Hydrosedimentology and hydrodynamics (2009-2010)

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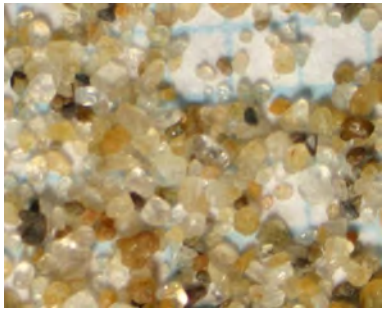
Hans Albert Einstein (°1904 - +1973)

“ My son! Whilst I appreciate you’ve chosen to specialize yourself in hydraulics and sediment-dynamics, I wonder if you couldn’t find something more complicated!? When you are about to find a solution, the phenomenae seem to escape every logic and you have to start all over again. Why don’t you specialize in something easier and simpler…like relativity, for instance?”

(Albert Einstein to his son, Hans Albert Einstein on his PHD’s graduation)

Dredging operation = the disruption of the cohesion of aquatic soils (sediments, rocks,…) + transport of debris + disposal

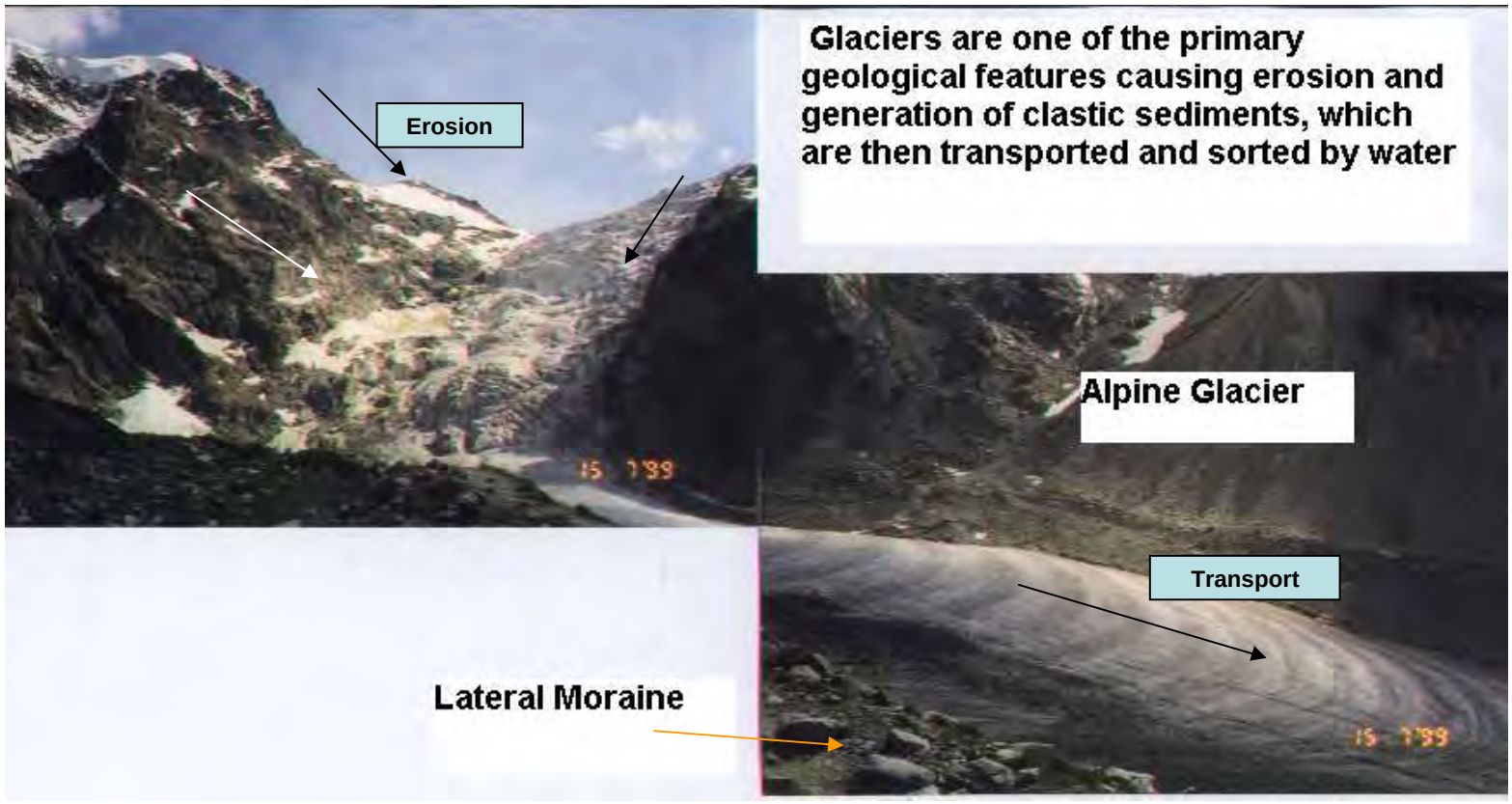
Dredged Materials: mainly 3 types

Cohesive sediments: Clay & Silts	Granular sediments: Sand	Granular sediments: gravel, boulders, . . .	Soft Rock
			
d50 < 63 µm	63 µm < d50 < 2 mm	2 mm < d50	UCS < 50 MPa

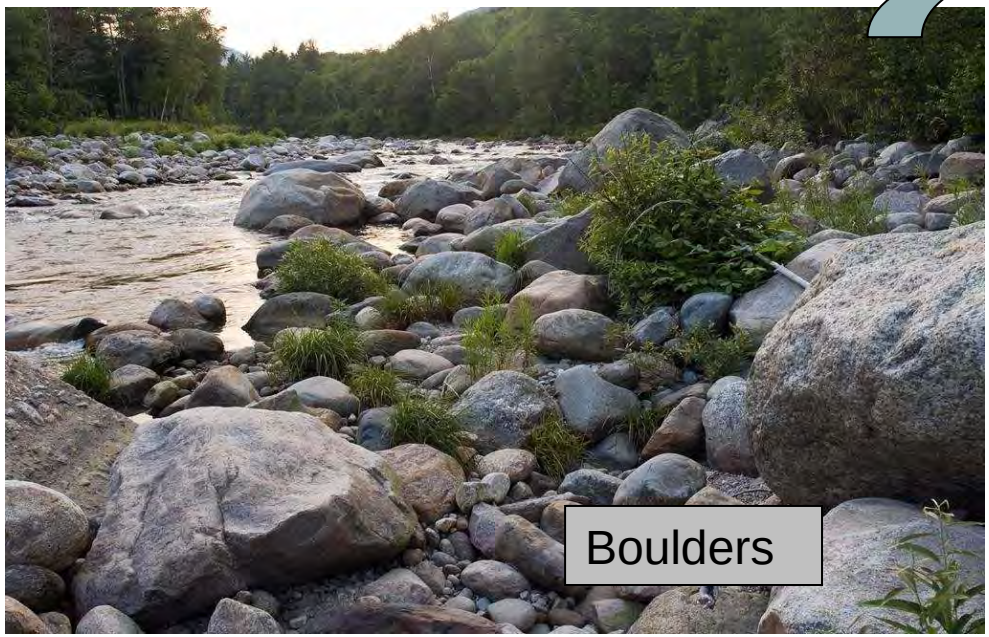
In hydraulic dredging the maximum allowable grain-size diameter of dredged materials is determined by the spherical aperture of the dredge pumps.

SEDIMENTS ARE GENERATED BY GEOLOGICAL EROSION AND CLASTIC PROCESSES OF IGNEOUS, METAMORPHIC OR SEDIMENTARY ROCKS:

SEDIMENTS ARE THEN TRANSPORTED BY ICE, WATER OR WINDS



Rivers continue the sedimentological sorting mechanism: sorting by size and/or density



The process of sorting continues downstream in rivers and estuaries

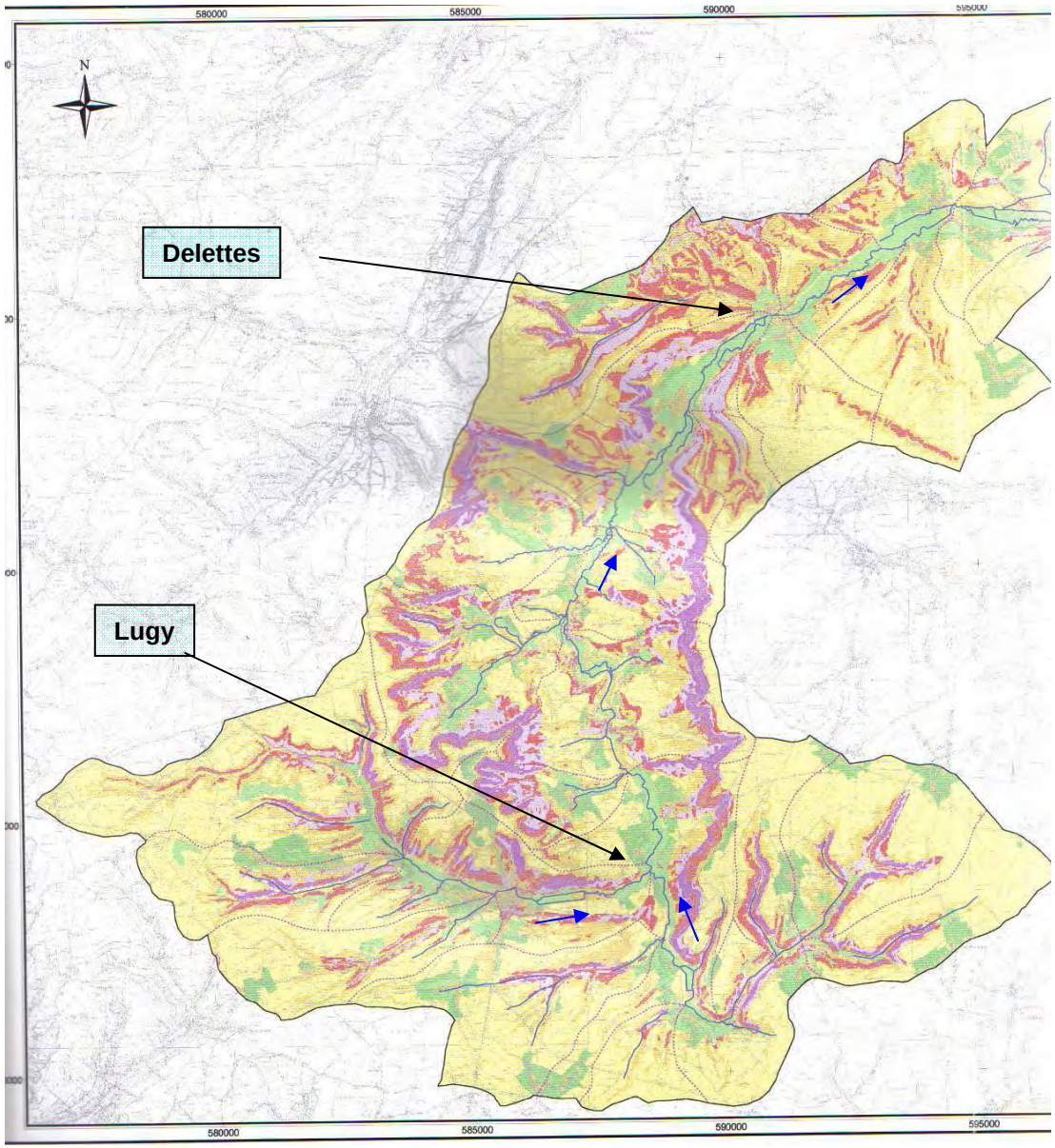
Schelde & Maas Estuarium

- **www.digitale-satellietbeelden.nl**

Sandbanks in Dorset, UK

Mudflats in Albany, California

SEDIMENT SUPPLY TO RIVER BY RUN-OFF



Aires s/l Lys

Case: Upper-Lys in France

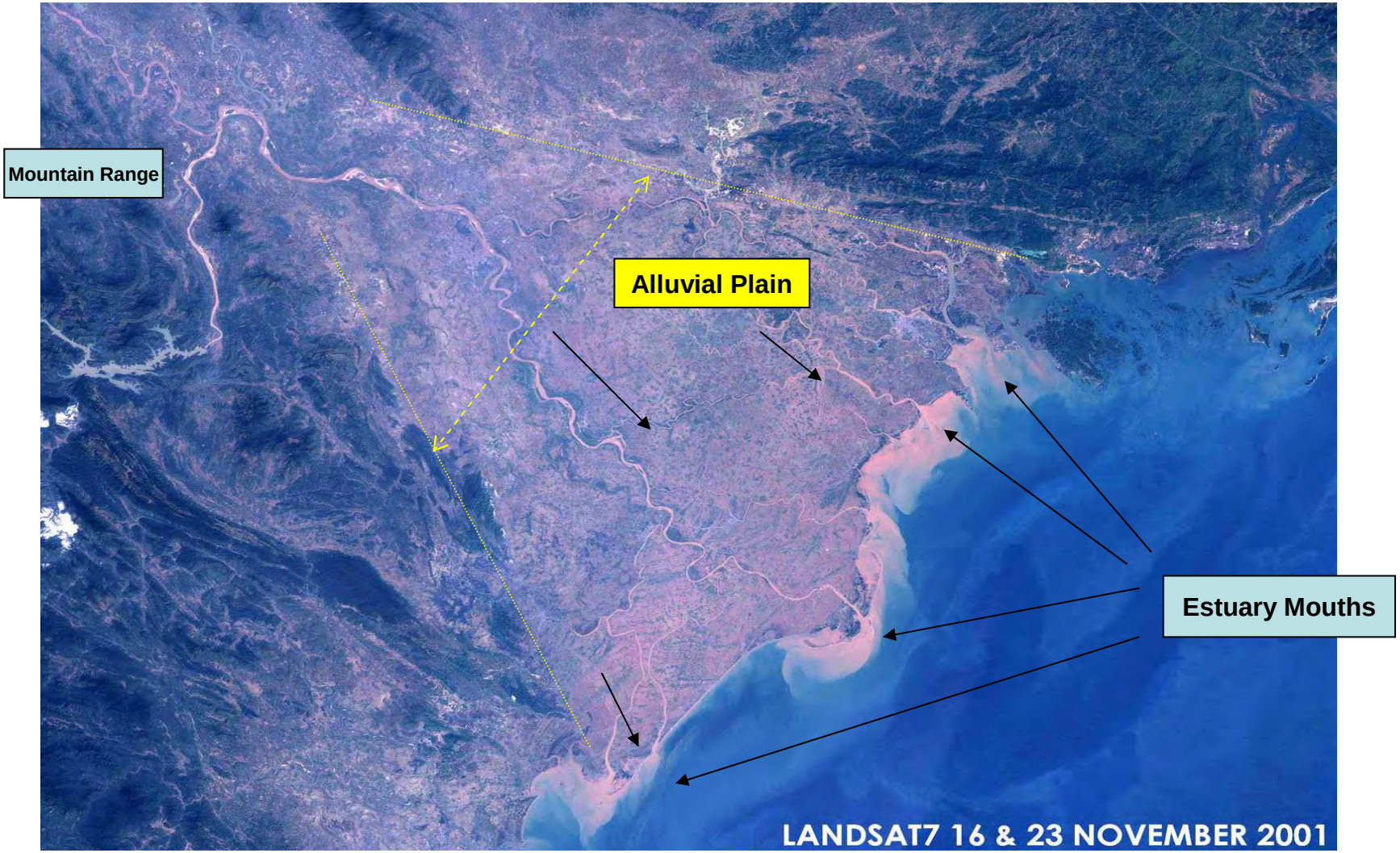
Map with Run-Off Coefficient RuC for Summer-conditions (Symsagel-Haecon, 2004)

Pink: RuC > 0,60

Yellow: 0,25< RuC<0,60

Green: RuC < 0,25

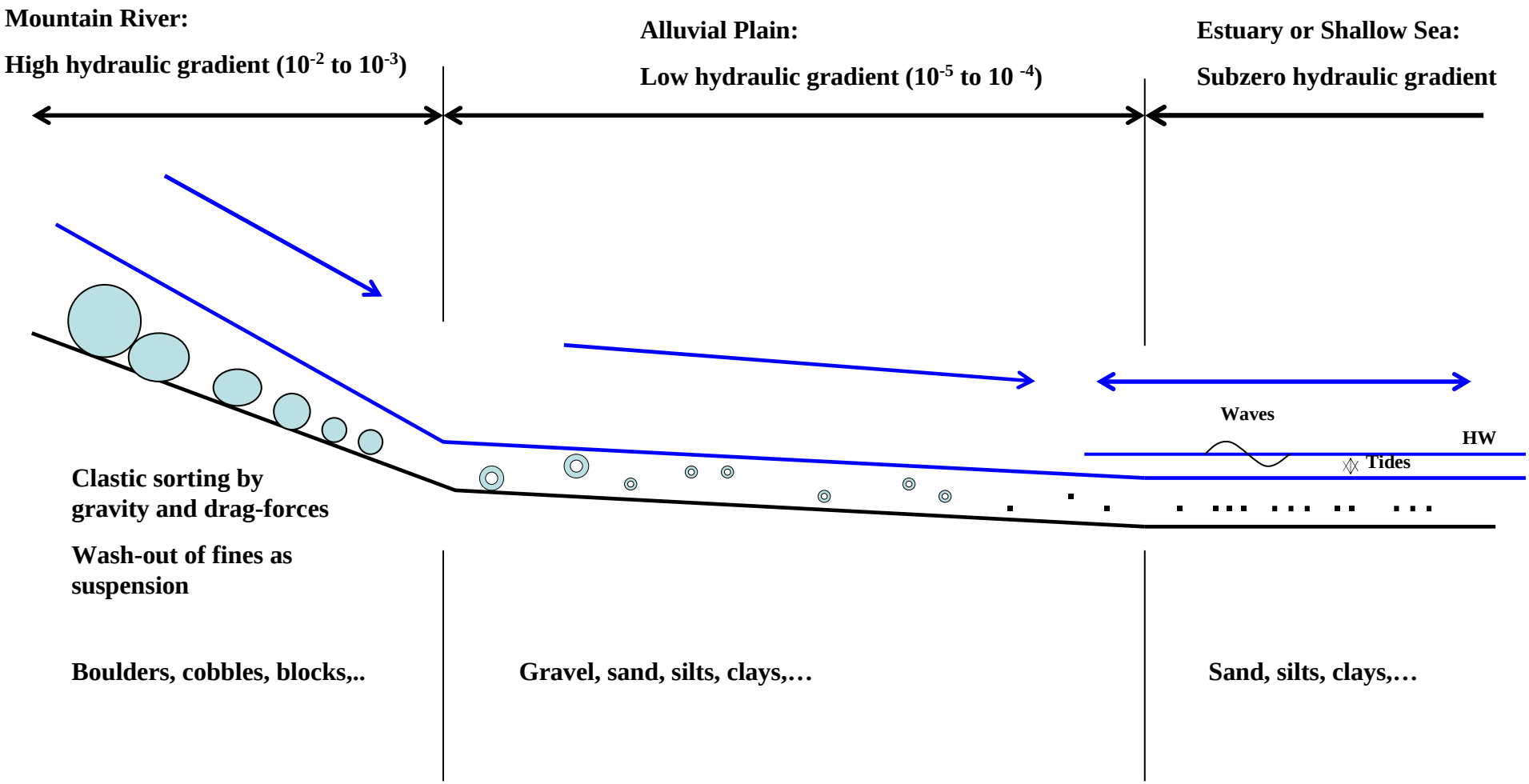
Transport of sediments than happens mainly by the water in the river-shed (River Basin), from erosion area to Alluvial Plain and finally to Estuary.



