

PIANC

InCom WG Report n° 198 - 2021



SALTWATER INTRUSION MITIGATION IN INLAND WATERWAYS

The World Association for Waterborne Transport Infrastructure





PIANC REPORT N° 198 INLAND NAVIGATION COMMISSION

SALTWATER INTRUSION MITIGATION IN INLAND WATERWAYS

July 2021

PIANC has Technical Commissions concerned with inland waterways and ports (InCom), coastal and ocean waterways (including ports and harbours) (MarCom), environmental aspects (EnviCom) and sport and pleasure navigation (RecCom).

This report has been produced by an international Working Group convened by the Inland Navigation Commission (InCom). Members of the Working Group represent several countries and are acknowledged experts in their profession.

The objective of this report is to provide information and recommendations on good practice. Conformity is not obligatory and engineering judgement should be used in its application, especially in special circumstances. This report should be seen as an expert guidance and state-of-the-art on this particular subject. PIANC disclaims all responsibility in the event that this report should be presented as an official standard.

PIANC Secrétariat Général Boulevard du Roi Albert II 20, B 3 B-1000 Bruxelles Belgique

http://www.pianc.org

VAT BE 408-287-945

ISBN 978-2-87223-014-3

© All rights reserved

TABLE OF CONTENTS

TAE	TABLE OF CONTENTS 1		
LIS	T OF F	GURES	. 4
LIS	T OF T	ABLES	. 8
1	GENE	RAL ASPECTS	. 9
1.	.1 S	SCOPE	. 9
1.	.2 T	ERMS OF REFERENCE	. 9
	1.2.1	Objective	. 9
	1.2.2		.9
1.	.3 F		.9
1.	.4 N		10
1.	.5 1		10
1.	.6 A		10
1.	./ (SENERAL ASPECTS OF SALTWATER INTRUSION IN INLAND WATERWAYS	11
	1.7.1	Saltwater Intrusion in Previous Literature and PIANC Reports	11
1. •	.8 3 MEOL		12
2	MECF	IANISMS OF SALTWATER INTRUSION IN INLAND WATERWATS	12
2.	.1 II 0 F		12
2.	.2 F		12
2.	.3 L	Lister of Definitions for Colinity	13
	2.3.1	Salinity, Units	13 14
	2.3.3	Effect on Density	15
2.	.4 N	IECHANISMS IN ESTUARIES	16
	2.4.1	General Considerations	16 17
	2.4.2	Tidally Averaged Conditions	17
	2.4.4	Tides	19 20
	2.4.5	Wind	20 23
	2.4.7	Weather Extremes (Typhoon, Etc.)	24
	2.4.8	Artificial Bathymetric Changes	26 27
	2.4.10	Interaction of Salinity and Sediments	28
2.	.5 N	IECHANISMS IN LOCKS	28
	2.5.1	General Considerations	28
	2.5.2	Theoretical Case	30 31
	2.5.4	Effect of the Presence of a Ship in the Lock	33
	2.5.5	Effect of Multiple Lockages in Sequence	33
2.	.6 5	SALTWATER INTRUSION IN GROUNDWATER SYSTEMS	33
	2.6.1	General Considerations	33 24
2			34 24
ງ			34 24
3.	ו וו. סר		ა4 ე⊿
3.	.∠ ⊦ 201	NOJECT GOALS. WHAT IS THE PURPOSE OF MEASURING AND MONITORING?	ა4 ე⊿
	3.2.1	Mechanism of Saltwater Intrusion	34 35
	3.2.3	What Problem/Concern is Being Addressed?	35

