 7.1: A compilation of field data, using the CERC-equation for immersed weight longshore sand transport rate $I$, as a function of the longshore component of wave energy flux $P$. Data of the current study are plotted using coloured markers whereby the study sites are indicated by numbers, as (1) Brighton; (2) South Leighton; (3) Mullaloo; (4) North Leighton; and (5) City beach. Field data of previous studies are plotted in the background (see Figure 2.1 for key).

The results of the current study show the same amount of scatter as in previous studies. The previous studies, indicated in Figure 7.1, generally took place on medium- to high-energy beaches, while the current study was undertaken at low-energy beaches. Accordingly, it was assumed that the longshore energy flux factor and immersed weight transport rate were relatively low, resulting in the current study being situated at lower extremity of the data-scatter. However, even though the studied beaches are classified as ‘low-energy’, in practice this study’s results place it at the higher extremity of the data-scatter, caused by the local effect of the large wave angles, strong longshore currents and resulting high sediment transport rates during the sea breeze. Longshore sediment
transport during sea breezes is mainly the result of a high longshore energy flux exerted by wind waves, similar to the effect of having a daily storm on the beach.

More specifically, Figure 7.1 displays the differences in the estimated longshore energy flux factor when using diverse input parameters in the CERC-equation, with 'CERC -wind' resulting in the lowest and 'CERC -incident' resulting in the highest energy flux. The transport rates at Mullaloo beach, in Figure 7.1, are situated outside the range of data-scatter, which might be the result of the very low recovery rates and significant erosion during the tracer experiment, therefore these values are omitted in further discussion. For the remaining project results, the amount of scatter is similar to that in previous studies.

<table>
<thead>
<tr>
<th>Table 7.4: Values of the empirical proportionality coefficient, $K_{rms}$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportionality coefficient, $K_{rms}$ (-)</td>
</tr>
<tr>
<td>'CERC -incident'</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Impoundment</td>
</tr>
<tr>
<td>lower limit*</td>
</tr>
<tr>
<td>upper limit*</td>
</tr>
<tr>
<td>Tracer</td>
</tr>
<tr>
<td>10.01.01 Brighton</td>
</tr>
<tr>
<td>18.01.02 South Leighton</td>
</tr>
<tr>
<td>25.01.02 Mullaloo**</td>
</tr>
<tr>
<td>12.02.02 North Leighton</td>
</tr>
<tr>
<td>OBS &amp; streamer trap</td>
</tr>
<tr>
<td>10.01.01 Brighton***</td>
</tr>
</tbody>
</table>

* Based on data from day 48 until day 90 (refer to Table 4.6).
** Based on unreliable tracer data.
*** Based on average during sea breeze (11:30-20:30 hrs).

The longshore energy flux factor, $P_h$, is related to the immersed weight transport rate, $I_h$, by the proportionality coefficient $K$ (see Equation 2.5). As a result, the coefficient $K$ according to 'CERC -wind' will be higher than the $K$ of 'CERC -incident' (Table 7.4). The CERC-equation has previously been validated for medium- to high energy, low-gradient beaches but the data of this study suggests the CERC-equation works similarly well for low-energy, steep-gradient beaches. This contrasts strongly with the findings of a number of recent studies on low-energy beaches with plunging breaker conditions, which concluded that the equations significantly under-predict longshore transport rates (Ciavola et al., 1997b; Nordstrom et al., 2003). These previous investigations were, however, conducted under reflective surf zone conditions, characterized by a surf similarity parameter (Battjes, 1974) of $\xi_s \approx 1.2$. Under such conditions, the surf zone is narrow and most of the longshore transport takes place within the swash zone. During the
current study the measurements at, for instance, Brighton beach were conducted during intermediate-to-dissipative conditions with plunging breakers ($\xi_b \approx 0.3$), where the maximum longshore transport rate occurred in the mid- to outer surf zone.