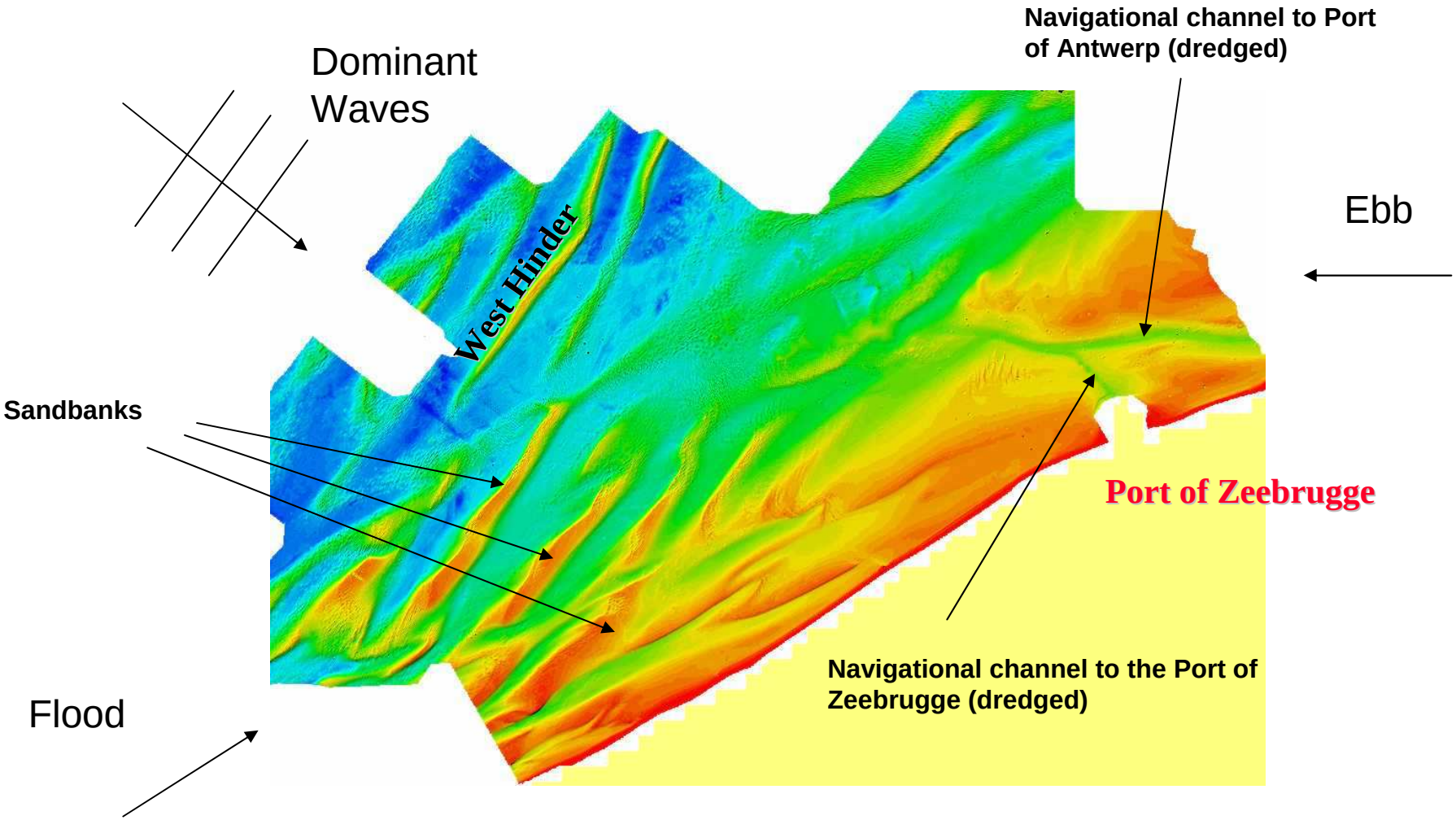
Sediment-transport in alluvial plain of rivers is governed by river-discharge and tidal effect of ebb- and flood: mainly flow, density currents,…

Here Rio Parana (Argentina) with high suspended solid concentrations (between 0,300 and 0,900 kg d.s. /m3)

Sediments are constituted of grains, particles, mainly the result of clastic weathering processes and of hydrodynamic sorting



Sediments are morphologically shaped by the (residual) hydraulic forces – currents, waves,…- and detailed cartography allows to get insight in the equilibrium of the system



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ESTUARIES: THE DISCHARGE OF SEDIMENTS TO OPEN SEAS

Mekong Delta, S Viet Nam

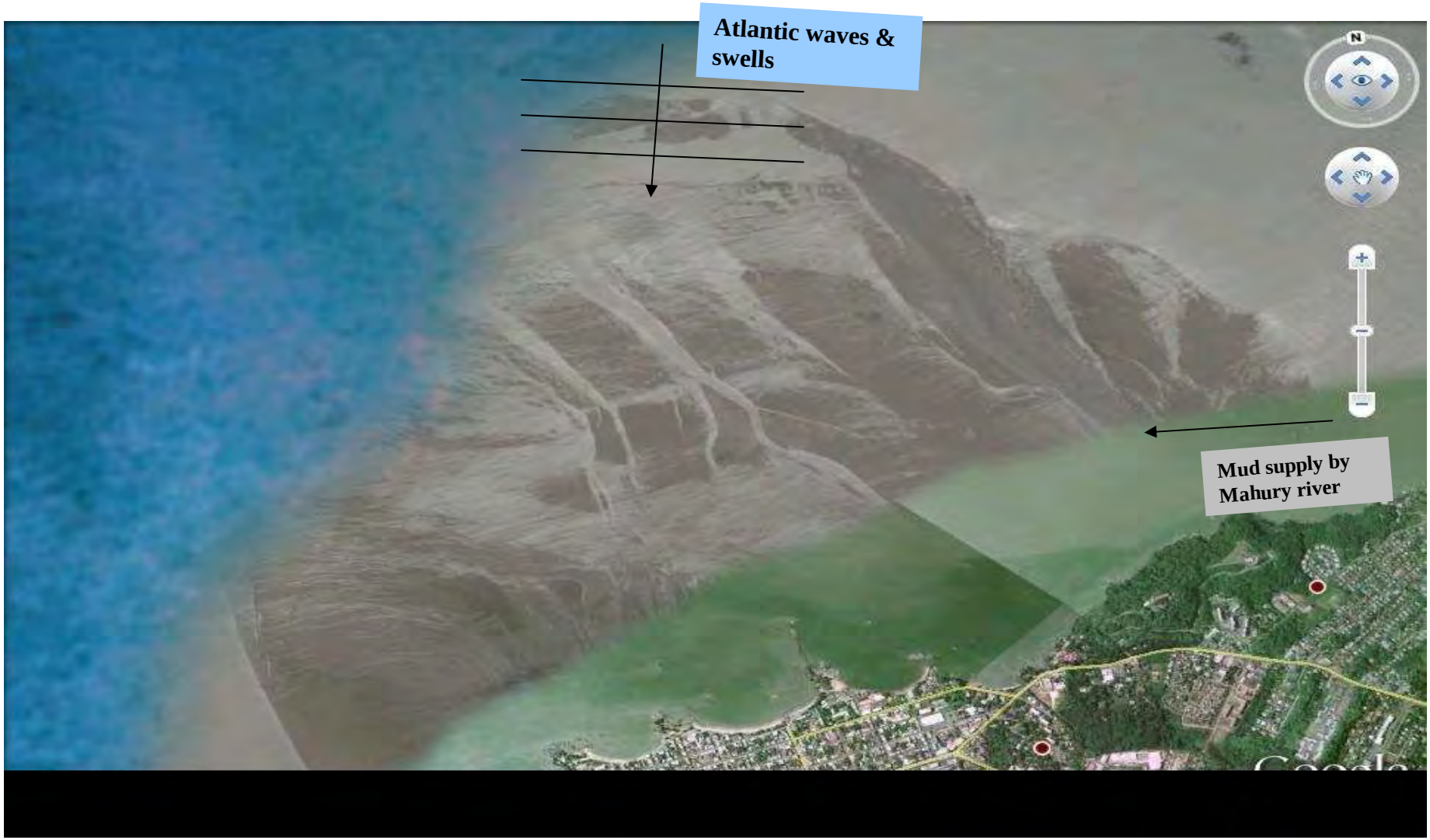
(Bassac River)

SEDIMENTS ARE REDISTRIBUTED BY TIDAL CURRENTS AND WAVES TO FORM COASTLINES

WHERE MUDDY SEDIMENTS PREDOMINATE, MUDFLATS AND MUDBANKS SHAPE THE COASTLINES

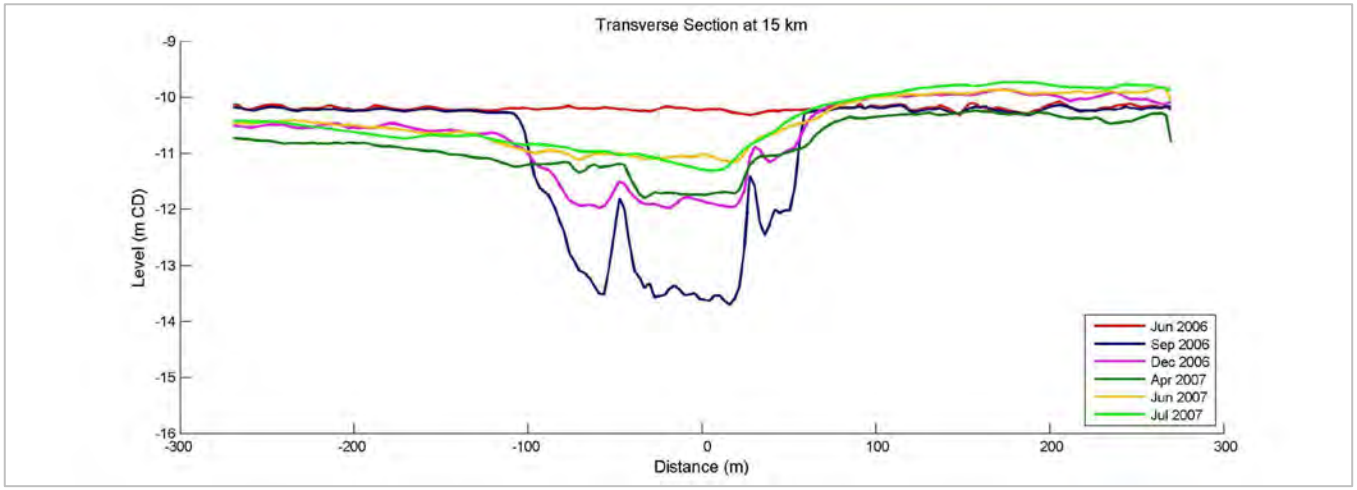
Atlantic Coastline in Suriname

Mudflats and Mudbanks



Guyane Française

Sediment-Dynamics will induce sedimentation in Access-Channels



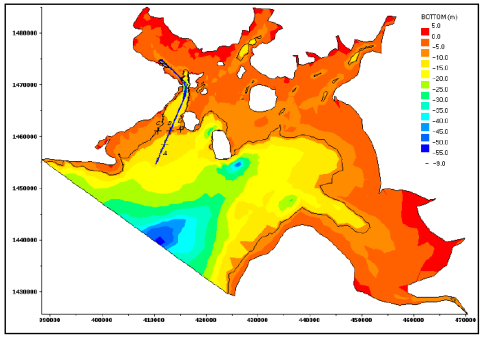
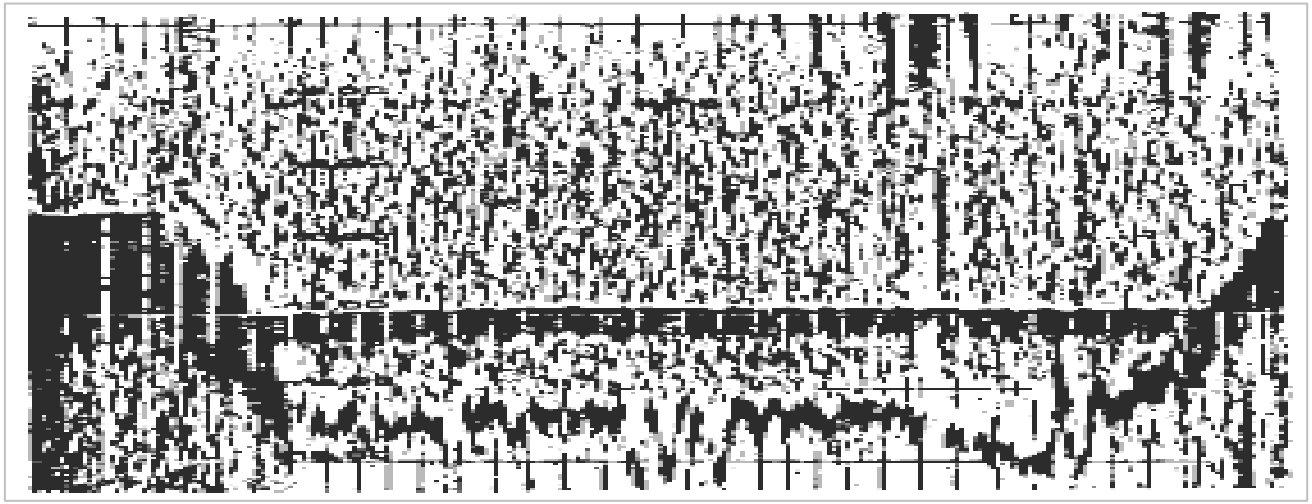
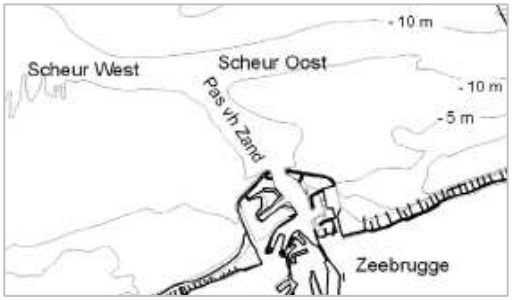


Figure 4 TELURAY model bathymetry showing location of proposed channel and nearshore wave climate prediction points

Cutuco Port, El Salvador





Zeebrugge Port, Belgium

Sediment management in dredging: use of characteristics of sediments for proper management. Landfills, beach restaurations, disposal upland, aquatic disposal,…

Land reclamation with medium sand (Abu Dhabi)

Beach restauration with fine sand (De Haan, Belgium)

Upland disposal of silt: consolidation (Singapore)

CHARACTERIZATION AND PHYSICAL PROPERTIES OF SEDIMENTS

Sediments are characterized by a number of parameters, that will also determine their physico-chemical behaviour:

Parameters:

- **Mineralogy**
- **Grain-size distribution**
- **Packing and in-situ volume-mass (or density)**
- **….**

Physical Properties:

- **Shear-strength, erosion-sensitivity,…**
- **Flow behaviour**
- **Flocculation potential and settling/consolidation behaviour**
- **Bearing capacity**
- **….**

Chemical Properties

- **Redox- potential and fermentation/micro-biological processes**
- **Adsorption-potential (for metals, contaminants, cation-exchange,…**
- **….**

Main characteristics of sediments

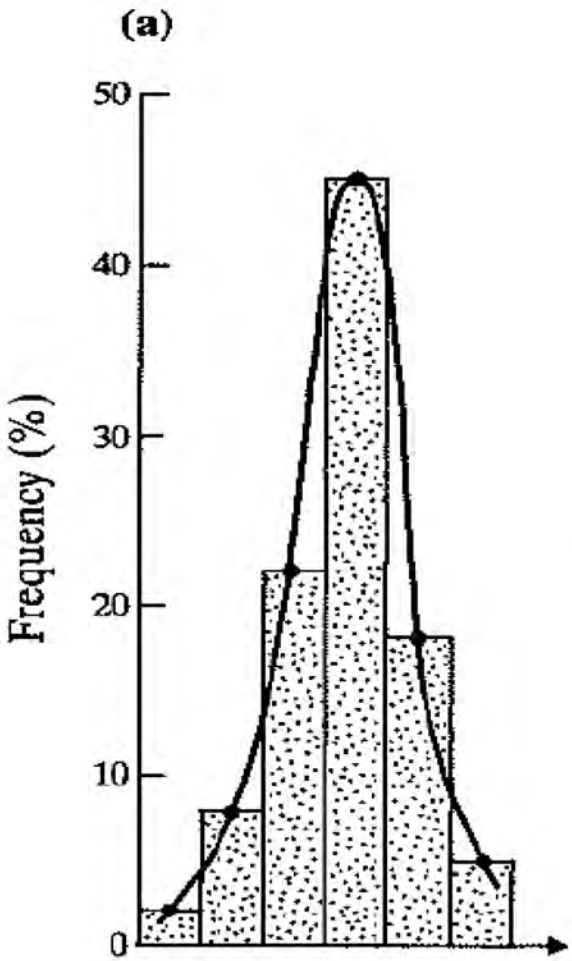
1. **Grain- size and grain - size distribution**
2. **Mineralogy of individual particles (minerals, hardness, specific density,. ..)**
3. **Bulk water-content (w in %) , c.q. in-situ (water-saturated) volume-mass (ρ_{sat} in kg/ m3) or dry - weight volume – mass (ρ_d in kg d.s./m3)**
4. **Roundness and shapes of particles**
5. **Shear-strength: rheologic characteristics (initial rigidity, viscosity, thixotropy): for cohesive sediments**
6. **Decantation and (primary) consolidation**
7. **Erosion-sensitivity**

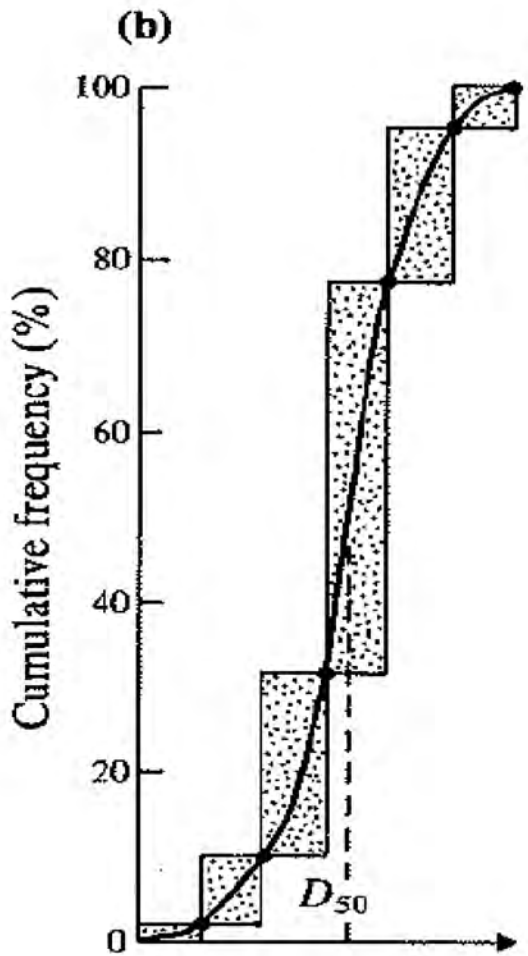
Mineralogy and specific characteristics of sediment-constituents (inspired from J.R.L Allen, 1997)

Table 2.1 Density of common minerals (solids density) and rocks (bulk density).