	3.3	PRACTICAL CONSIDERATIONS: HOW TO DESIGN A MEASUREMENT/MONITORING PLAN	. 35
	3.3.1 3.3.2 3.3.3 3.3.4	Strategic and Tactical Pre-Planning Measuring Salinity Measuring Salt Transport Designing a Boat-Based Campaign (Vertical and Longitudinal Profiling)	. 35 . 36 . 36 . 37
	3.3.5	Designing a Synoptic Station-Based Monitoring Campaign	. 37
	3.3.6	Designing a Long-Term Monitoring Campaign Data Collection for Model Development and Validation	. 38 38
	3.3.8	Determination of the Effects of Navigation Projects or Mitigation Measures on Saltwater Intrusion:	the
	Role	of Modelling	. 39
	3.4	EXAMPLES	. 39
	314	Campaigns	30
	3.4.2	2 Long-Term Monitoring	. 33 . 43
1	міті	GATION MEASURES AND SOLUTIONS	13
-			. 40
	4.1		. 43
	4.2	MITIGATION IN ESTUARIES	. 43
	4.2.1	General Considerations for Estuaries	. 43
	4.2.2	2 Enclosure Works	. 44
	4.2.3	Flow Diversion and Water Resource Management River Works	. 46 48
	4.2.5	Artificial Channels	. 53
	43	MITIGATION AT LOCKS	54
	1.0		. U I
	4.3.	Ceneral Considerations for Locks	. 54 54
	4.3.3	8 Methods to Reduce Exchange Flows	. 59
	4.3.4	Methods of Saltwater Withdrawal	. 65
	4.3.5	Methods of Saltwater Substitution	. 72
	4.4	MITIGATION IN GROUNDWATER	. 79
	4.4.1	Seepage Screen	. 80
	4.5	CONCLUDING REMARKS	. 80
5	тос	LS AND METHODS FOR SIMULATION AND ASSESSMENT	. 81
	5.1	INTRODUCTION	. 81
	514	Some Preliminary Remarks	. o . 81
	5.1.2	2 Modelling Salt Transport	. 82
	5.1.3	B From Reality to Model	. 82
	5.1.4	Domain Discretisation	. 82
	5.2	SIMPLIFIED METHODS	. 83
	5.2.1	For Estuaries	. 83
	5.2.2	P For Locks	. 84
	5.3	NUMERICAL MODELLING	. 86
	5.3. ² 5.3.2	Specific Modelling Issues for Saltwater Intrusion Studies	. 86 . 89
	5.4	GROUNDWATER MODELLING	. 91
	55	PHYSICAL MODELS	91
	0.0 E E A		
	5.5.	Basic Concepts Historical Models of Estuaries	. 91 92
	5.5.3	Models for Mitigation Measures	. 93
	5.5.1	Example of a Physical Lock Model: Exchange Flows and Interaction with Ship Approach for the Ne	ew
	Pana	ama Locks	. 94
	5.6	SOFTWARE, MODEL SELECTION AND RECENT APPLICATIONS	. 96
	5.6.1	Software	. 96
	5.6.2	2 Model Selection	. 96
	5.6.3	o ividuel calibration and validation	. 97

5.6.4 Recent Applications of Models	98
5.7 CONCLUDING REMARKS	. 100
6 APPENDIX A: TERMS OF REFERENCE	. 101
TERMS OF REFERENCE	. 101
7 APPENDIX B: PROJECTS OVERVIEW	. 104
7.1 PROJECT REVIEW GUADALQUIVIR ESTUARY	. 104
 7.1.1 Project Overview 7.1.2 Navigation in the Waterway 7.1.3 Stakeholders and Their Needs 7.1.4 Saltwater Intrusion Measurements and Modelling 	104 104 105 105
8 APPENDIX C: COMPARISON OF EFFECTIVENESS OF MITIGATION MEASURES	. 110
9 APPENDIX D: DETAILED DESCRIPTION OF VARIANTS OF SALTWATER SUBSTITUTION SYSTEMS IN LOCKS	. 111
9.1 VARIANTS OF THE DUNKIRK SYSTEM	. 111
9.2 SALTWATER CONTAINER LIFT	. 117
10 APPENDIX E: TOOLS AND METHODS FOR SIMULATION AND ASSESSMENT – NUMERICAL MODELLING	. 120
10.1 APPLICATION TO DENSITY DRIVEN FLOW	. 120
10.1.1 1-D Modelling	120 121 121 121 122
10.2 EXAMPLES OF PRESENTLY USED SOFTWARE PACKAGES	. 123
11 APPENDIX F: LIST OF ABBREVIATIONS	. 124
12 BIBLIOGRAPHY	. 125