7.6 IMPLICATIONS AND FUTURE RESEARCH CONSIDERATIONS

The research reported in this thesis was the first to use four different techniques, some applied simultaneously, to measure longshore sediment transport along a single stretch of coast. This unique approach has provided invaluable information about practicalities of using the different methodologies and the reliability of their results (Table 7.5). It is hoped that this research project may serve as a useful comparative resource for any future longshore transport studies. Several considerations and directions for further research became apparent while conducting the present research and are outlined below.

Using an impoundment study, littoral drift can be measured on large temporal and spatial scales. Such a study is easy to put into practice using conventional equipment. Interpretation of the results is relatively straightforward, although the derivation of longshore and cross-shore transport from the total volume changes can be questionable. Overall, the longshore sediment transport rate is expected to be under-estimated and the large temporal scale of transport measurement complicates comparison with the wave parameters.

Littoral drift on medium scales can be determined by a tracer study. Even though the use of tracer sand had been a recognised technique for a long time, there is still not a clear, generally accepted methodology available. The use of tracer sand is very labour intensive during preparation, sampling and analysis. Furthermore, it has large associated uncertainties (e.g., defining mixing depth) and is sensitive to local accretion or erosion, resulting in unreliable results. Regarding these issues, it can be concluded that tracer sand is useful in qualitative means, for example in researching transport pathways, but the derived longshore transport rates are unreliable. Transport estimates based on tracer studies have been used to calibrate the CERC-equation, therefore this equation needs to be reconsidered.
Table 7.5: Comparison of techniques to measure longshore sediment transport.

<table>
<thead>
<tr>
<th>Section</th>
<th>Impoundment Tracer</th>
<th>Streamer trap</th>
<th>Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal scale</td>
<td>Hours–weeks</td>
<td>Minutes–hours</td>
<td>Seconds–Minutes</td>
</tr>
<tr>
<td>Spatial scale</td>
<td>100's metres</td>
<td>10's metres</td>
<td>0.01's metres</td>
</tr>
<tr>
<td>Equipment</td>
<td>Surveying equipment</td>
<td>Tracer sand, equipment sampling tubes</td>
<td>Portable rack with vertical array of sediment traps</td>
</tr>
<tr>
<td>Method</td>
<td>Blocking of LST* by shore-normal groyne</td>
<td>Monitoring movement of tagged native sediment</td>
<td>Sampling sediment at different heights above the bed</td>
</tr>
<tr>
<td>Transport rate calculation using</td>
<td>Volume change</td>
<td>Advection velocity &amp; mixing depth</td>
<td>Trapped amount sediment</td>
</tr>
<tr>
<td>Transport mode</td>
<td>Total transport</td>
<td>Total transport</td>
<td>(Near-bed) suspension</td>
</tr>
<tr>
<td>Transport direction</td>
<td>Only longshore transport</td>
<td>Longshore &amp; cross-shore</td>
<td>Either longshore or cross-shore</td>
</tr>
<tr>
<td>Preparation time</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Field sampling:</td>
<td>- Human resources 2</td>
<td>6 Intermediate</td>
<td>3 Easy</td>
</tr>
<tr>
<td></td>
<td>- Difficulty</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td>Data analysis:</td>
<td>- Labour intensity Low</td>
<td>High Intermediate</td>
<td>Easy</td>
</tr>
<tr>
<td></td>
<td>- Difficulty</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Poor (consistent underestimate)</td>
<td>Poor (variable)</td>
<td>Good</td>
</tr>
</tbody>
</table>

* LST: Longshore sediment transport
The deployment of streamer traps results in small-scale suspended longshore transport measurements. Streamer traps can be used to determine gross (near-bed) suspended transport in any one direction, and simultaneous deployment at several cross-shore locations can be informative on the cross-shore distribution of the longshore transport. Deployment and data analysis is easy and the results regarded accurate.

Sensors, such as an OBS or EMCM, are relatively expensive instruments that need to be mounted on a sturdy frame together with a power supply and data logger for deployment in the surf-zone. The combination of suspended sediment concentration and current velocity provides information on the suspended transport rate. A large amount of equipment is needed in order to measure transport rates simultaneously at several distances from bed-level at a number of cross-shore locations. While the preparation and data gathering are rather easy, the data analysis is complicated. The results can be accurate and provide a continuous time-series of suspended sediment transport, which can be partitioned into mean and fluctuating components.