Name	Formula	Density (kg m^{-3})	Hardness (Moh's)
Common minerals			
aragonite	$CaCO_3$	2930	
biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	2800–3400	
calcite	$CaCO_3$	2710	5
dolomite	$CaMg(CO_3)_2$	2870	
gypsum	$CaSO_4 \cdot 2H_2O$	2320	3
microcline	$KAlSi_3O_8$	2560	
muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	2800–2900	
orthoclase	$KAlSi_3O_8$	2550	
plagioclase series	$(Na,Ca)(Al,Si)AlSiO_2O_8$	2620–2760	7
quartz	SiO_2	2650	
Accessory minerals			
apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	3100–3250	
corundum	Al_2O_3	3990	
epidote	$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$	3250–3500	
fluorite	CaF_2	3180	
garnet group	$(Fe,Al,Mg,Mn,Ca,Cr)_5(SiO_4)_3$	3560–4320	
haematite	Fe_2O_3	5270	
hornblende	$NaCa_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$	3000–3470	
ilmenite	$FeTiO_3$	4790	
kyanite	Al_2SiO_5	3670	
monazite	$(Ce,La,Y,Th)PO_4$	5270	
olivine series	$(Mg,Fe)_2SiO_4$	3210–4390	
pyrite	FeS_2	5020	
pyroxene group	$(Ca,Mg,Fe)_2(Si,Al)_2O_6$	3200–3550	
rutile	TiO_2	4250	
staurolite	$FeAl_4Si_2O_{10}(OH)_2$	3700	
tourmaline	$Na(Mg,Fe)_3Al_6(BO_3)_3(Si_6O_{18})(OH)_4$	3030–3100	
zircon	$ZrSiO_4$	4670	
Clay minerals			
kaolinite	$Al_4Si_2O_5(OH)_4$	2600	
illite	$KAl_2(AlSi_3O_{10})(OH)_2$	2800–2900	
chlorite series	$(Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$	2600–3300	
smectite	$Al_2Si_4O_{10}(OH)_2 \cdot nH_2O$	2000–2700	
Rock types			
diorite		2720–2960	
gabbro		2850–3120	
gneiss		2660–2730	
granite		2520–2810	
granodiorite		2670–2790	
sandstone		2170–2700	
schist		2700–3000	
slate		2720–2840	

Grain-size distributions of sedimentary particles



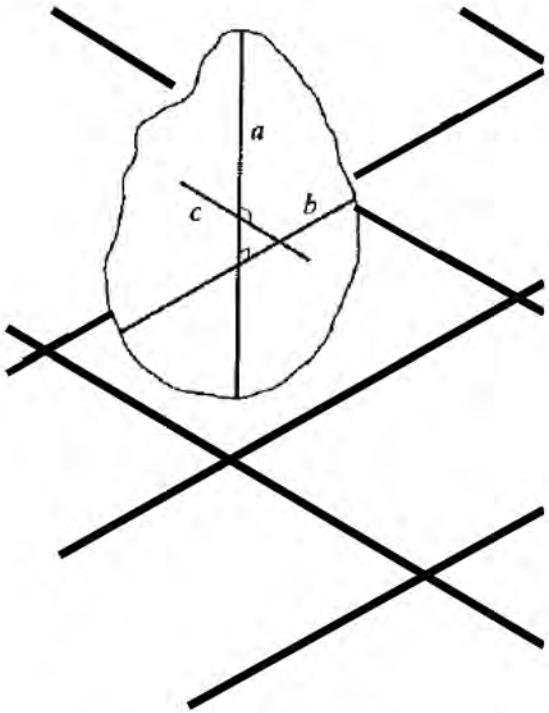


Increasing grain-diameter D

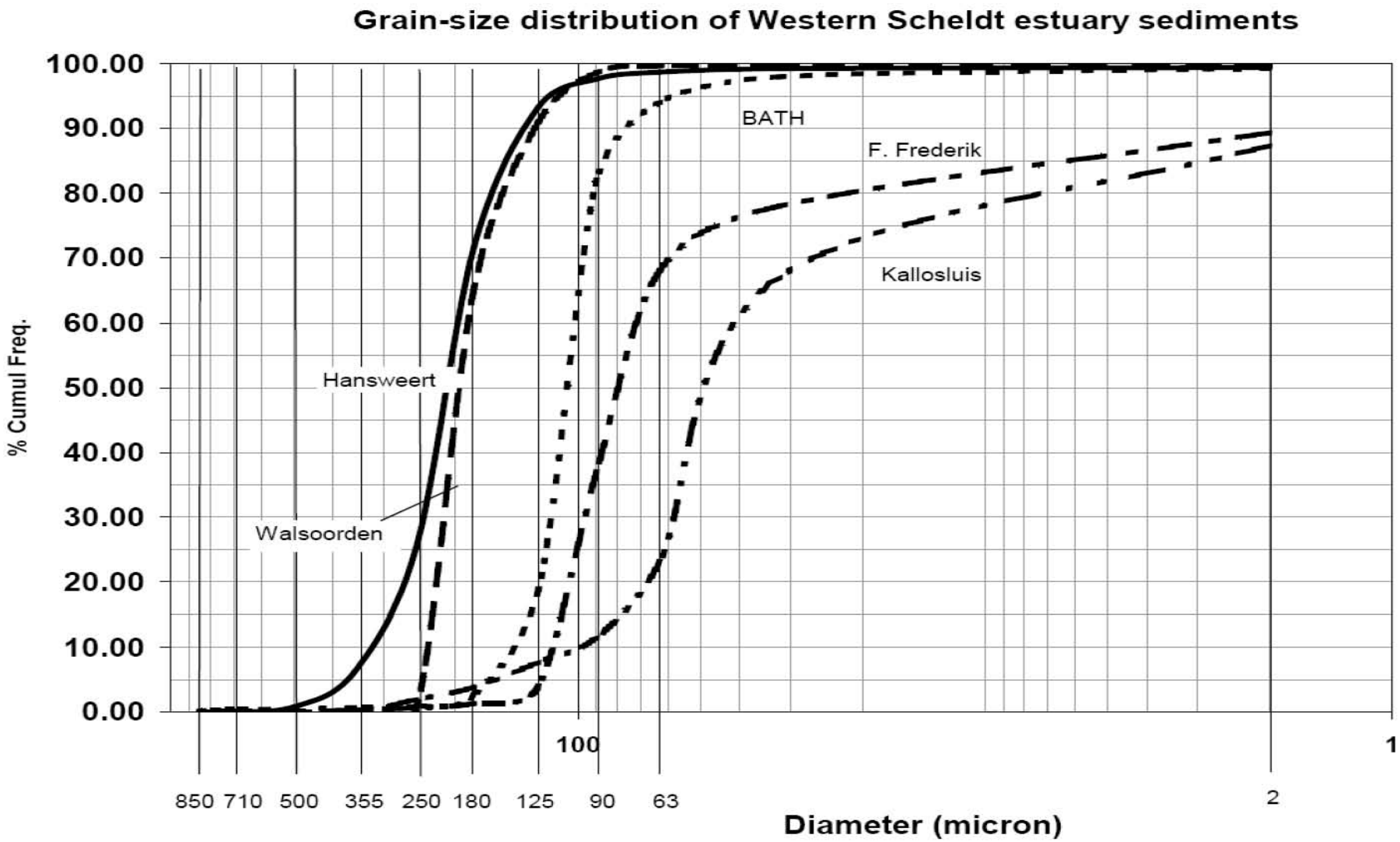
Increasing grain-diameter D

Increasing grain-diameter D

The 3 dimensions of an irregular sedimentary grain



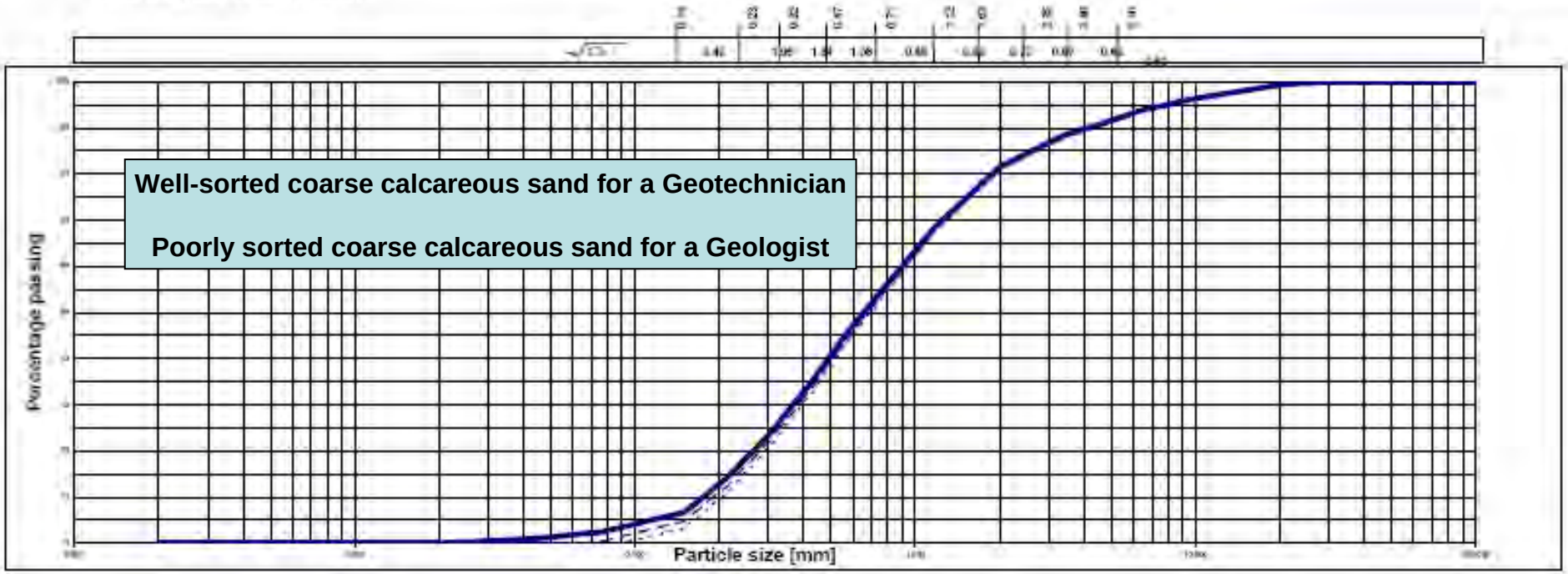
Examples of Grain-size distributions from Uniform Medium Sand to Mud (in Sedimentology sciences: from coarse to fine)



In Geotechnical sciences grain-size distributions are given from fine to coarse !!

Sieve analyses Dubai TSHD.xls

15/10/20



Clay	Silt 2%			Sand 79.5%			Gravel 18.5%			C & B
0%	fine 0%	medium 0%	coarse 2%	fine 10.9%	medium 34.4%	coarse 34.2%	fine 11.7%	medium 6%	coarse 0.7%	0%

1			d_{50} [mm]	dmf [mm]	$\sqrt{C_c}$	ψ	$\sqrt{C_c}$ old
full sample		———	0.654	1.124	1.413	0.814	1.185
without fraction < 0.09 mm	3.5%	- - - - - -	0.691	1.177	1.341	0.843	1.231
without fraction < 0.063 mm	2%	– – – – –	0.675	1.154	1.379	0.831	1.379
reduced fraction < 0.14 mm reduced to 20%	6.3%	—·—·—	0.654	1.124	1.413	0.814	1.185

AASHTO material designation

Size in millimeters	Size class
500	Cobbles
76.2	Coarse Gravel
19.05	Fine Gravel
4.75	Coarse Sand
2.0	Medium Sand
0.425	Fine Sand
0.075	Silt or Clay

Udden-Wentworth scale

Size in millimeters	Size class
4096	Boulder
256	Cobble
64	Pebble
4	Granule
2.0	Very Coarse Sand
1.0	Coarse Sand
0.5	Medium Sand
0.25	Fine Sand
0.125	Very Fine Sand
0.0625	Coarse Silt
0.031	Medium Silt
0.0156	Fine Silt
0.0078	Very Fine Silt
0.0039	Clay
0.002	

Generally adopted grain-size classification systems

Descritive Terms derived from Graphic Granulometry

Grain Size: (from graphic mean)

- boulder -12 to -8 phi
- cobble -8 to -6 phi
- pebble -6 to -2 phi
- granular -2 to -1 phi
- very coarse grained -1 to 0.0 phi
- coarse grained 0.0 to 1.0 phi
- medium grained 1.0 to 2.0 phi
- fine grained 2.0 to 3.0 phi
- very fine grained 3.0 to 4.0 phi
- coarse silt 4.0 to 5.0 phi
- medium silt 5.0 to 6.0 phi
- fine silt 6.0 to 7.0 phi
- very fine silt 7.0 to 8.0 phi
- clay 8.0 phi and smaller

Sorting: (from inclusive graphic standard deviation)

- very well sorted under 0.35 phi
- well sorted 0.35 to 0.50 phi
- moderately well sorted 0.50 to 0.71 phi
- moderately sorted 0.71 to 1.0 phi]
- poorly sorted 1.0 to 2.0 phi
- very poorly sorted 2.0 to 4.0 phi
- extremely poorly sorted over 4.0 phi

Sorting skewness: (from inclusive graphic skewness)

- strongly fine-skewed +1.00 to +0.30
- fine-skewed +0.30 to +0.10
- near symmetrical +0.10 to -0.10
- coarse-skewed -0.10 to -0.30
- strongly coarse skewed -0.30 to -1.00

Sorting kurtosis: (from graphic kurtosis)

- very platykurtic under 0.67
- platykurtic 0.67 to 0.90
- mesokurtic 0.90 to 1.11
- leptokurtic 1.11 to 1.50
- very leptokurtic 1.50 to 3.00
- extremely leptokurtic over 3.00

US Standard Sieve Mesh	Opening in millimeters	Phi Scale
	4096	-12
	1024	-10
	256	-8
	64	-6
	16	-4
5	4	-2
10	2.00	-1.0
18	1.00	0.0
35	0.50	1.0
60	0.25	2.0
120	0.125	3.0
230	0.0625	4.0
325	0.044	4.5
	0.031	5.0
	0.0039	8.0
	0.00006	14.0

Graphic Mean

$$M_z = \left(\frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}\right)$$

Inclusive Graphic Standard Deviation

$$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

Inclusive Graphic Skewness

$$SK_I = \frac{\phi_{16} + \phi_{84} - 2(\phi_{50})}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2(\phi_{50})}{2(\phi_{95} - \phi_5)}$$

Kurtosis

$$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$$

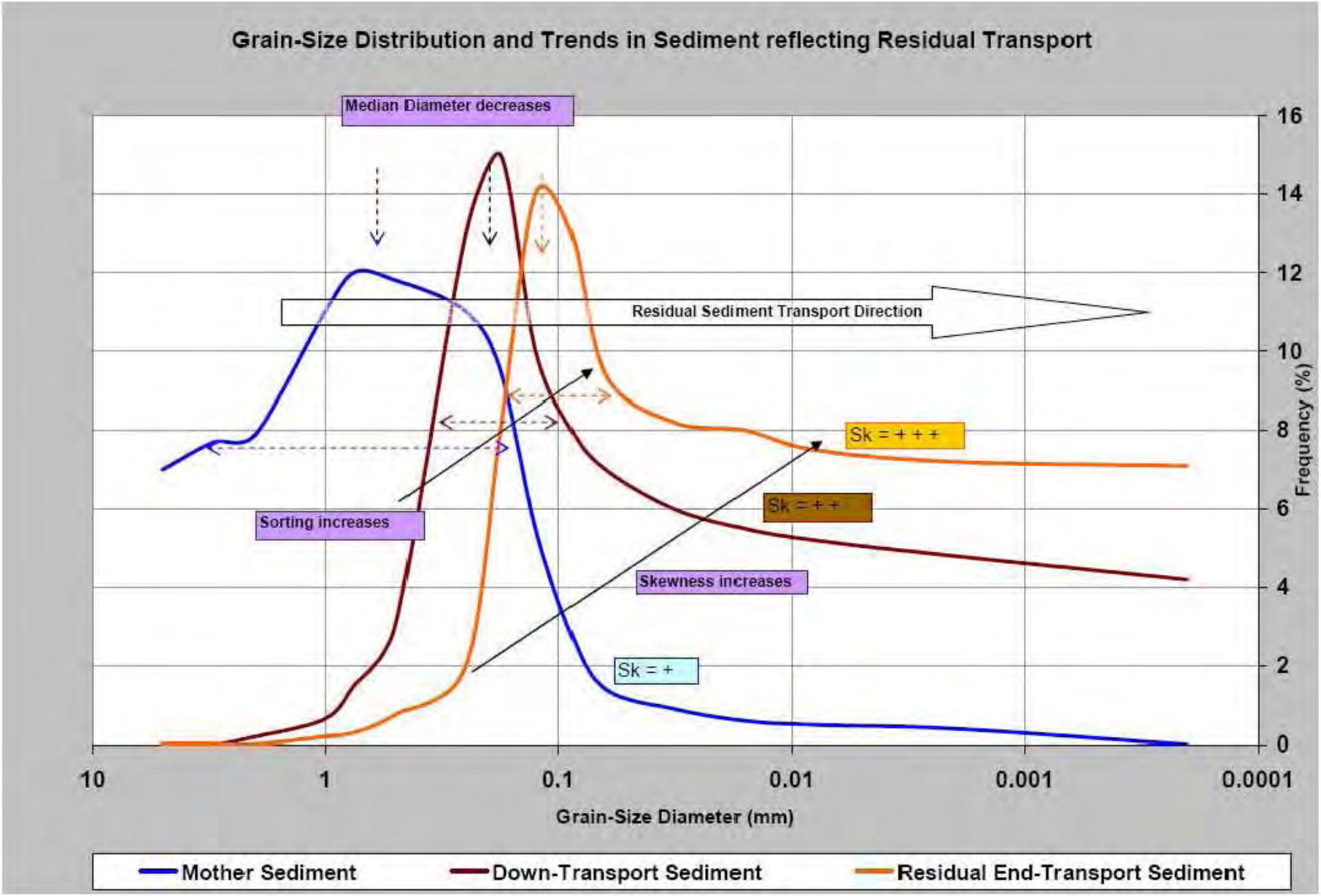
Concept of Sediment Maturity

Sediment maturity is a measure of **distance/time** from the source area to the depositional site. A lot of factors play in here, especially the climatic condition of weathering and transport and the mineralogical make up of the source area rock. As a general rule the greater the transport distance and the greater the length of time in the transport medium the more mature a resultant sediment becomes. Maturity can be gauged in terms of texture ***(textural maturity***), mineralogy (***minerologic maturity)***, and composition (***compositional maturity***). The terminology we use to describe maturity is relatively simple**: immature, submature, mature, and supermature**.

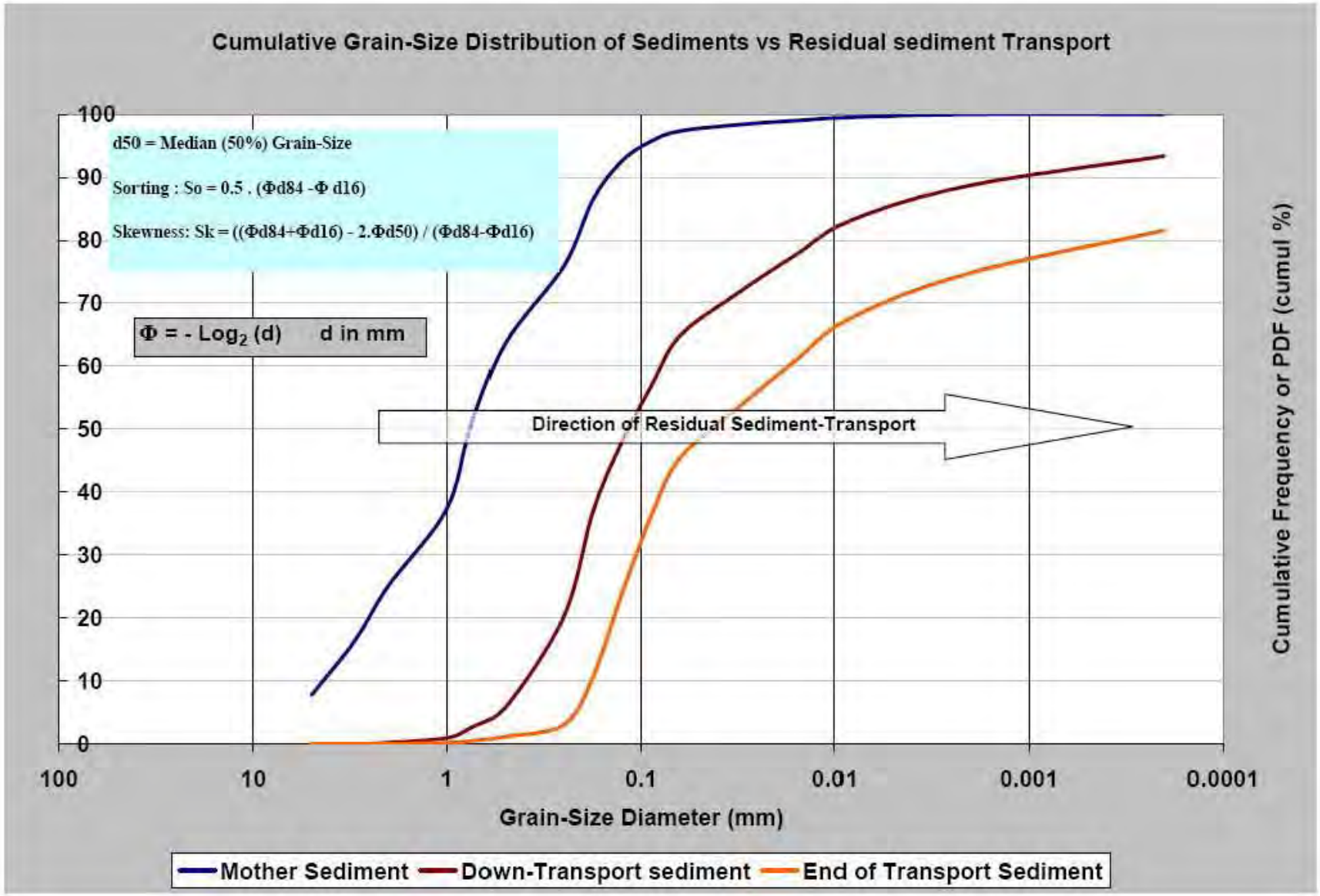
Textural maturity is gauged largely in terms of grain size, grain sorting, and grain roundness. At a source site the weathering process tends to generate a wide range of grain sizes but generally big chunks. And these tend to have a rough or angular exterior. The maturation process makes big things smaller up to a point that is. Grains of medium sand size tend to resist further size reduction. The maturation process also knocks of the ruff edges reducing the grain exterior to a smooth or rounded surface. Therefore:

	Immature	**Submature**	**Mature**	**Supermature**
Sorting	Extremely poorly sorted to very poorly sorted	poorly sorted to moderately sorted	moderately well sorted to well sorted	very well sorted
Grains Size	very coarse or bigger	coarse	medium	Medium
Roundness	Angular	subangular	rounded	well rounded

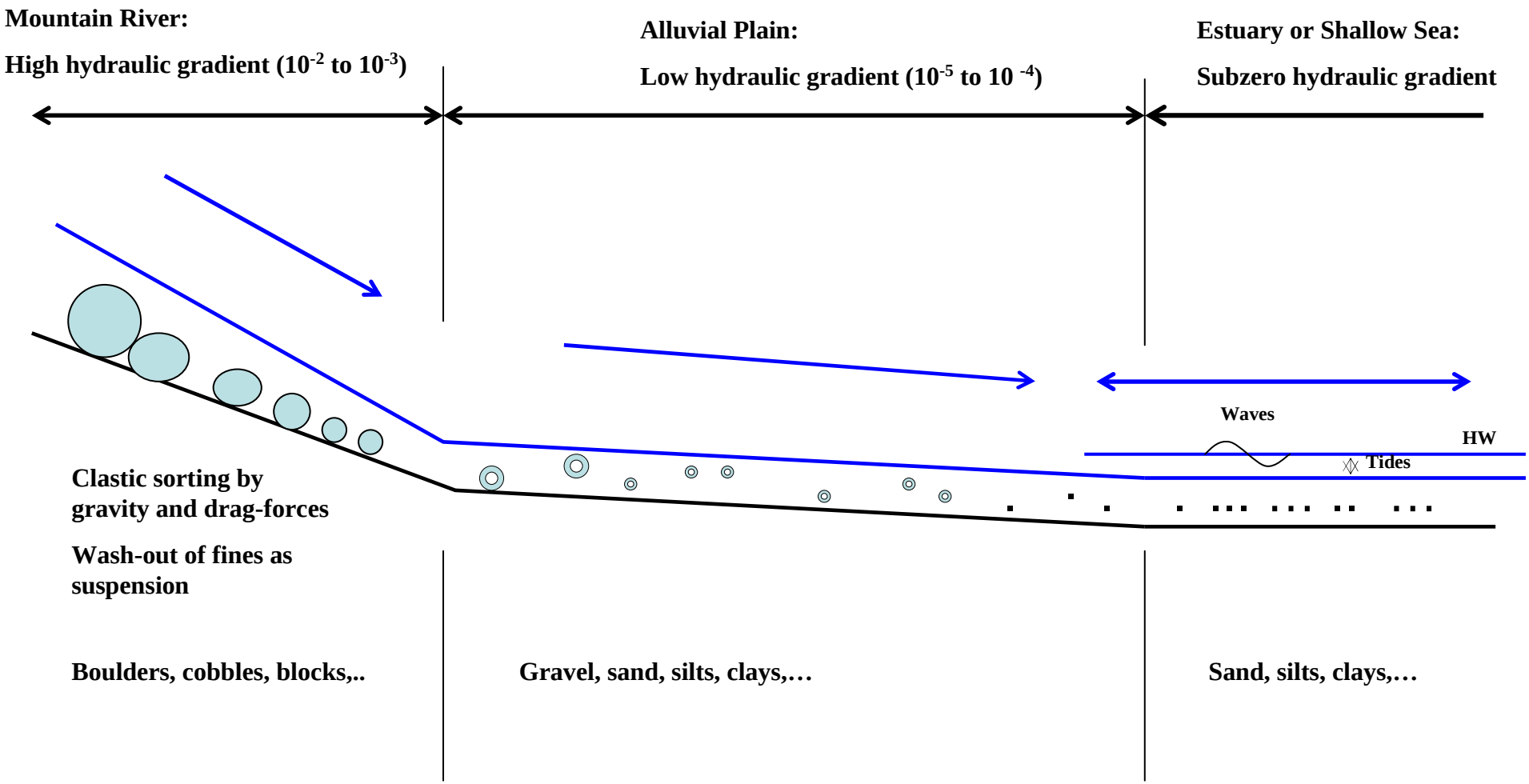
TREND IN GRAIN-SIZE DISTRIBUTION REFLECTING RESIDUAL SEDIMENT-TRANSPORT



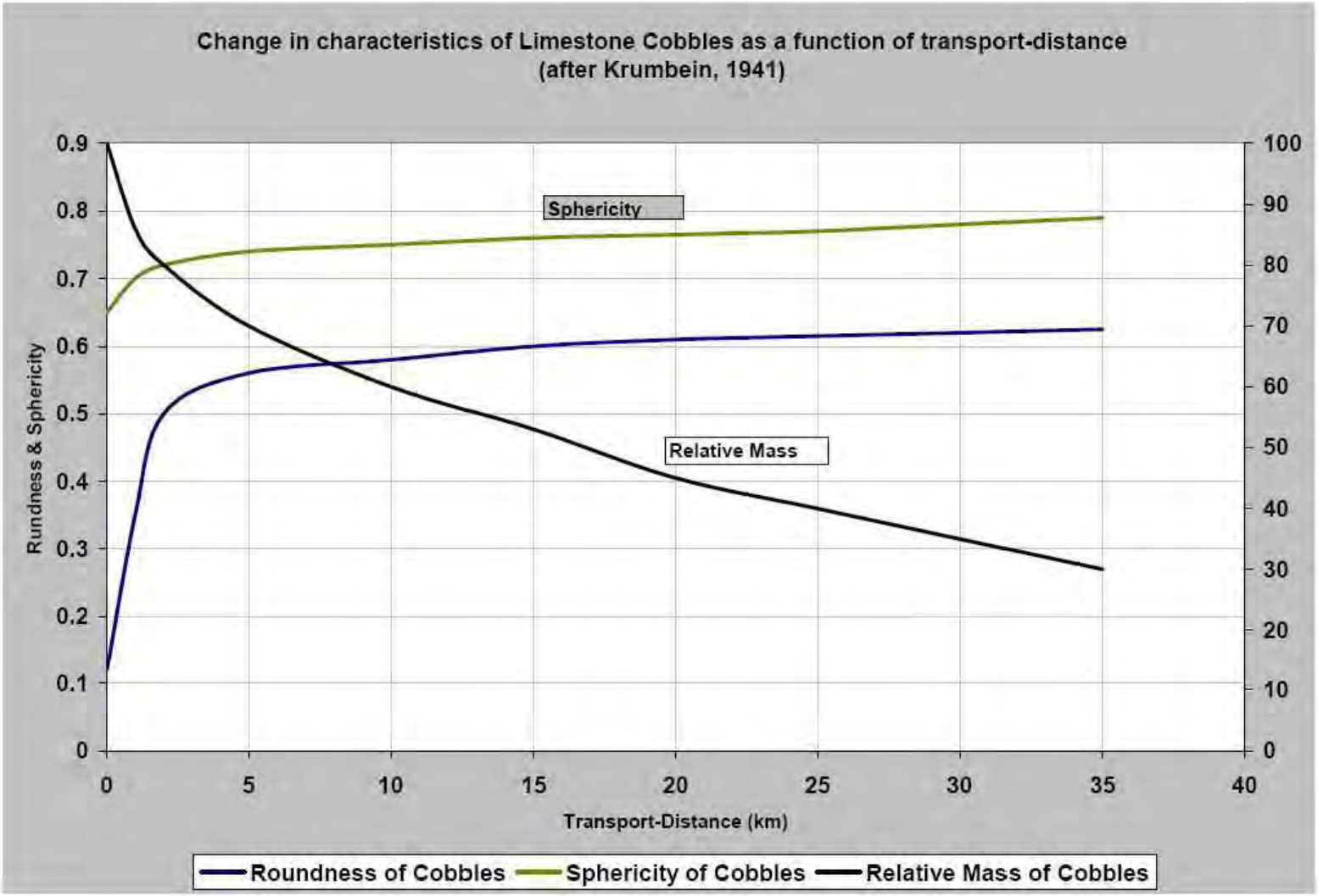
TRENDS FOR CUMULATIVE GRAIN-SIZE DISTRIBUTIONS



Sediments are constituted of grains, particles, mainly the result of clastic weathering processes and of hydrodynamic sorting



CHANGE OF ROCK-DEBRIS ALONG TRANSPORT-PATH



Shapes of sedimentary particles (after J.R.L. Allen)

(a) Oölite sand

(b) Quartz sand

(c) Abraded pumice sand (lava)

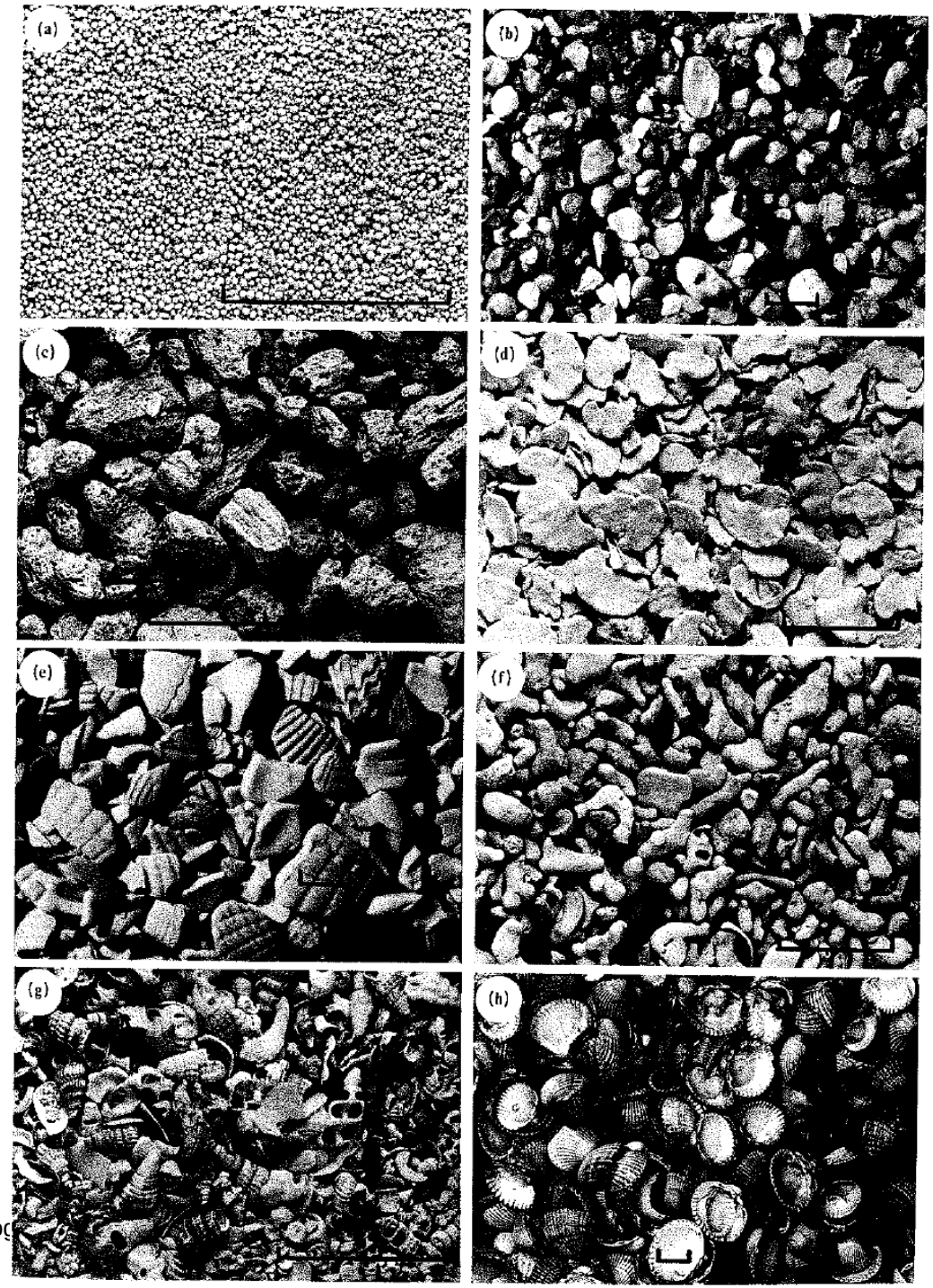
(d) Halimedes fragments sand
(carbonate-secreting algae)

(e) Cockle shell sand

(f) Lithothamnium sand(carbonate-secreting algae)

(g) Gasterpod-shell fragment sand

(h) Cockle shells



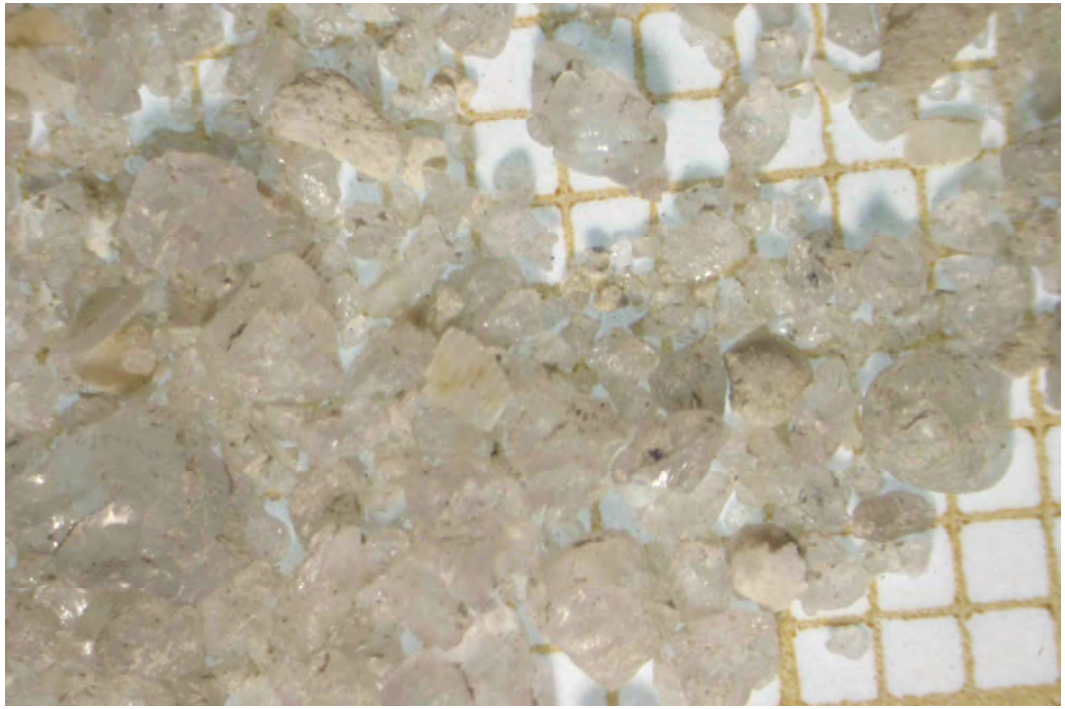
Microscope-shots of sand

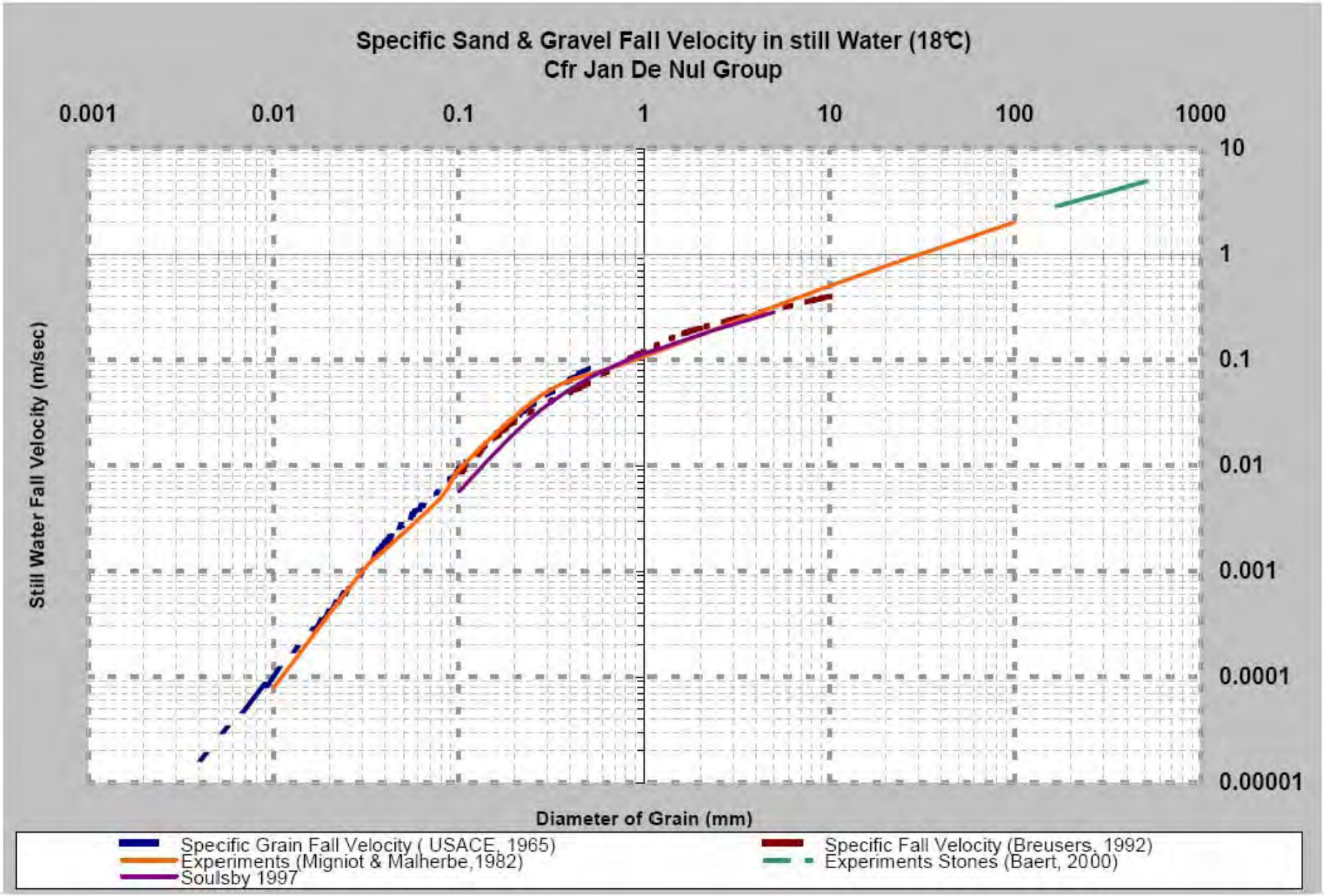
Calcareous Sand (Dubai)

D50 = 0,654 mm

Quartz Sand (S Afrika)