LIST OF FIGURES

Figure 2.1: Mean salinity concentration for the year 2014 based on model results in southern North Sea illustrating the typical locations of saltwater intrusion in (a) sea locks (here at the Lake IJssel) and (b) in estuaries (here the Elbe estuary) [BAW]
Figure 2.2: TS diagram showing the relationship between temperature (t), salinity (S), and density (the last three digits of the density can be read on the σ_t line) (Copyright © 1998-2021 by Eni Generalic)
Figure 2.3: Different categories of estuary: (a) stratified, (b) partially mixed and (c) well mixed [BAW] 18
Figure 2.4: Exchange flow for an idealised partially mixed estuary showing (a) the velocity and salinity as along channel cross-section and (b) vertical profiles for salinity and velocity (figure adapted from (MacCready and Geyer, 2010))
Figure 2.5: River discharge related changes in the Weser Estuary with forcing from a) tides at a position within the mixing zone at Weser-km 65, b) river discharge at Weser-km 0 and c) the resulting tidally averaged salinity concentration in along-stream direction (Weser-km) with the tidal weir at km 0 [BAW]
Figure 2.6: Surface and bottom salinity along the Loire estuary (top: neap tide; bottom: spring tide) [Artelia] 20
Figure 2.7: Location and topography of the Yangtze Estuary. Salinity measurements presented in Figure 2.8 and Figure 2.9 are taken from Chong Xi Station (black dot) and Chen Hang Reservoir (red star) (Li et al., 2012) 21
Figure 2.8: Change of salinity with time in Chongxi hydrological station from November 2009 to February 2010 (Li et al., 2012)
Figure 2.9: Salinity change of Chenhang reservoir under different wind speeds and for different wind directions. (Wu, 2006)
Figure 2.10: (a) Location of the Pearl River Estuary, (b) the topography around the Pearl River Estuary and (c) the Modaomen Waterway (Wang et al., 2012a)
Figure 2.11: Salinity profile in PSU along the longitudinal SEC1 at flood slack (left panels) and ebb slack (right panels) during the moderate tide after the neap tide for (a) no wind and (b) strong wind case (Wang et al., 2012a)
Figure 2.12: Locations of the Beidagang Reservoir and experimental results of the effect of wind on the salinization of shallow water (Zhao et al., 2005)
Figure 2.13: Layout of the idealized estuary model (left) and definition of different locations (Liling, 2007)
Figure 2.14: Time-series of modelled salinity at location A for the situation with and without waves (Liling, 2007)24
Figure 2.15: Study area and map of the path of the typhoons Tiantu and Nasha (Pan et al., 2019)
Figure 2.16: Measured surface salinity at Magangben and flow at Makou station for typhoonsNasha(upper figure) and Tiantuo (lower figure) (Pan et al., 2019)
Figure 2.17: Changes of salinity before and after typhoon 'Compass' (Wang et al., 2012b)
Figure 2.18: Changes in sea surface salinity caused by (a) fast moving typhoon and (b) slow moving typhoon. (Wu and Ling, 2015)
Figure 2.19: Effect of dredging a navigation channel in case of a river mouth bar [Deltares]
Figure 2.20: Maximum salinity along the Elbe estuary. Black: mean freshwater discharge (MQ). Red: mean freshwater discharge and a sea level rise of 80 cm. Blue: low freshwater discharge (SoMNQ). Green: low freshwater discharge and a sea level rise of 80 cm (Seiffert and Hesser, 2014)
Figure 2.21: Influence of salinity on the settling velocity based on data of Owen, Krone and Allersma presented in van Rijn (1993)
Figure 2.22: Photo of the lock exchange at the IJmuiden locks in the Netherlands (Middle lock and vessel exiting from the Northern lock), the freshwater layer is visible as a darker area fanning out from the locks as the gate is opened. A saltwater current will be flowing in the opposite direction into the lock at lower depths. [ANP © 2020 photo Siebe Swart]
Figure 2.23: Steps in the lockage process, example from a downward lockage from sea to lake. Step 1: after gate at sea side closed, lock chamber filled with saltwater; Step 2: before levelling (emptying), lockage prism volume highlighted as hashed area; Step 3: lockage prism emptied onto lake, saltier water sinks to bottom; Step 4: gate opened, lock exchange flow commences (green arrows indicate flow direction); Step 5: exchange complete, lock chamber filled with freshwater. [Deltares]
Figure 2.24: Schematic illustration of a lock exchange. The dotted line indicates the initial location of a gate which has been removed or opened [Deltares]