The simultaneous use of streamer traps and OBS-sensors, as applied in this thesis, provides a reliable measurement of suspended transport rates, and proves informative on the processes at small spatial and temporal scales. The streamer traps are a useful means of calibrating the OBS-sensors, while the surf-zone sensors provide a continuous time-series of suspended sediment transport. A logical continuation from this research would be to simultaneously deploy streamer traps and arrays of OBS and current sensors at more cross-shore locations, and to repeat similar strategies at several beaches.

7.7 CONCLUSION

This study was the first to utilise a range of techniques, some applied simultaneously, to measure longshore sediment transport on low-energy sandy beaches subjected to strong sea breezes. Surf-zone instruments, streamer traps, fluorescent tracer sand and an impoundment study were all employed and the results indicate the strengths and weaknesses of each technique. The measured littoral drift rates are reasonably similar, with the highest transport rates calculated from tracer studies and the lowest rates derived from the impoundment study.
Of the four measurement techniques applied during this project, the simultaneous use of streamer traps and OBS-sensors provides the most reliable transport rate. A logical continuation from this research would be to use this simultaneous deployment at more cross-shore locations, and to repeat similar strategies at several beaches. A complete study might ideally include measurements across the swash and surf zones of local sediment transport, wave height, wave period, longshore current, bed profile, vertical suspended sediment distribution and grain size. Only then can the longshore sediment transport processes be properly evaluated, including an identification of the cross-shore distribution of longshore sediment transport rates and the ratio of suspended versus bedload transport. This will make the further testing of existing transport equations and development of more accurate longshore transport models achievable.

The relatively simple equations of Inman and Bagnold (1963) and CERC (1984) reproduce the measured data well, and demonstrate how the longshore sediment transport during sea breezes is mainly the result of a high longshore energy flux exerted by wind waves. The more complicated Kamphuis (1991b)-equation has proven unsuitable as a result of the bimodal wave field, characteristic of the sea breeze affected coastline of Southwestern Australia.

Of concern are the relatively poor results of the tracer method, since the conventional CERC (1984)-equation has been calibrated using mainly results of previous tracer studies. Therefore, this equation should be reconsidered using more reliable data. It is important to define a widely used procedure that objectively determines the mixing depth, since varying definitions of mixing depth result in large differences in resulting transport rates. Consistent results were found when using a cut-off at a minimum concentration of 0.5 grains per gram instead of the 80% cut-off percentage implemented by Kraus et al. (1982).

The temporal tracer distribution (TIM) exhibits a series of concentration peaks, which indicates that sediment moves in discrete pulses. These pulses are probably related to the patchy distribution of tracer on the beach, short-term burial and re-excavation of some dyed sand, minor beach topography that might affect the small-scale water circulation patterns, or may arise from low frequency oscillations in the forcing functions of waves and currents.
In a wider context this study has shown that the simultaneous application of a variety of measurement techniques across different spatial and temporal scales within a single environment can be informative in several ways. Not only can limitations endemic to different methodologies be isolated, but the results also offer a deeper appreciation of the processes involved. For example, in case of the current study, the laboratory calibration of the OBS-sensors was improved by using additional in-situ measurements taken by the streamer traps. Additionally, the transport rates of the different methodologies provided insight into the contribution of suspended sediment transport to the total load.

This combination of spatial scales is especially important from a practical engineering viewpoint. The design of a coastal project would feasibly require data for both ‘steady state’ processes as well as detailed data about ‘extreme’ events. Given that the majority of annual sediment transport is noted as being the result of a few large storms (Miller, 1998) it is clear that the application of measurements to understand the two process types, and critically the interaction between them, is key to long term appreciation of geomorphologic processes, and thus to allow real world solutions to be derived from experimental data.
REFERENCES


References


FAIRCHILD, J.C., 1977. Suspended sediment in the littoral zone at Ventnor, New Jersey and Nags Head, North Carolina. Technical Paper No. 77–5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.