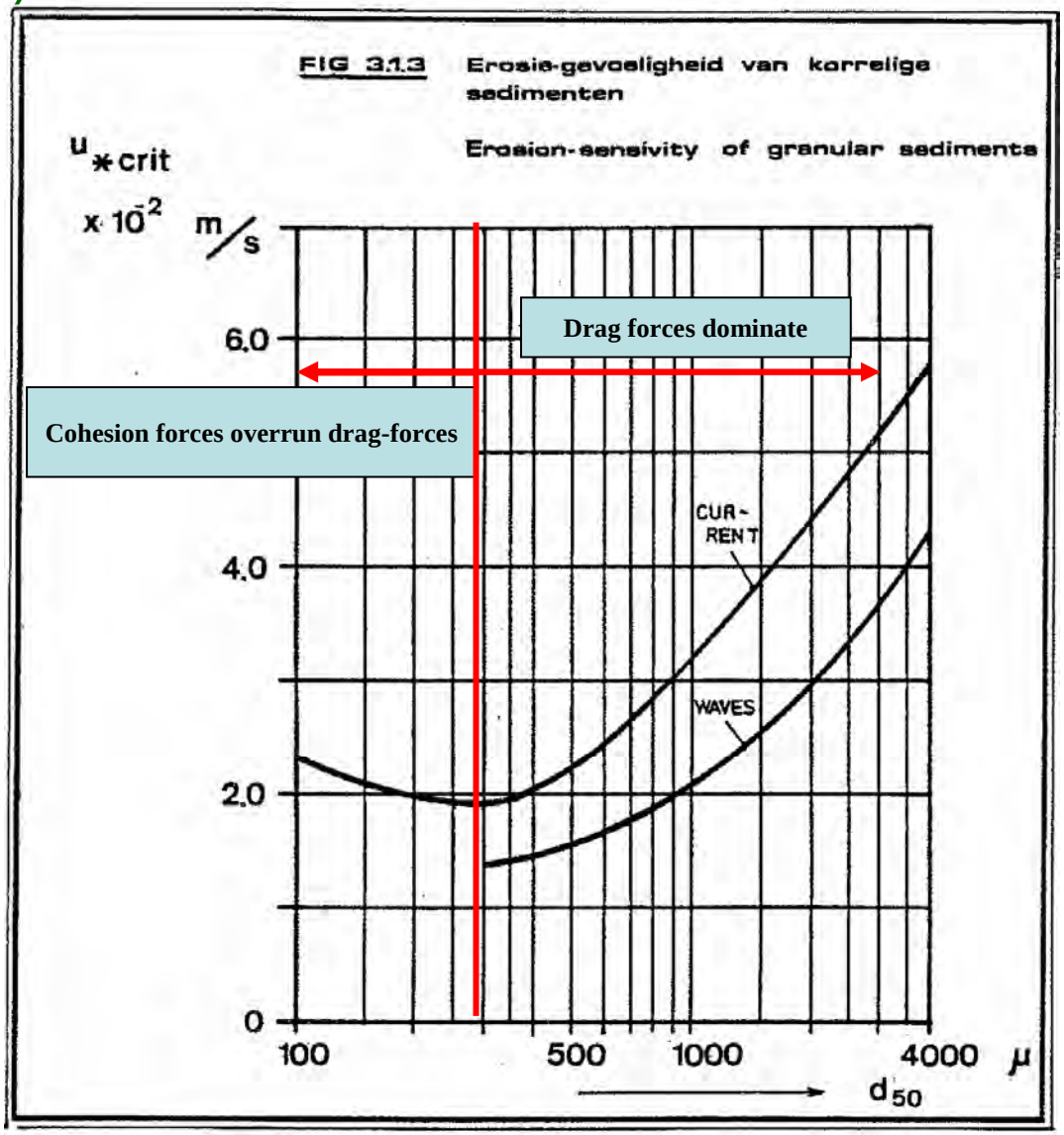
D50 = 0,700mm



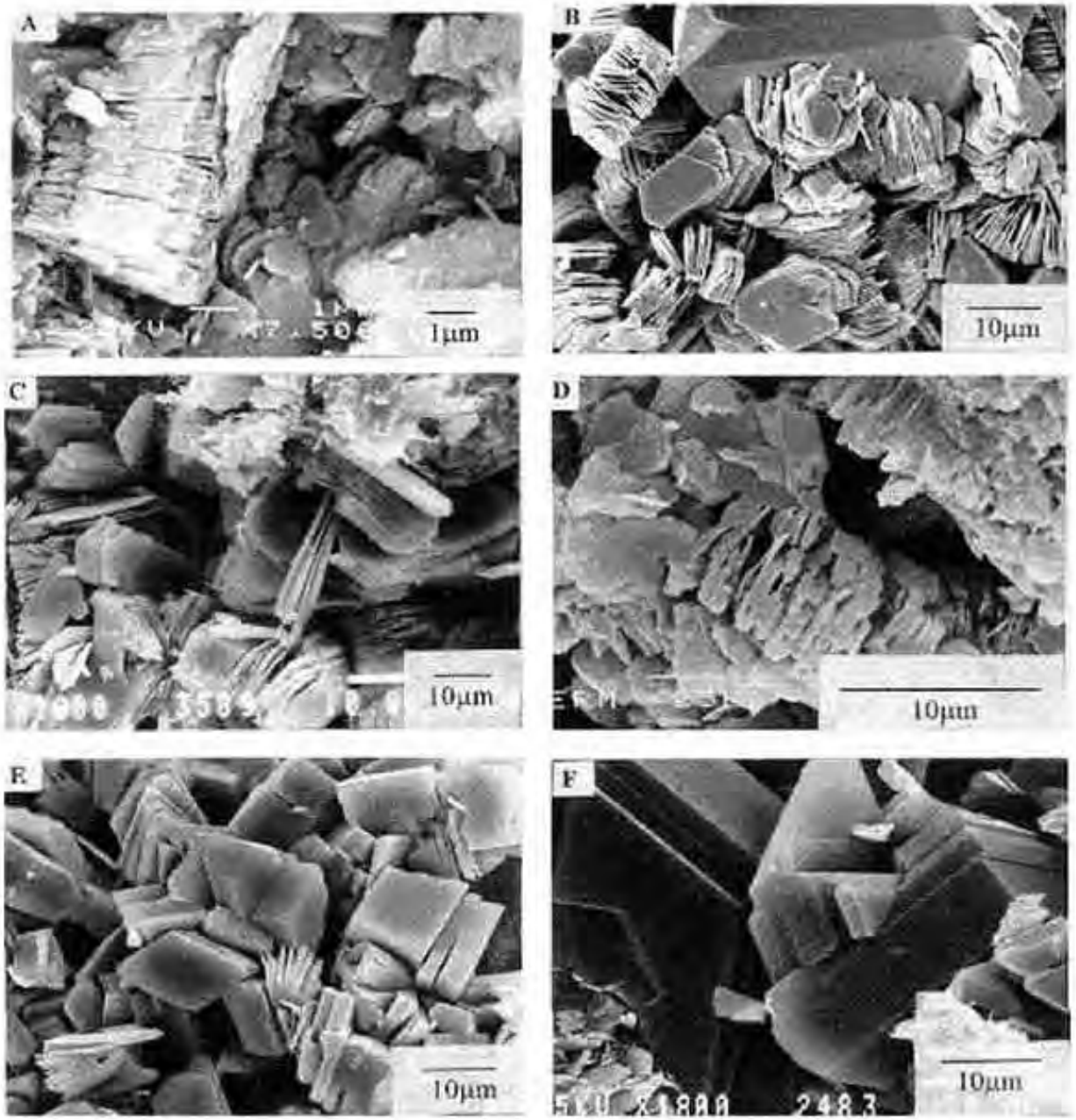

Specific Sand & Gravel Fall Velocity in still Water (18°C)
Cfr Jan De Nul Group
0.001
0.01
0.1
1
10
100
1000
10
1
0.1
0.01
0.001
0.0001
0.00001
Still Water Fall Velocity (m/sec)
Diameter of Grain (mm)
Specific Grain Fall Velocity (USACE, 1965)
Experiments (Migniot & Malherbe,1982)
Soulsby 1997
Specific Fall Velocity (Breusers, 1992)
Experiments Stones (Baert, 2000)

Erosion-sensitivity (u*crit: critical shear-stress velocity) of sand

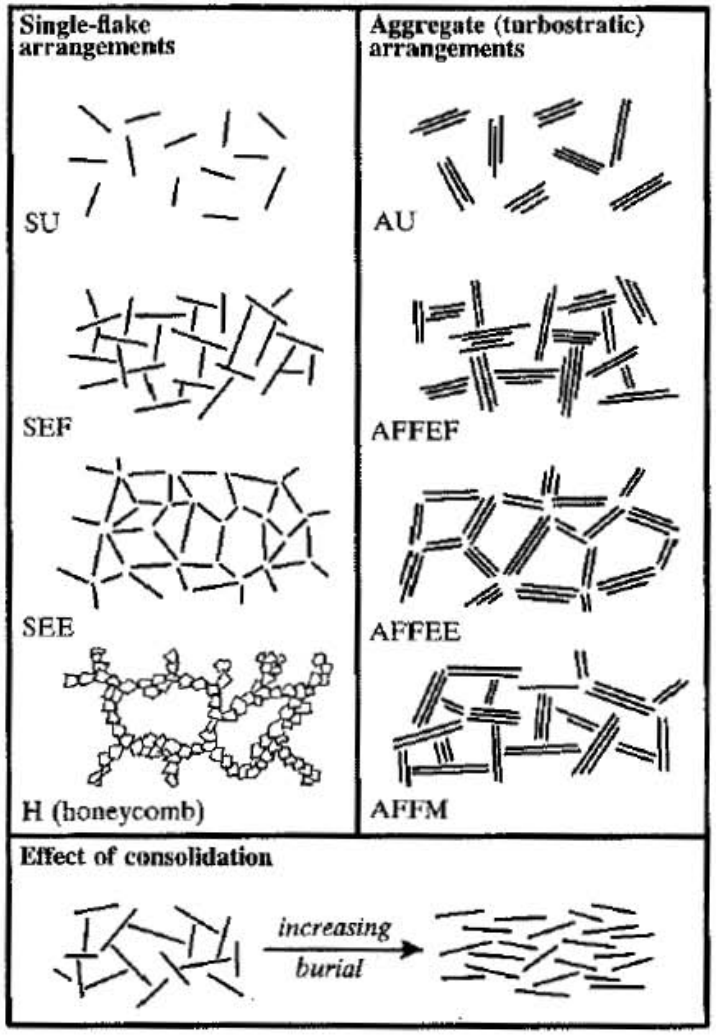
(B. Malherbe PhD Thesis)

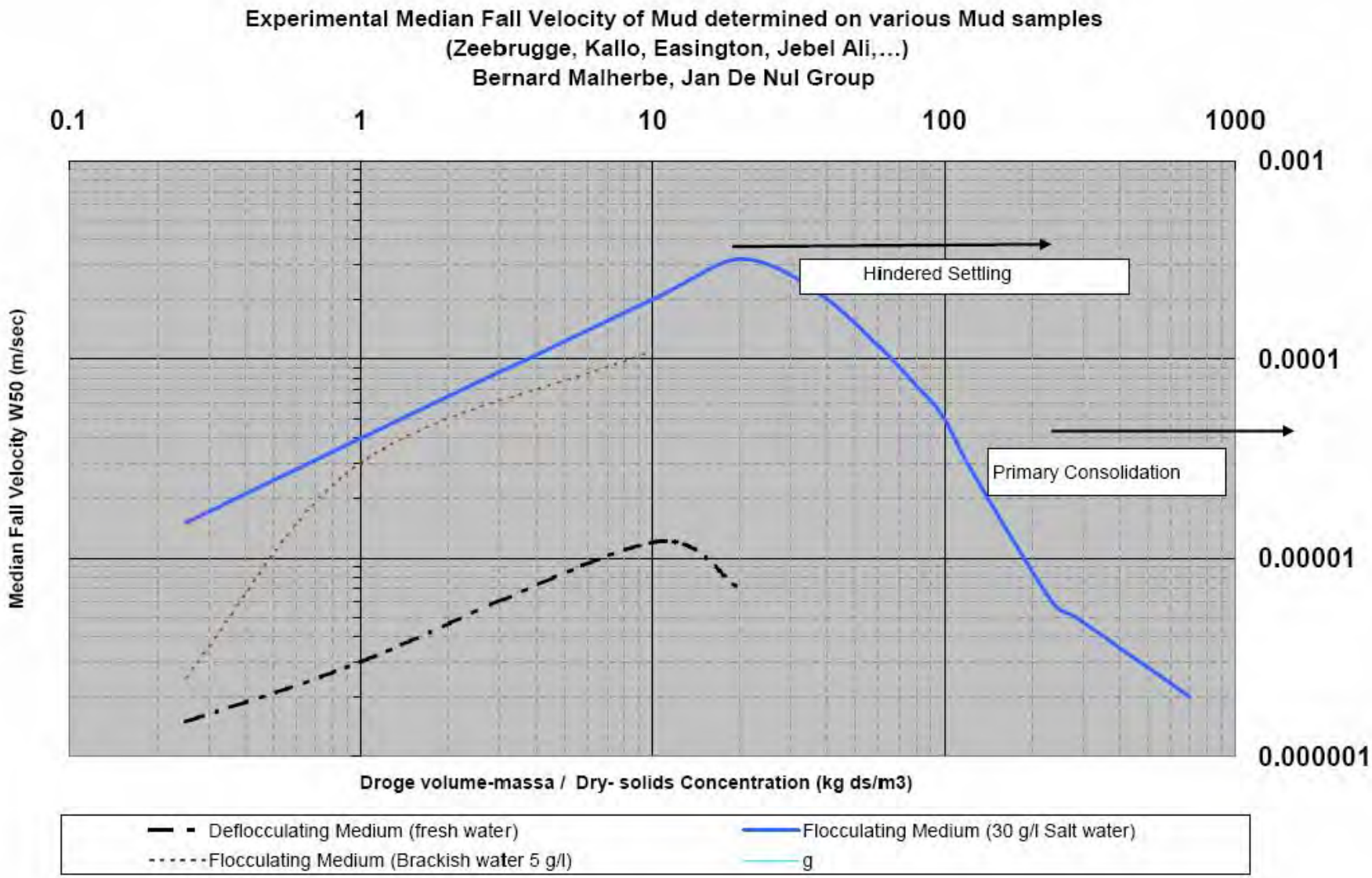


Electronic-microscope shots of Illite and Kaolinite clay minerals

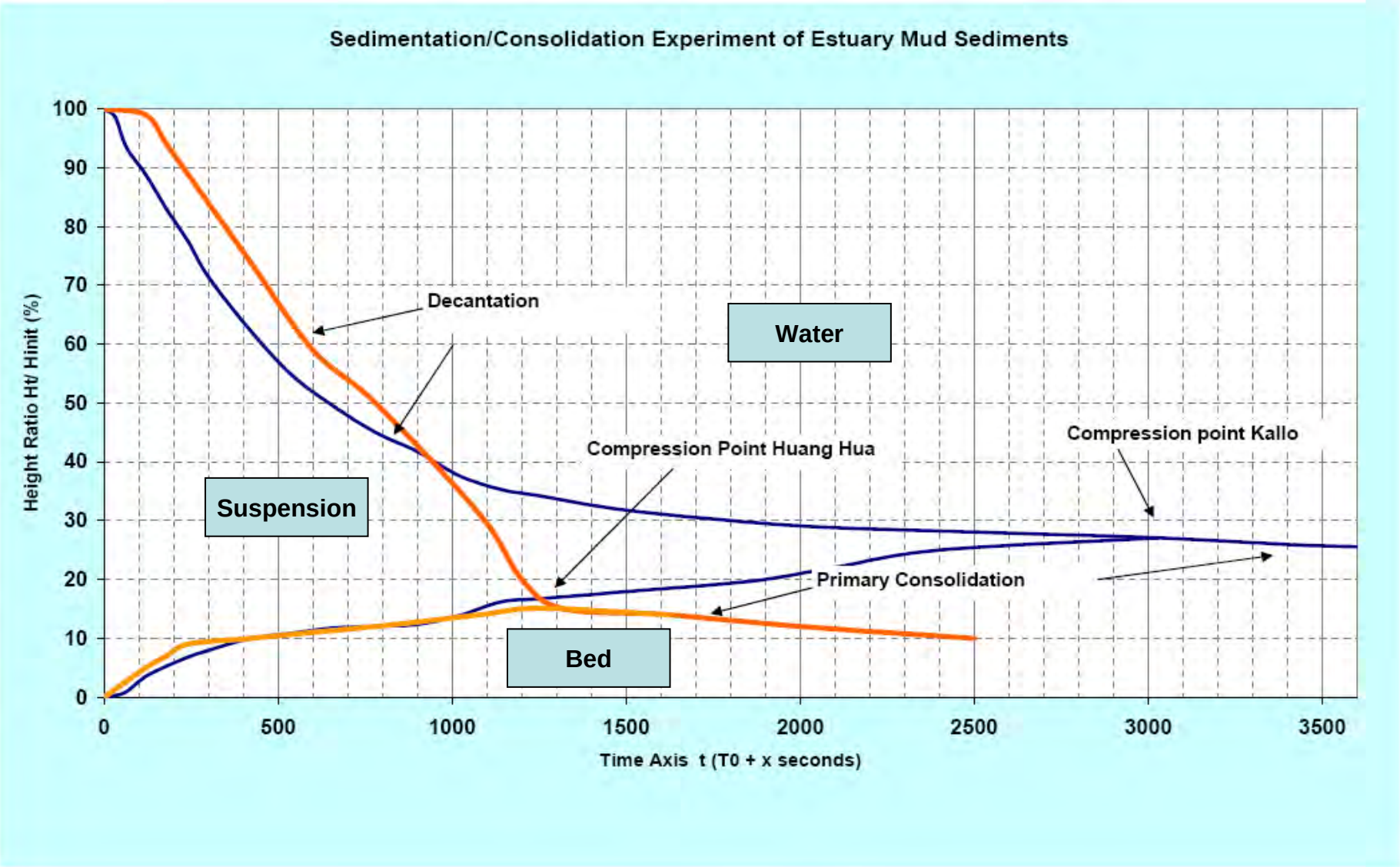


Packing models for clayey sediments and the effect of consolidation

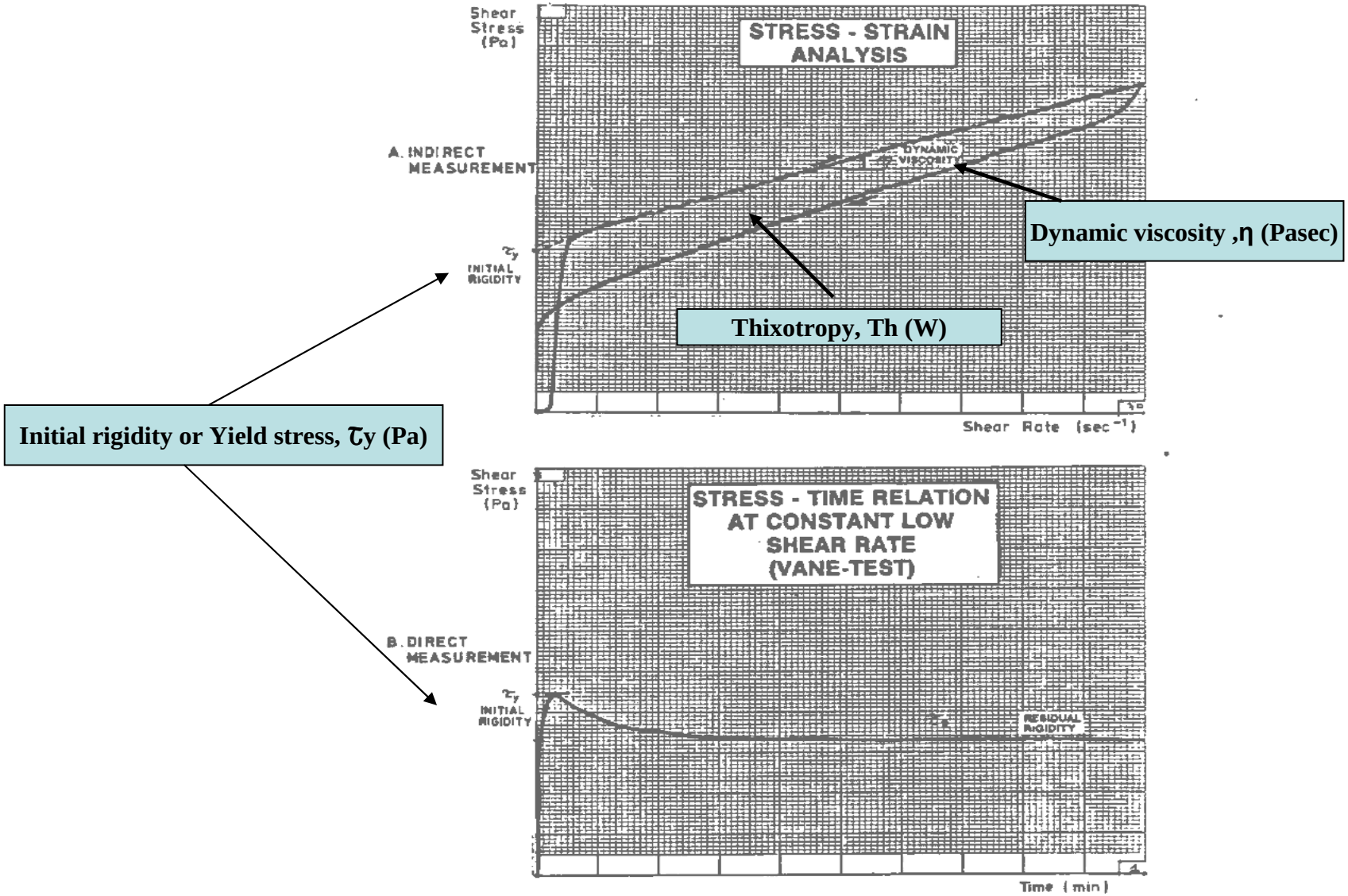



Experimental Median Fall Velocity of Mud determined on various Mud samples
(Zeebrugge, Kallo, Easington, Jebel Ali,...)
Bernard Malherbe, Jan De Nul Group
0.1
1
10
100
1000
0.001
0.0001
0.00001
0.000001
Median Fall Velocity W50 (m/sec)
Hindered Settling
Primary Consolidation
Droge volume-massa / Dry- solids Concentration (kg ds/m3)
Deflocculating Medium (fresh water)
Flocculating Medium (30 g/l Salt water)
Flocculating Medium (Brackish water 5 g/l)
g