Figure 2.25: Relative lock exchange as function of the gate open time [Deltares]
Figure 2.26: Schematic representation of the exchange of water between lock chamber and forebay owing to the movement of the ship (here as an example the ship exiting towards the sea side). For ease of presentation, the lock exchange process is not represented here although it acts simultaneously with the ship movements. [Deltares]
Figure 3.1: Vertical profiles of salinity and the resulting integration into a contour plot of salinity in a vertical cross section of the Stevin lock during a field campaign (Uittenbogaard et al., 2015a) [Deltares]
Figure 3.2: Time signal of measurements in the Stevin lock: top, total salt mass in the lock (left axis, blue line) salinity difference between lock and sea and between lock and lake (right axis, black line and red lines respectively); middle Operation of the valves and gate, 0 both closed, 1 valves open, 2 gate open (blue line - sea side gate and valves, green-line lake side gate and valves); bottom, water levels on the sea side (black) and in the lock (red). (Uittenbogaard and Cornelisse, 2011) [Deltares]
Figure 3.3: Mean current profiles (ADCP measurements) along the Ghent-Terneuzen canal (15/05/2018) [Flanders Hydraulics Research]
Figure 3.4: Measured vertical salinity profiles (grey dots are individual CTD measurements) and interpolated concentrations along the canal length and depth (15/05/2018) [Flanders Hydraulics Research]
Figure 3.5: Measured vertical profiles suspended sediment concentrations (grey dots are individual measurements) and interpolated concentrations along the canal length and depth (15/05/2018) [Flanders Hydraulics Research]
Figure 4.1: The Neches River Saltwater Barrier [Lower Neches Valley Authority]
Figure 4.2: Satellite imagery of the 'smart gates' at the Keith Lake Fish Pass at Port Arthur, Texas. [Google Earth dd. 2018-01]
Figure 4.3: Dutch water priority sequence, used in periods with (severe) water shortages [Rijkswaterstaat] 47
Figure 4.4 Salt barrier sill in the Mississippi River [USACE]
Figure 4.5: Saltwater intrusion without (left) and with (right) intervention to increase vertical mixing, side view of a river mouth, dashed lines represent isolines of salt concentration [Rijkswaterstaat]
Figure 4.6: Breeddiep connection between Rotterdam Waterway and the Caland Canal. The North Sea is located left in the figure and Rotterdam to the right of the figure. [Deltares]
Figure 4.7: Principle of pumping vessels (RHDHV, 2015)
Figure 4.8: Effect of different mixing methods on salinity in the Rotterdam Waterway (Groenenboom and Veenstra, 2017) [Deltares]
Figure 4.9: Temporary mobile bubble screen in the Amsterdam-Rhine canal in the Netherlands in 2018 [Rijkswaterstaat]
Figure 4.10: Principle of bubble boats (Groenenboom and Kranenburg, 2016) [Deltares]
Figure 4.11: Effect of the location of a harbour, X, on saltwater intrusion length, L, for different estuary types (Roelfzema and van Os, 1978) [Deltares]
Figure 4.12: Relative lock exchange (U, red lines; see Section 2.5.3) and relative salt transport (Z, green lines) as a function of the relative gate open time [Deltares]
Figure 4.13: Canal Gent-Terneuzen (red) connecting the city of Ghent with the Western Scheldt [Google Earth] 57
Figure 4.14: Surface chloride continuous measurements at the Dutch-Belgian border (Sas van Gent) (black) with the annual mean concentration (blue) and 3-years mean summer concentration (purple) and the upward freshwater discharge (blue bars). The red lines are the limit values for the maximum 3-y summer mean and minimum annual required discharge. [Bikswaterstaat: https://waterberichtgeving.rws.pl/monitoring/tso-metingen/kanaal-gent-terpeuzen] 57
Figure 4.15: Relative lock exchange (U, red lines) as a function of the relative gate open time, showing an unprotected lock head (continuous lines) and a lock head with bubble screen (dotted lines). [Deltares]
Figure 4.16: New design of air injector for a closely packed air curtain (△-type) with evenly distributed air flux over the width of the lock entrance (Keetels et al. 2011) [Riikswaterstaat / Loes de Jong]
Figure 4.17: Results from in-situ measurements by Abraham et al. (1973) and Uittenbogaard et al. (2015a) combined, showing the salt transmission factor η as a function of Froude air number. Black dots show earlier field measurements of Abraham and Van der Burgh, red dots show combination of bubblescreen with water screen, blue dots show bubblescreen only and green dots show combination of bubble screen and sill. (Uittenbogaard et al., 2015a) [Deltares]