Decantation and Primary Consolidation of Mud

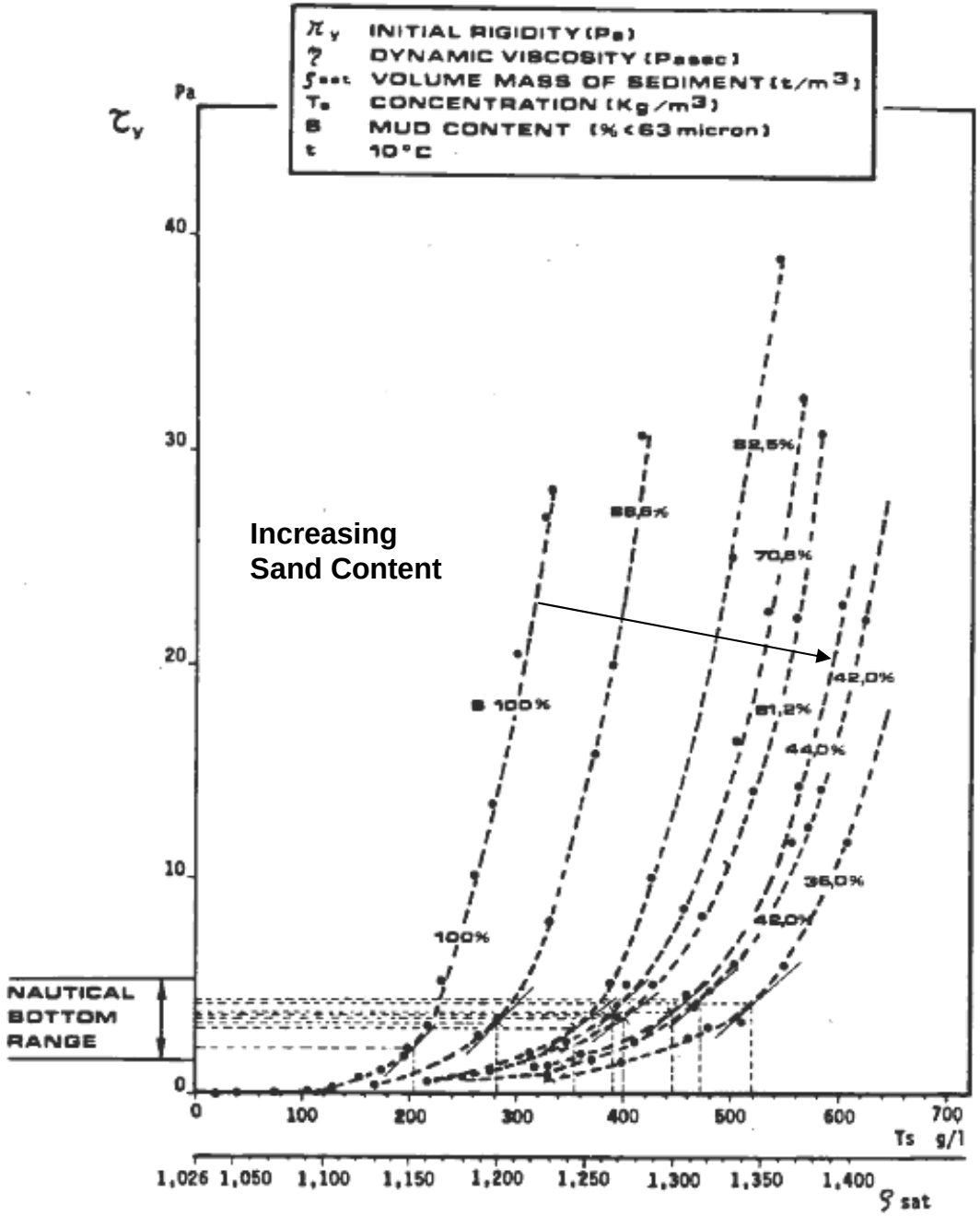


Cohesive sediments are characterized by their rheologic properties: shear-stress / strain relationships

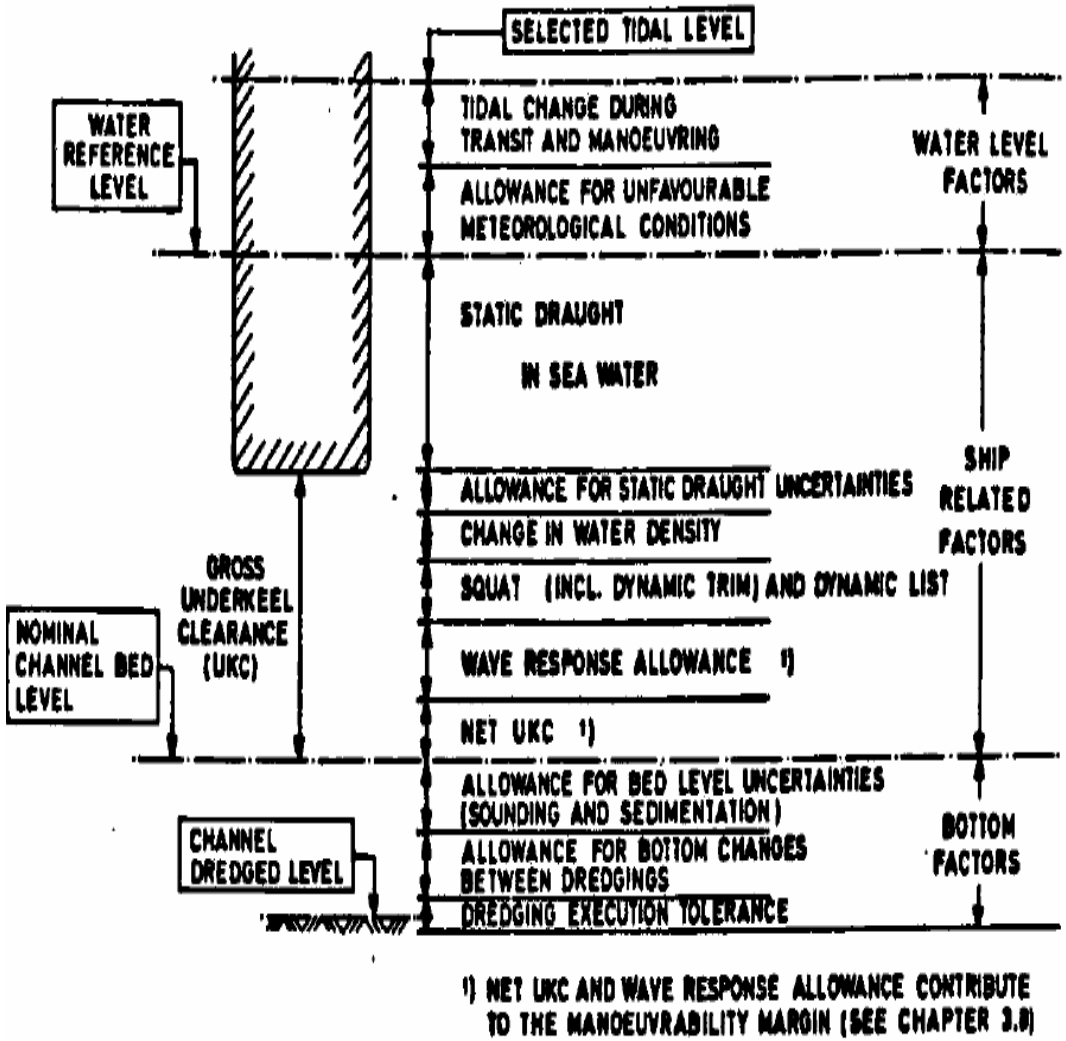


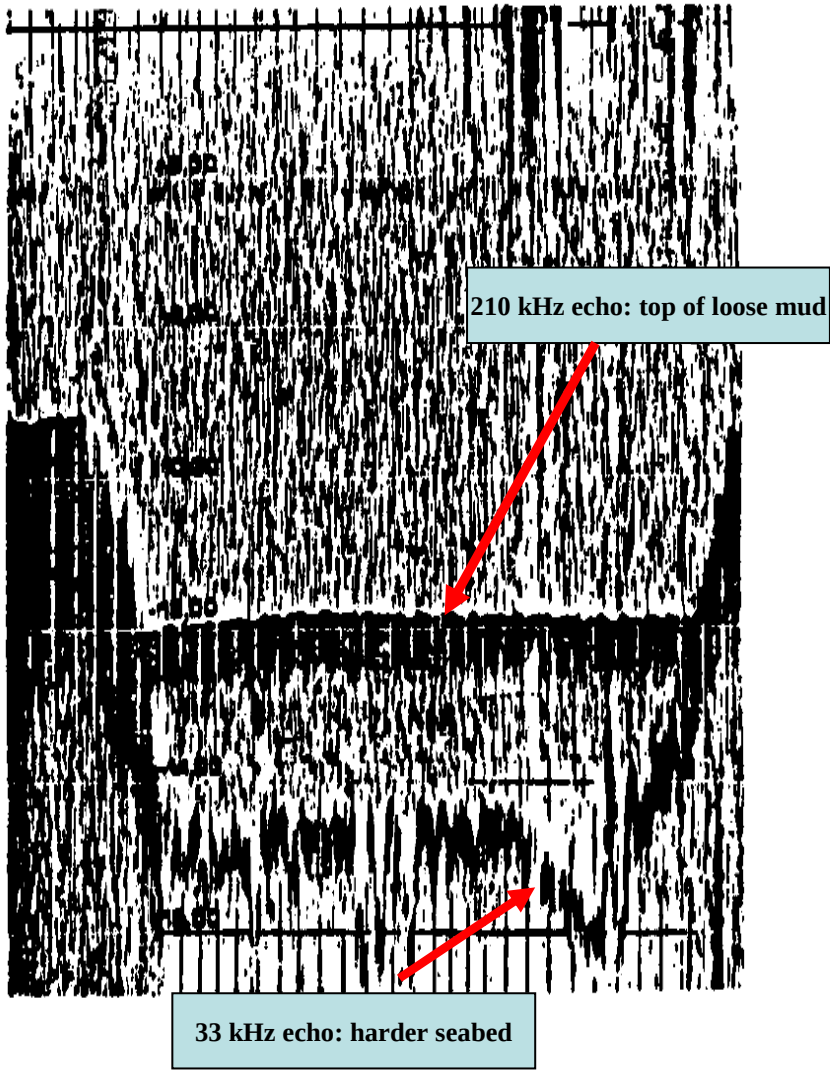
Rheology of mud: initial rigidity as a function of volume-mass and sand-content

(**B Malherbe, 1986)**

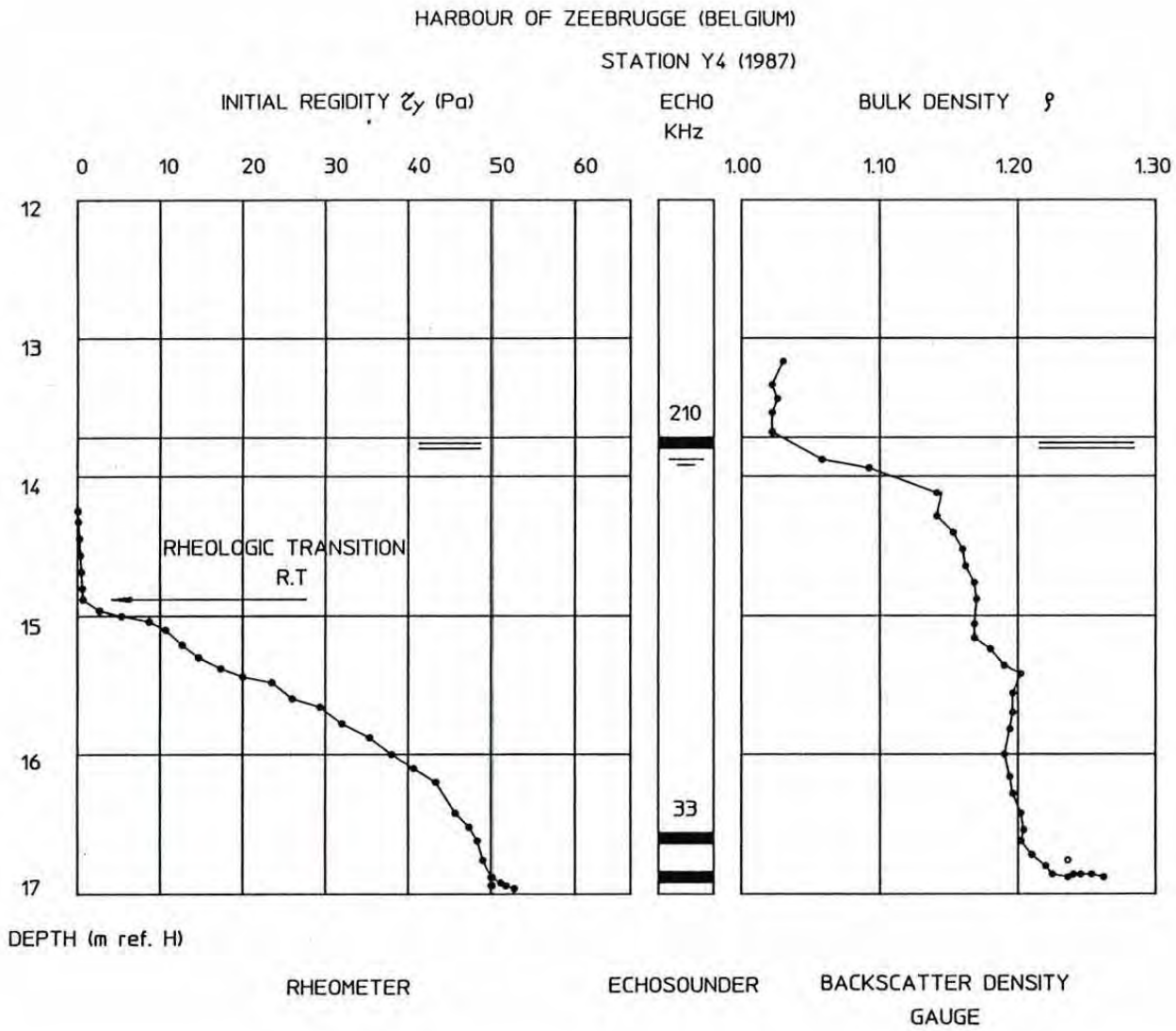


Sedimentation of loose mud deposits in access-channels (B Malherbe, 1986)

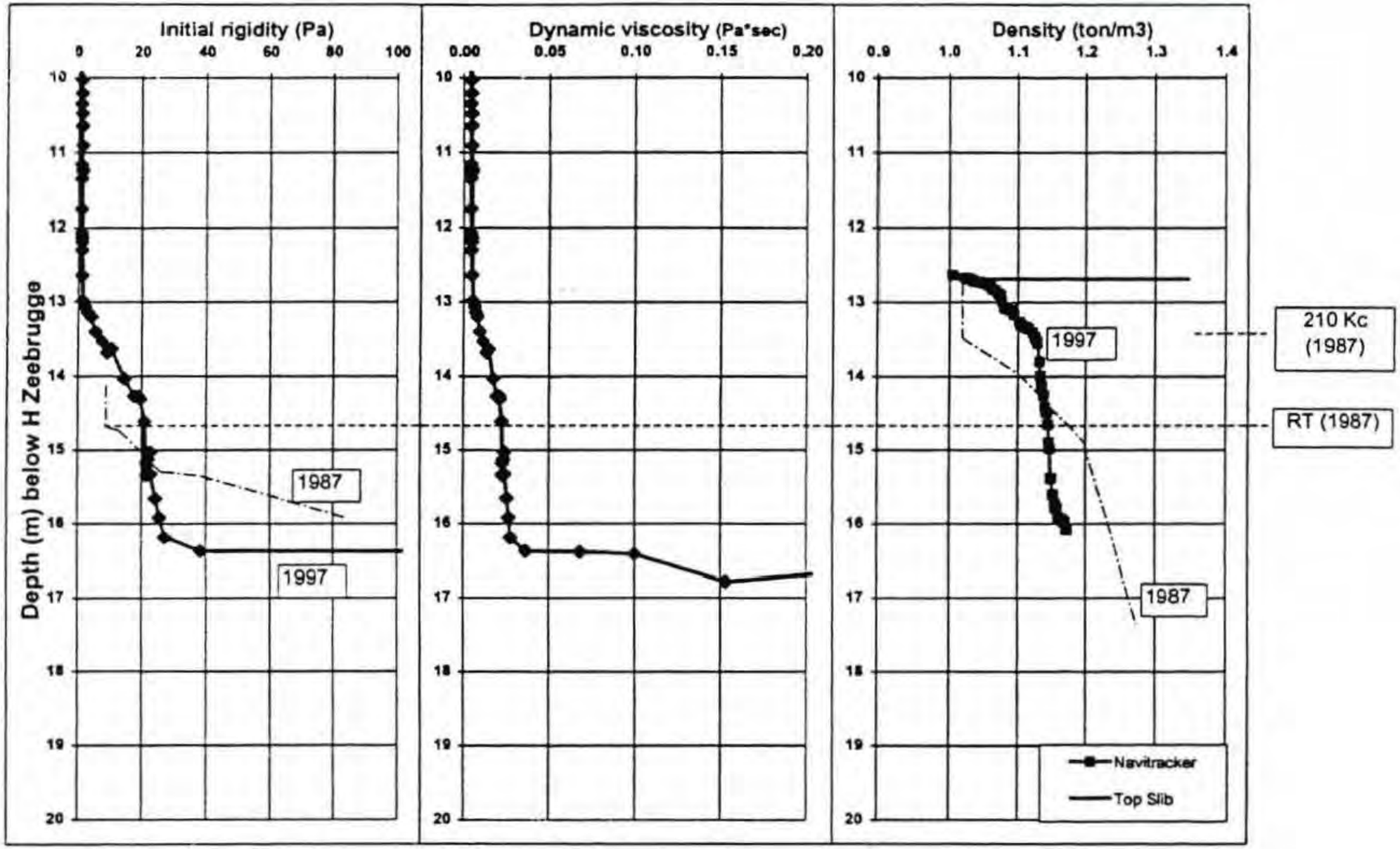




Determination of Nautical Bottom, using the Rheological Characteristics of Mud (Malherbe, 1986)