Figure 4.18: Bubble screen in the Krammer recreational lock. [Rijkswaterstaat / KeesJan Meeuse]	. 62
Figure 4.19: Principle of a sill at the landward lock gate. [Deltares]	. 63
Figure 4.20: Development of the lock exchange flow for different sill heights from a numerical model. Runs 1 -3 show increasing sill height [Deltares]	. 63
Figure 4.21: Figure showing the situation at the Kreekrak locks in the Netherlands with the freshwater bubble located on the southern side, along the canal towards Antwerp. [Rijkswaterstaat]	. 64
Figure 4.22 Principle of a salt buffer illustrated with a side view of a freshwater canal near a lock. Top: a salt buffer without retaining basin, below: a salt buffer with receiving basin [Deltares]	. 65
Figure 4.23 Principle of the reduction in velocity of the lock-exchange flow through flushing through the lock chamber as studied in van Beek (2021). The vertical black line indicates the initial location of the lock gate which is removed to initiate the lock exchange. The figures are contour plots of density with red indicating the initial density of saltwater and blue freshwater. Top an unhindered lock-exchange flow, middle flushing with velocity one half of the theoretical front velocity, bottom flushing with velocity equal to the theoretical front velocity [Deltares].	. 66
Figure 4.24: Two-dimensional salt screen in two-layer flow with design condition $B < 2/3$ hr. (based on Jirka (1979), reprinted by permission of the publisher (Taylor & Francis Ltd)). LHS the hydrostatic condition with $q = 0$, RHS the supercritical condition with $q = q1 + q2 > qc$, for $q1/q2$ the ratio of flow from the upper and lower layers respectively.	. 67
Figure 4.25: Selective withdrawal diagram for two-dimensional salt screen (from Jirka (1979), reprinted by permission of the publisher (Taylor & Francis Ltd))	. 68
Figure 4.26: Aerial view of the Koopvaarders shipping lock near Den Helder in the Netherlands [Google Earth, Rijkswaterstaat]	. 69
Figure 4.27: Principle of direct saltwater withdrawal at Terneuzen [Deltares / Rijkswaterstaat]	. 70
Figure 4.28: Withdrawal culverts during construction at the Terneuzen lock [Rijkswaterstaat]	. 70
Figure 4.29: Principle of saltwater withdrawal from a salt pit [Deltares / Rijkswaterstaat]	. 71
Figure 4.30: Operating principle of the syphon (Artelia, 2018) [Artelia]	. 71
Figure 4.31: The Krammer lock complex with two large locks and one small lock [Rijkswaterstaat]	. 73
Figure 4.32: Longitudinal and cross section of the large Krammer locks [Deltares / Rijkswaterstaat]	. 73
Figure 4.33: Locking cycle of the large Krammer locks [Deltares / Rijkswaterstaat]	. 75
Figure 4.34: View of the lateral wall openings and perforated floor of the large Krammer locks, during construction [Rijkswaterstaat]	. 76
Figure 4.35: Cross section of the slabs of the perforated lock floor of the large Krammer locks [Deltares / Rijkswaterstaat]	. 76
Figure 4.36: Cross & horizontal section of the wall openings of the large Krammer locks (Kerstma et al., 1994) [Deltares / Rijkswaterstaat]	. 77
Figure 4.37: Minimal mixing condition [Deltares / Rijkswaterstaat]	. 77
Figure 4.38: Saltwater sewers under construction at the large Krammer locks [Rijkswaterstaat]	. 78
Figure 4.39: Overview of the Krammer lock complex [Rijkswaterstaat]	. 78
Figure 4.40: Asymmetrical blocking due to moored ships in the lock chamber [Rijkswaterstaat]	. 79
Figure 4.41: The effect of asymmetrical blocking in the lock chamber on the salt-fresh boundary plane [Deltares / Rijkswaterstaat]	. 79
Figure 4.42: Concept of the seepage screen at the coastal zone of the Netherlands. Protecting the hinterland from salinisation of the agricultural lands. [Deltares]	. 80
Figure 5.1: Saltwater intrusion along the Rotterdam Waterway at high water slack with different stationary discharges of the river Rhine (van der Burgh, 1972) [Deltares]	. 84
Figure 5.2: Measured and iFlow modelled salinity along the Delaware, Scheldt and Columbia estuaries. (Wei et al., 2016) (© American Meteorological Society. Used with permission)	. 84
Figure 5.3: LES simulation of saltwater intruding into a lock chamber (Thorenz et al., 2018) [BAW]	. 89
Figure 5.4: Length section of the North Sea Canal from IJmuiden (left) to the IJ (right). The colours illustrate a possible salt profile of the North Sea Canal in a period with little upstream supply. [RWS]	. 90