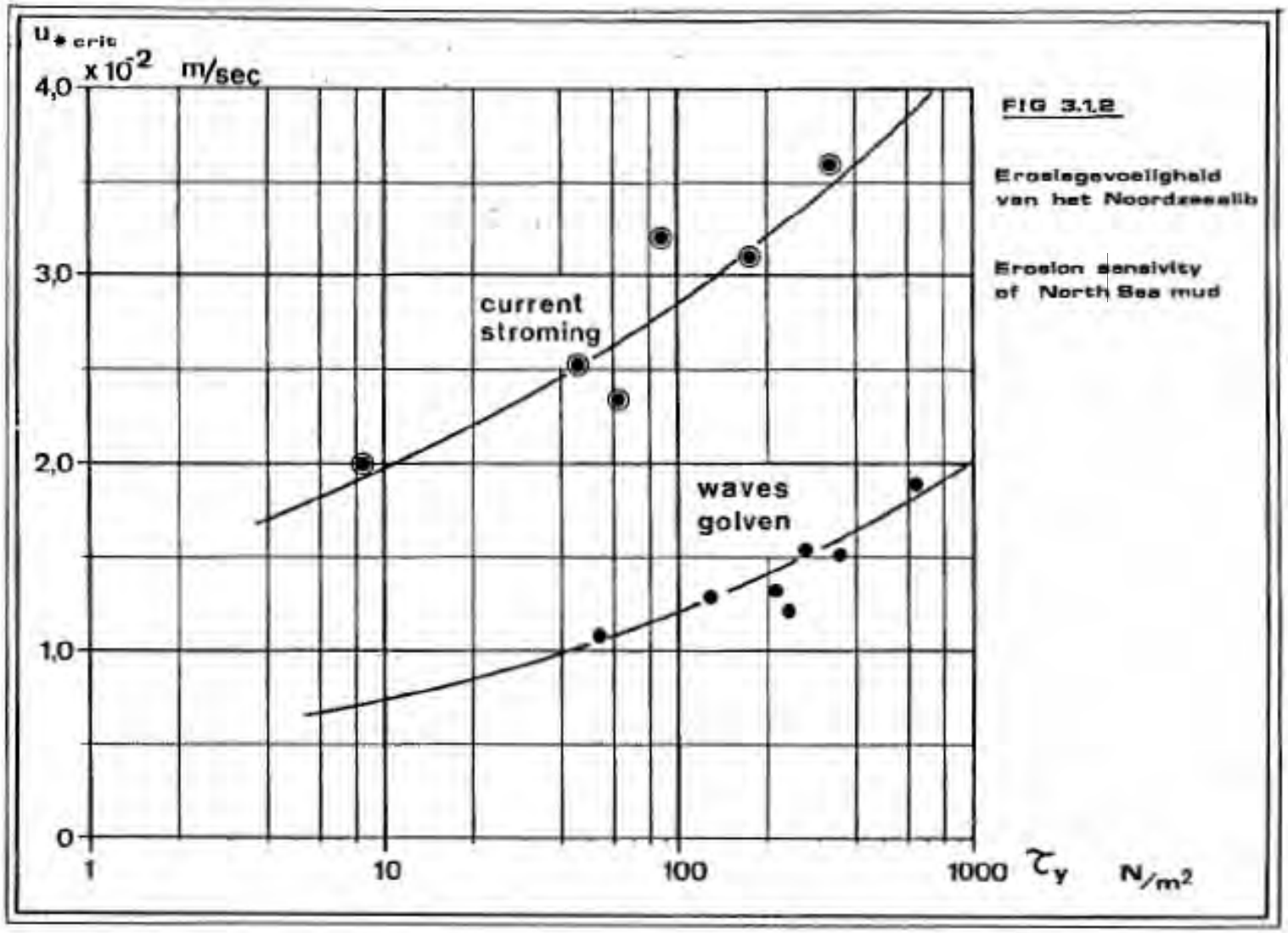


Rheologic & Density Profiling in Loose Mud (ref Malherbe PIANC, 1997)



Erosion-sensitivity (expressed as u*crit) for cohesive sediments

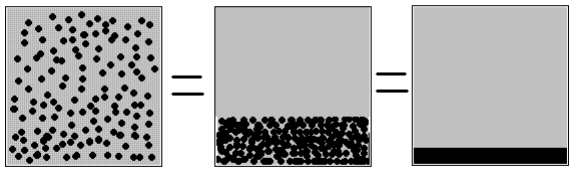
(B Malherbe PhD thesis)



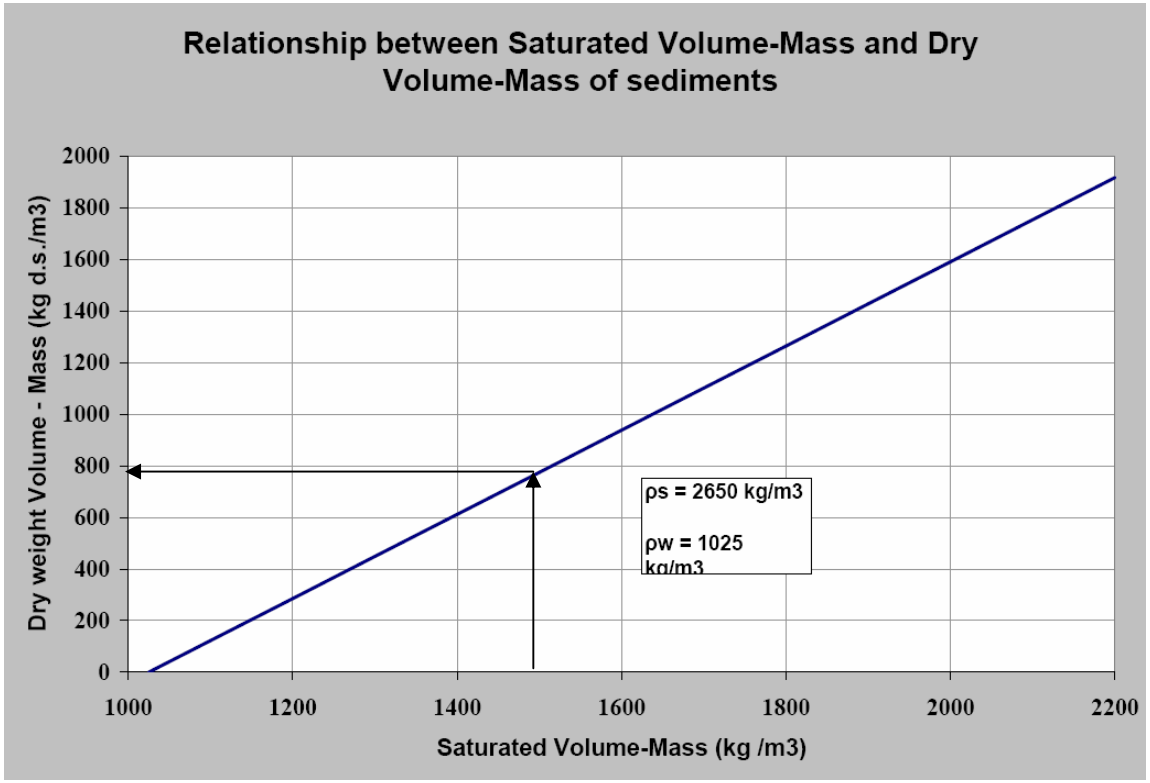
Relationship between Saturated and Dry Volume-Mass of Sediments

Bulking, compaction or consolidation

Conservation of dry-solid content



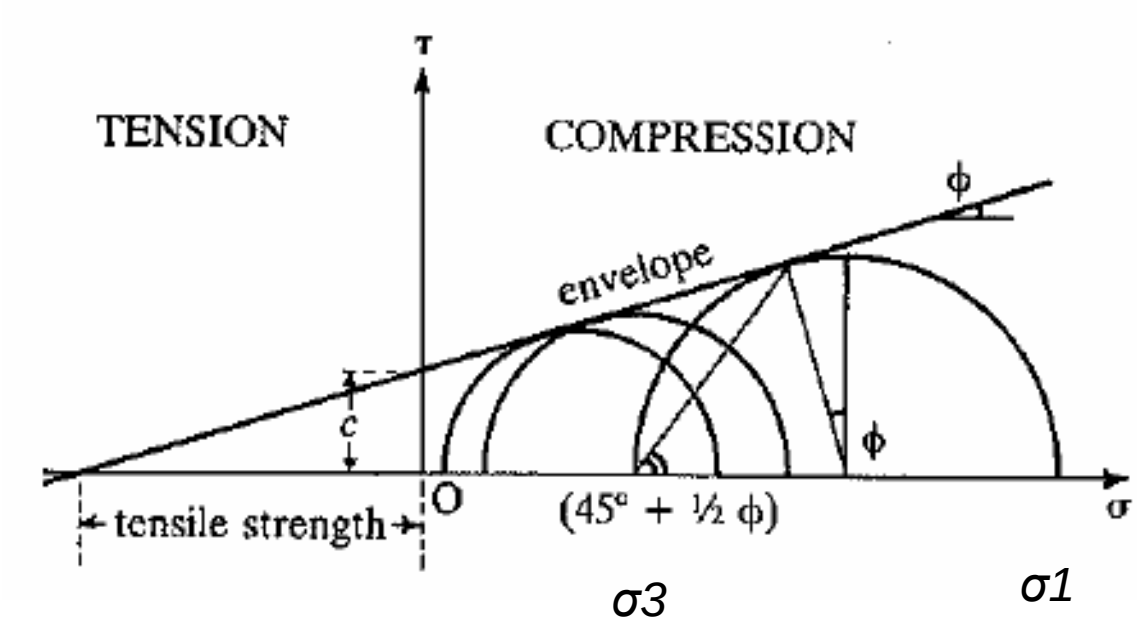
$$C_f = \frac{\rho sat1 - \rho w}{\rho sat2 - \rho w}$$



Geotechnical characteristics of some common sediments

Sediment Type	Porosity n (%)	Water Content w (%)	Volume-mass Dry (kgds/m3)	Volume-mass Sat (kgds/m3)	Sand Content > 0,063mm (%)	Relative Density Dr (%)
Uniform loose sand	46	32	1,43	1,89	97	< 35
Uniform dense sand	34	19	1,50	2.09	97	65 - 85
Well-graded sand	26	16	1.86	2.16	85	88
Glacial till	20	9	2.12	2.32	20	
Mud (silt-clay)	84	195	0.43	1.27	15	

Basics of Soil-Mechanic properties of sediments



Undrained Shear Strength $\tau = Su = (\sigma 1 - \sigma 3)/2 = c + \tan\varphi.\sigma$

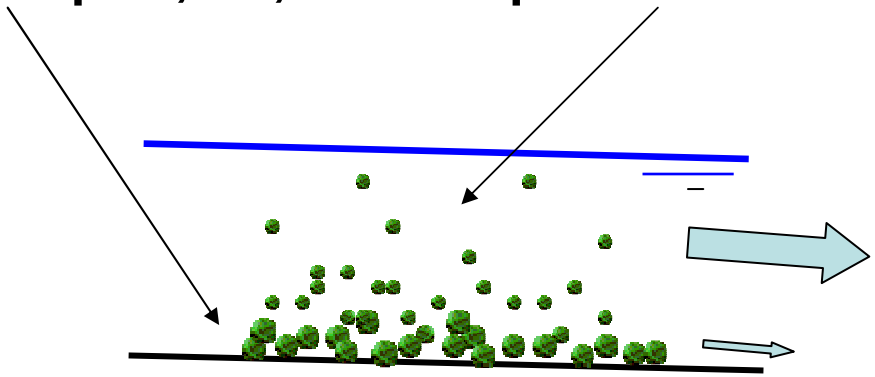
Cohesion (at σ = 0 confinment stress) c

Very soft : Su < 20 kPa
Soft : Su = 20 – 40 kPa
Firm : Su = 40 – 75 kPa

SEDIMENT-TRANSPORT

Sediment-Transport by water occurs mainly via

Bed-Load Transport, Sb, and Suspension-Transport, Ss.



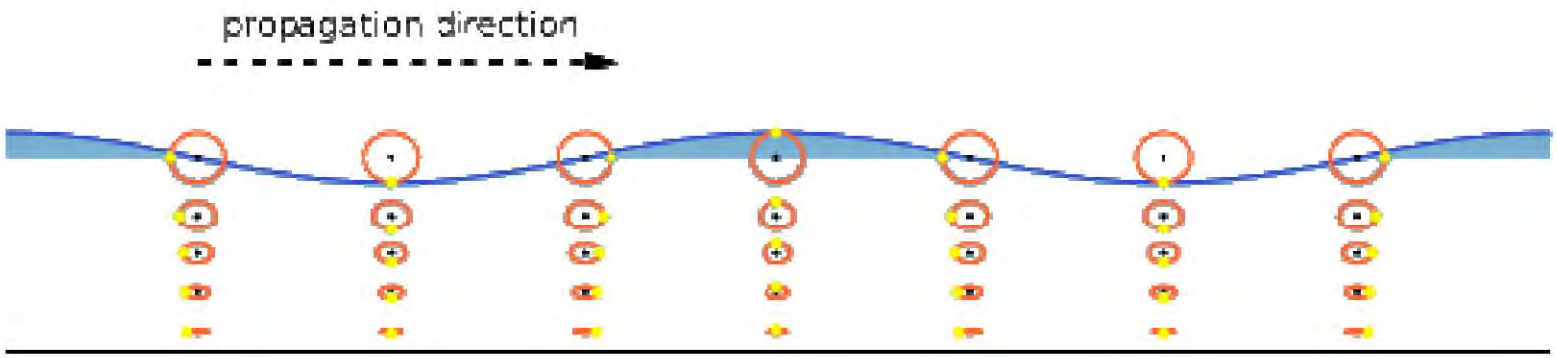
One has to distinguish between the Instanteneous sediment transport – Sbi and Ssi – and the Residual sediment-transport – Sbr and Ssr.

Sbi and Ssi will reflect the transport capacity of the open system, for which the currents, the turbulence and the wave-actions are the main driving forces.

Sbr and Ssr will reflect the ultimate fate and transport-pathways over longer periods, e.g. a full tidal-cycle with ebbs and floods, or a hydrological cycle with high and low discharge over seasons.

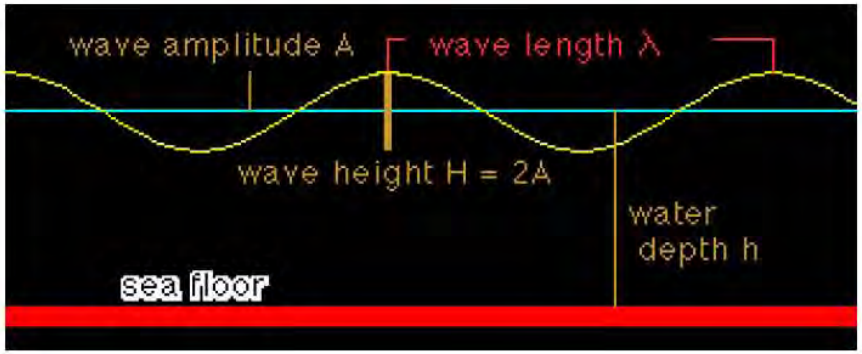
Action of Waves on Sediments

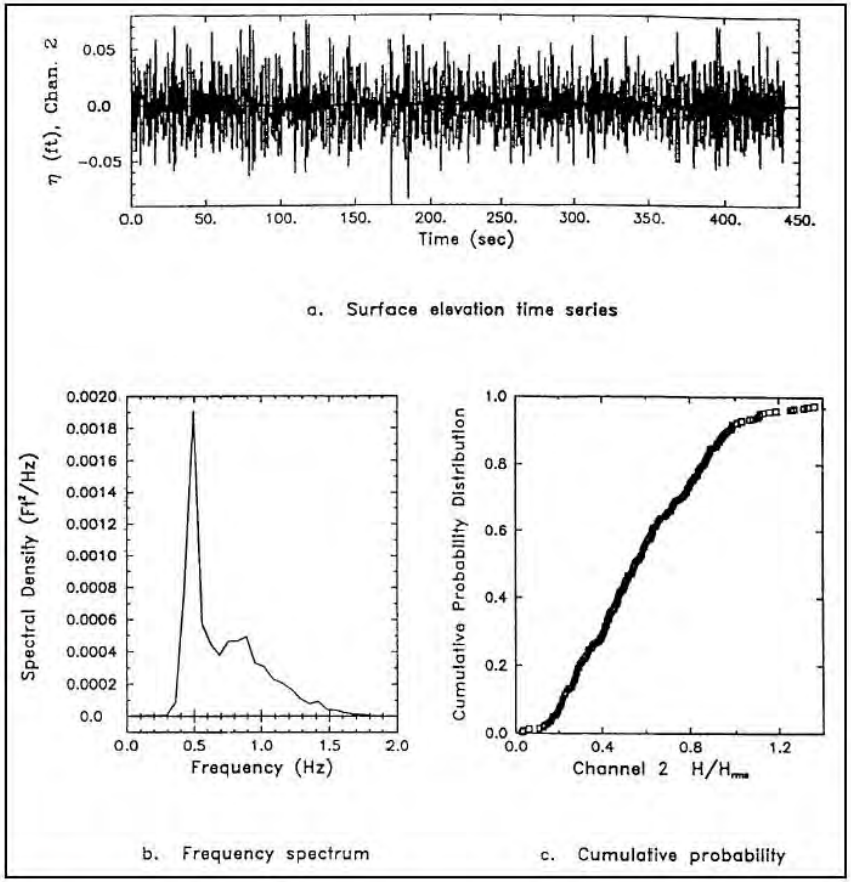
Linear Wave Theory (Airy Wave Theory)

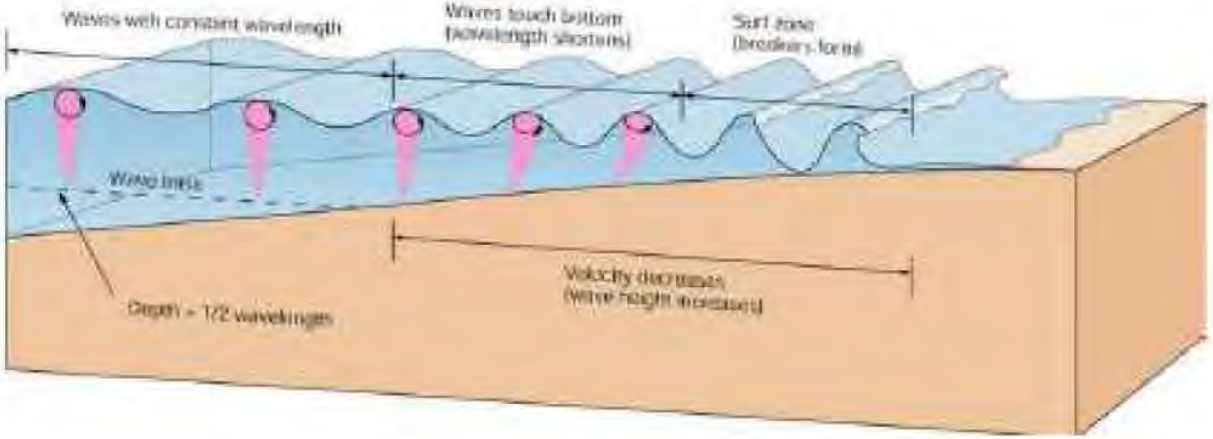


Wave action on seabed and physics

(ref: USACE Coastal Engineering Manual)