Figure 5.5: Map if the Tidal Model Rijnmond M2000 [Deltares]	93
Figure 5.6: Top view model design. Left: Lock chamber, right: access channel (Atlantic side) with ship guidance structure (piles) [Flanders Hydraulics Research]	95
Figure 5.7: Example of a test with an approaching ship 2 (top), 5 (middle) and 10 minutes after opening the gate (full scale time) [Flanders Hydraulics Research]	95
Figure 5.8: Visualisation of surface flow velocity due to density driven lock exchange. The colours correspond to the time in minutes (full scale time) after opening the gate. [Flanders Hydraulics Research]	s 95
Figure 5.9: Layout of the Scaldis model including Belgian Coast, Eastern Scheldt and Western Scheldt Estuar Highest resolution and focus point of the model is the Upper Sea Scheldt. [Flanders Hydraulics Research]	ry. 99
Figure 5.10: Modelled and measured salinity in Sea Scheldt at Antwerp area. [Flanders Hydraulics Research]	99
Figure 7.1: Location of Guadalquivir estuary near Sevilla, Spain	. 104
Figure 7.2: Detailed satellite view of the estuary	. 105
Figure 7.3: Pumping station for rice fields at the Guadalquivir shore	. 106
Figure 7.4: Location of the installed CTDs	. 106
Figure 7.5: Annual minimum, average and maximum salinity	. 106
Figure 7.6: Bathymetry of the study area and the high resolution finite element mesh used for the Guadalquivi estuary model, which used 7,000 nodes in 9 vertical layers based on Z vertical coordinate.	r . 107
Figure 7.7: (Upper panel) A comparison of modelled (black line) and real values (dots) of tidal amplitude and phase of several tidal constituents and distances (km) from the estuary mouth. (Lower panel): Mean salinity modelled values (black line) and real average values (dots) obtained from different sources, such as scientific literature and local government institutions. The model results show a good agreement with in situ	
measurements	. 108
Figure 9.1: Cross section of the Dunkirk lock (PIANC, 1986)	. 111
Figure 9.2: Difference between the Dunkirk lock (freshwater sewers) and Krammer/Kreekrak locks (enfolding freshwater with short conduits) (Kerstma et al., 1994)	. 111
Figure 9.3: Principle of the 'saltwater lock' in the freshwater sewers of the Dunkirk lock (Kerstma et al., 1994) Deltares / Rijkswaterstaat	. 112
Figure 9.4: Double valve system in the lateral wall openings of the Kreekrak locks (Kerstma et al., 1994) Deltares / Rijkswaterstaat	. 112
Figure 9.5: Simplified Dunkirk system. [Deltares / Rijkswaterstaat]	. 112
Figure 9.6: Transverse freshwater with longitudinal saltwater withdrawal – system 1. [Deltares / Rijkswaterstaat]	. 113
Figure 9.7: Longitudinal freshwater with transverse saltwater withdrawal – system 2. [Deltares / Rijkswaterstaat]	. 113
Figure 9.8: Longitudinal section of the small Krammer recreational locks [Deltares / Rijkswaterstaat]	. 114
Figure 9.9: Locking cycle of the small Krammer recreational locks [Deltares / Rijkswaterstaat]	. 114
Figure 9.10: Freshwater loss in case of high blockage vessels close to the saltwater intake, cf. small Kramme recreational locks [Deltares / Rijkswaterstaat]	r . 115
Figure 9.11: Schematical longitudinal and cross section of the Bergsediep lock (system 2) [Deltares / Rijkswaterstaat]	. 115
Figure 9.12: Locking cycle of the Bergsediep locks [Deltares / Rijkswaterstaat]	. 116
Figure 9.13: Longitudinal section of the Bergsediep locks Deltares / Rijkswaterstaat]	. 116
Figure 9.14: Influx of freshwater in case of adjustable lifting gates in the Bergsediep locks [Deltares / Rijkswaterstaat]	. 117
Figure 9.15: Double lock with intermediate separation wall [Deltares / Riikswaterstaat]	. 118
Figure 9.16: Principle of the saltwater container lift [Deltares / Riikswaterstaat]	. 118
Figure 9.17: Locking cycle of the saltwater container lift [Deltares / Riikswaterstaat]	. 119
Figure 10.1: Branch-Mouth relations [Deltares]	. 120

LIST OF TABLES

Table 2.1: Estuary types based on estuary number N or stratification n	. 17
Table 4.1: Approximate effectiveness of different measures	81
Table 5.1: Design and construction steps of physical and numerical models	96
Table 5.2: Principal and practical limitations of physical and numerical models	96
Table 7.1: Maximum allowable drafts at different tides	105
Table 7.2: Parameters used in the barotropic model calculations	107
Table 8.1: Comparison of effectiveness of mitigation measures	110
Table 10.1: Examples of presently used software packages	123