Wave approaching a coast: wave transformation by interaction with seabed

Wave- refraction: decrease of celerity

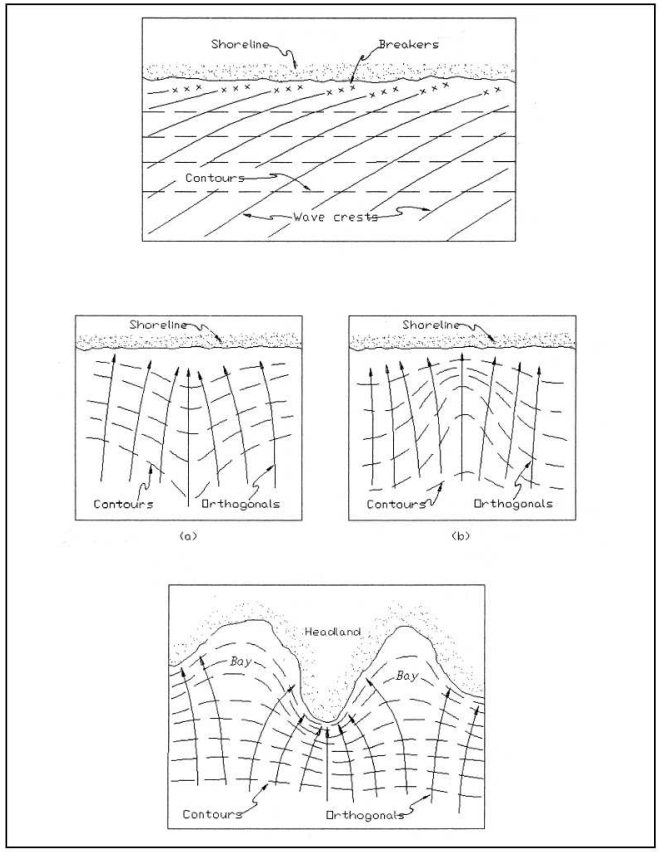
Wave – diffraction

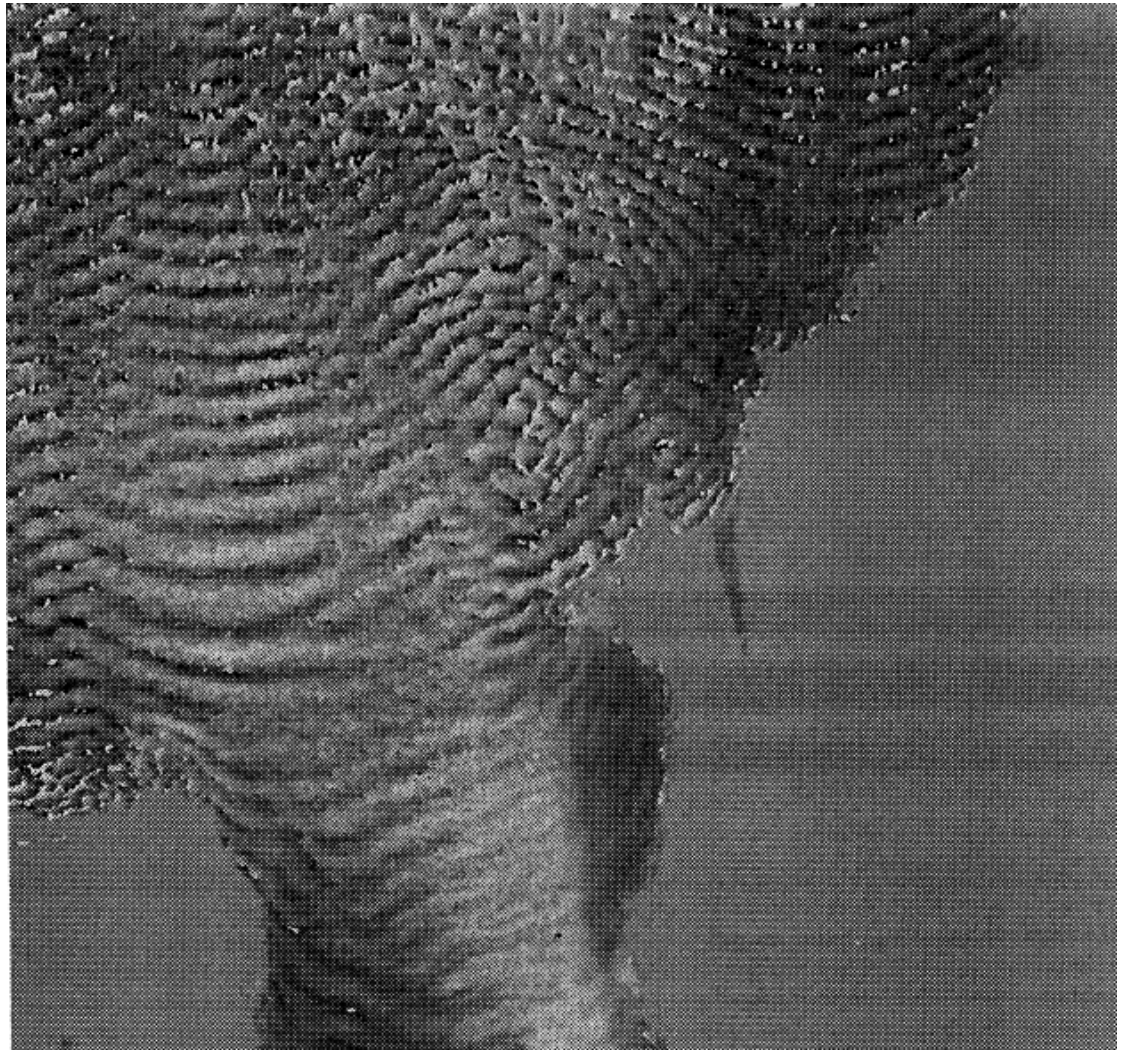
Wave - reflection

Wave-shoaling

Wave-interference

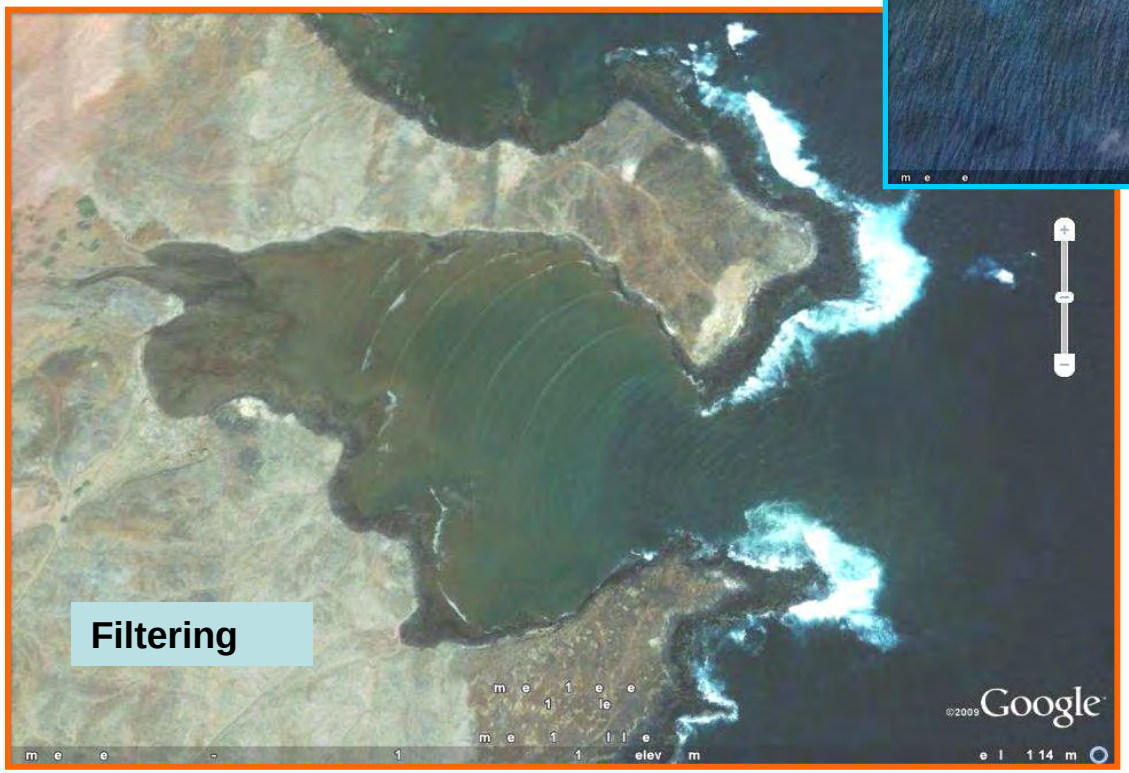
Wave breaking





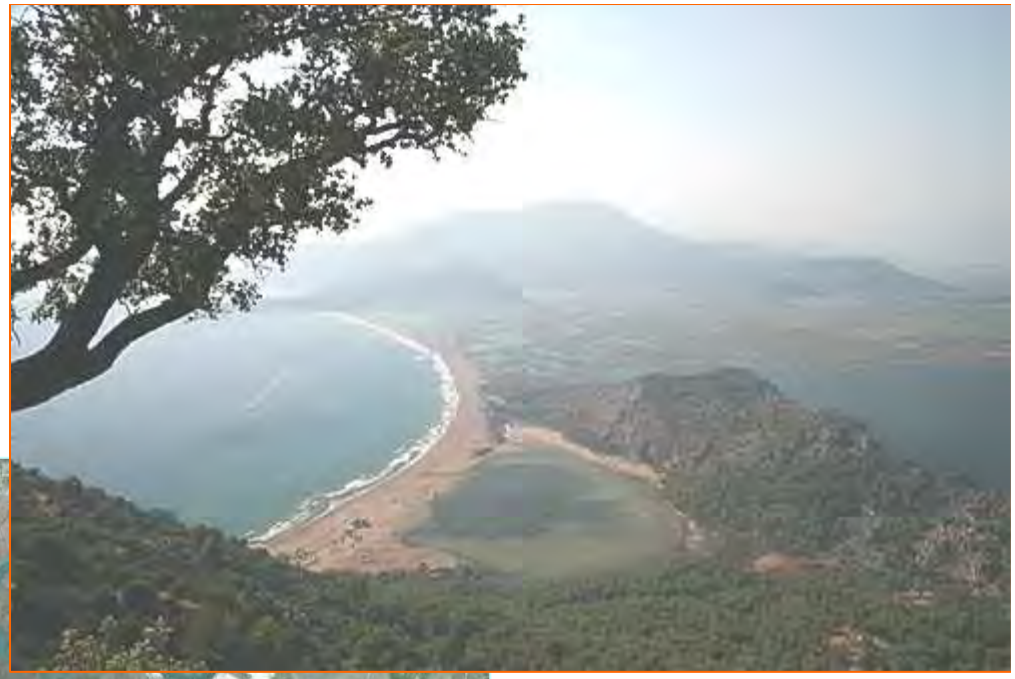
Ref: USACE Coastal Engineering Manual

Wave – seabed & coast interaction

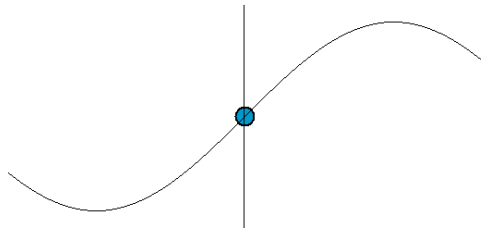


Offshore Bar at river outlet

Dalyan Sand Spit, Turkeye



Waves: elementary physical characteristics



λ = wave length

Tm = average wave- period (sec)

Tp = peak- wave-period (sec): = ca. 1,10 x Tm

Hs = significant wave-heigth (m): average of highest 1/3 of waves in wave-train

H 10% = 10th percentile of highest waves

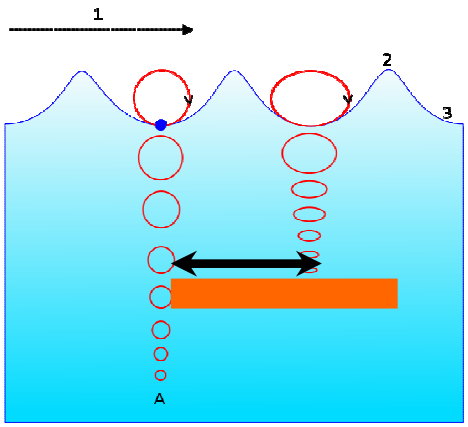
H 1% = 1st percentile of highest waves

C= celerity of wave-front (m/sec)

k = 2 x π/λ:wave-number

d = waterdepth

v = cinematic viscosity of seawater



λ = c x T

λ / H = 1/ wave-steepness (typical values between 7 and 60; normal value = 14)

$\lambda_0 = T_o^{\,2} \times g/(2.\pi)$: in deep water

$C_o = 1{,}25 \times \sqrt{\lambda_o}$

C = 1,25 x √g x h: in shallow water

U0 = oscillatory velocity near the seabed

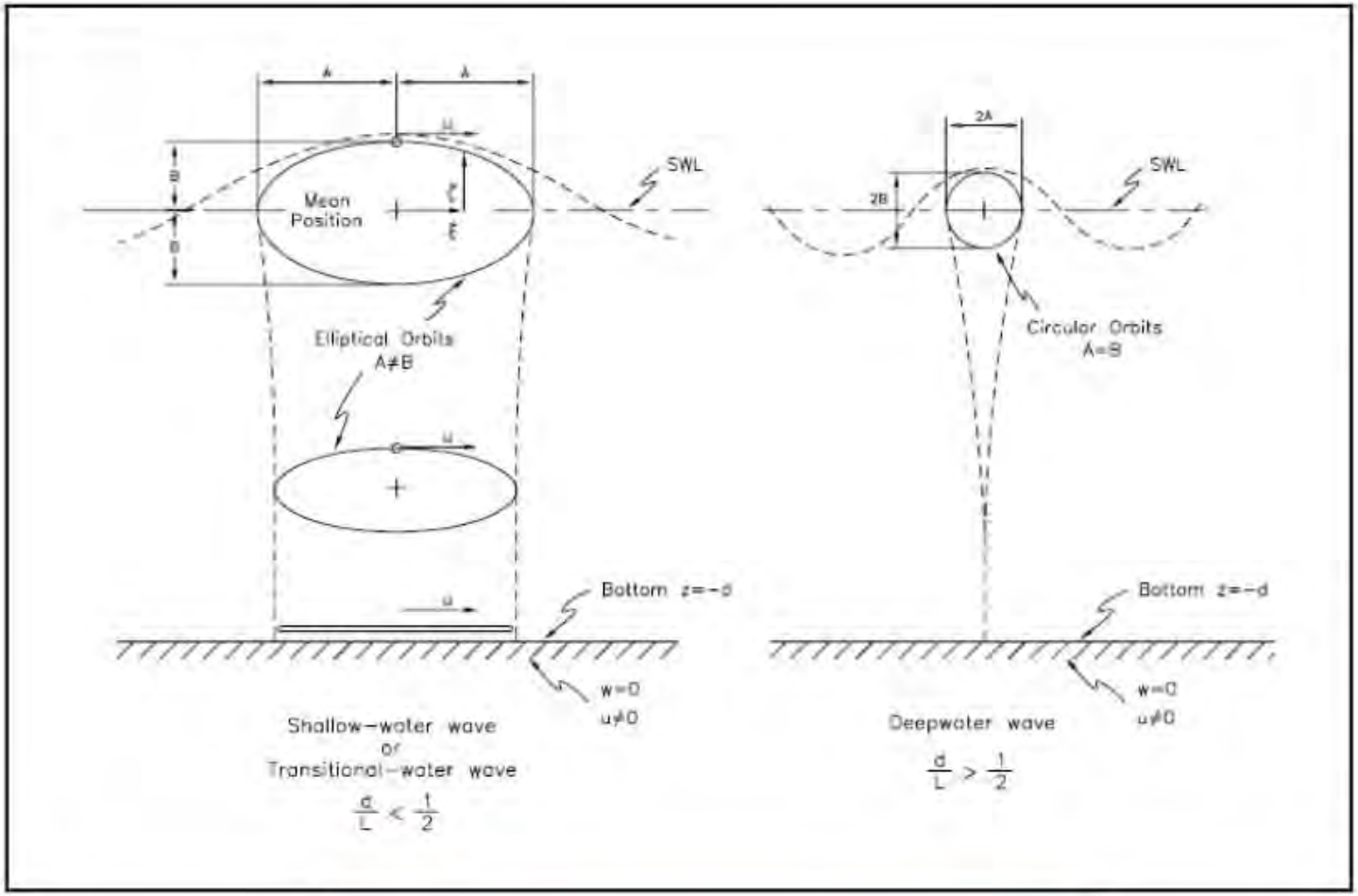
Alternating shear-stress exerted by orbital velocity close to seabed

$$U0 = \pi.Hs / (Tm.sh\,(2.\pi.d/\lambda))$$

$$\tau 0\ max = \rho.U0.\ (2.\pi.v/Tm)^{0.5}$$

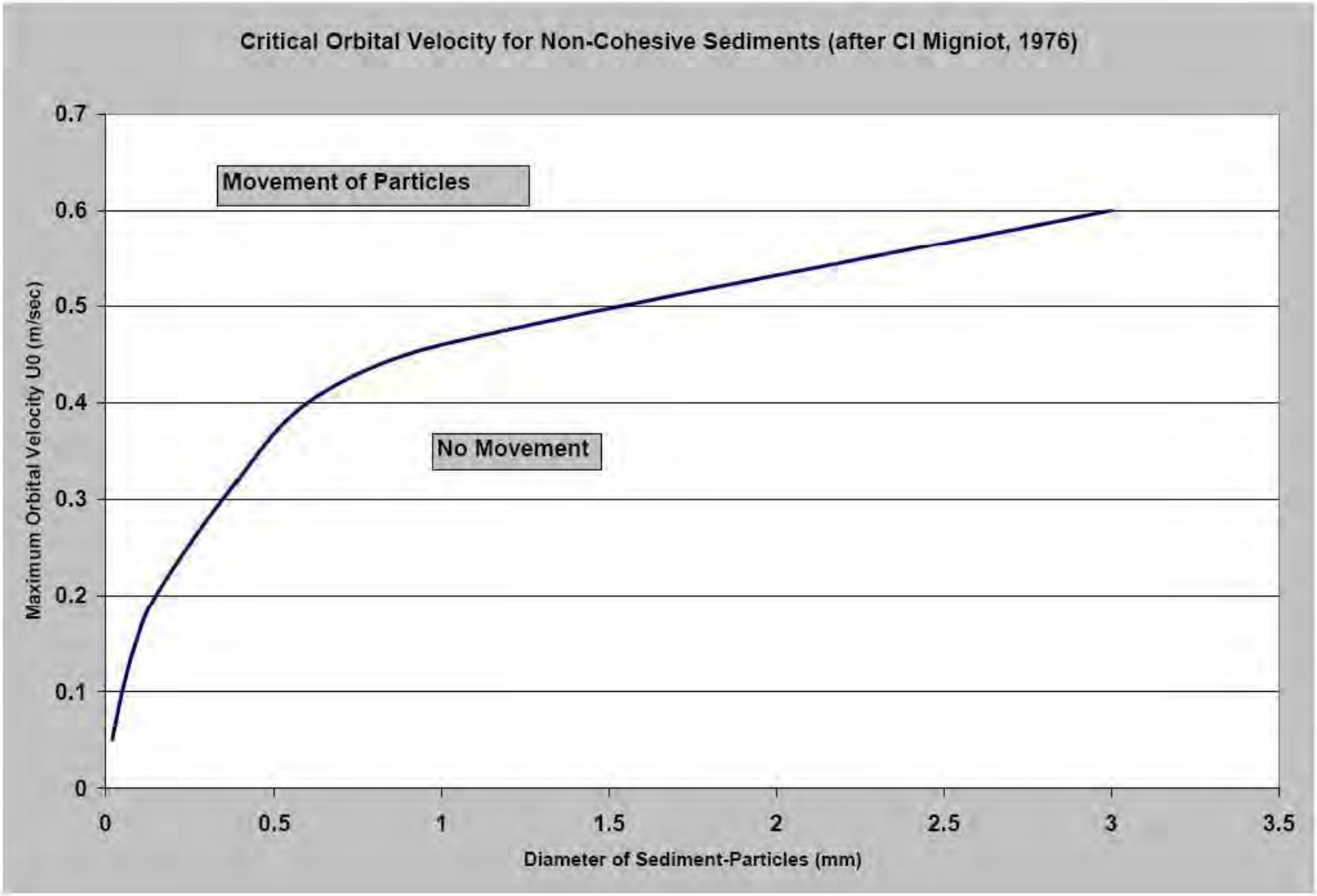
$$u^* = (8.v.U0^2/\pi.Tm)^{0.25}$$

Orbital wave-velocity on seabed



$$u = \frac{H}{2}\,\frac{gT}{L}\,\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\cos\theta$$

Experimental Determination of Critical Nearbed Orbital Velocity



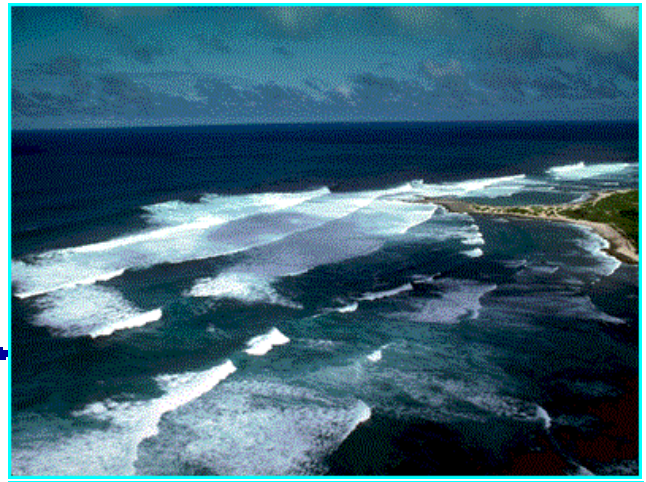
Wave-Breaking: transfer of wave-energy to the seabed

Fundamentals: Breakers

There are three types of breakers:

- **Spilling breakers** break gradually over a considerable distance.

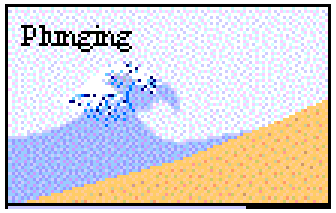
High steepness waves on gently sloping beaches $\xi 0 < 0,5$



- **Plunging breakers** tend to curl over and break with a single crash. The front face is concave, the rear face is convex.

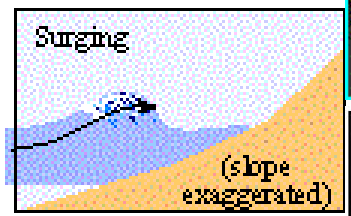
Intermediate steepness waves on steeper sloping beaches

$0,5 < \xi 0 < 3,3$



- **Surging breakers** peak up, but surge onto the beach without spilling or plunging. Even though they don't "break," surging waves are still classified as breakers.

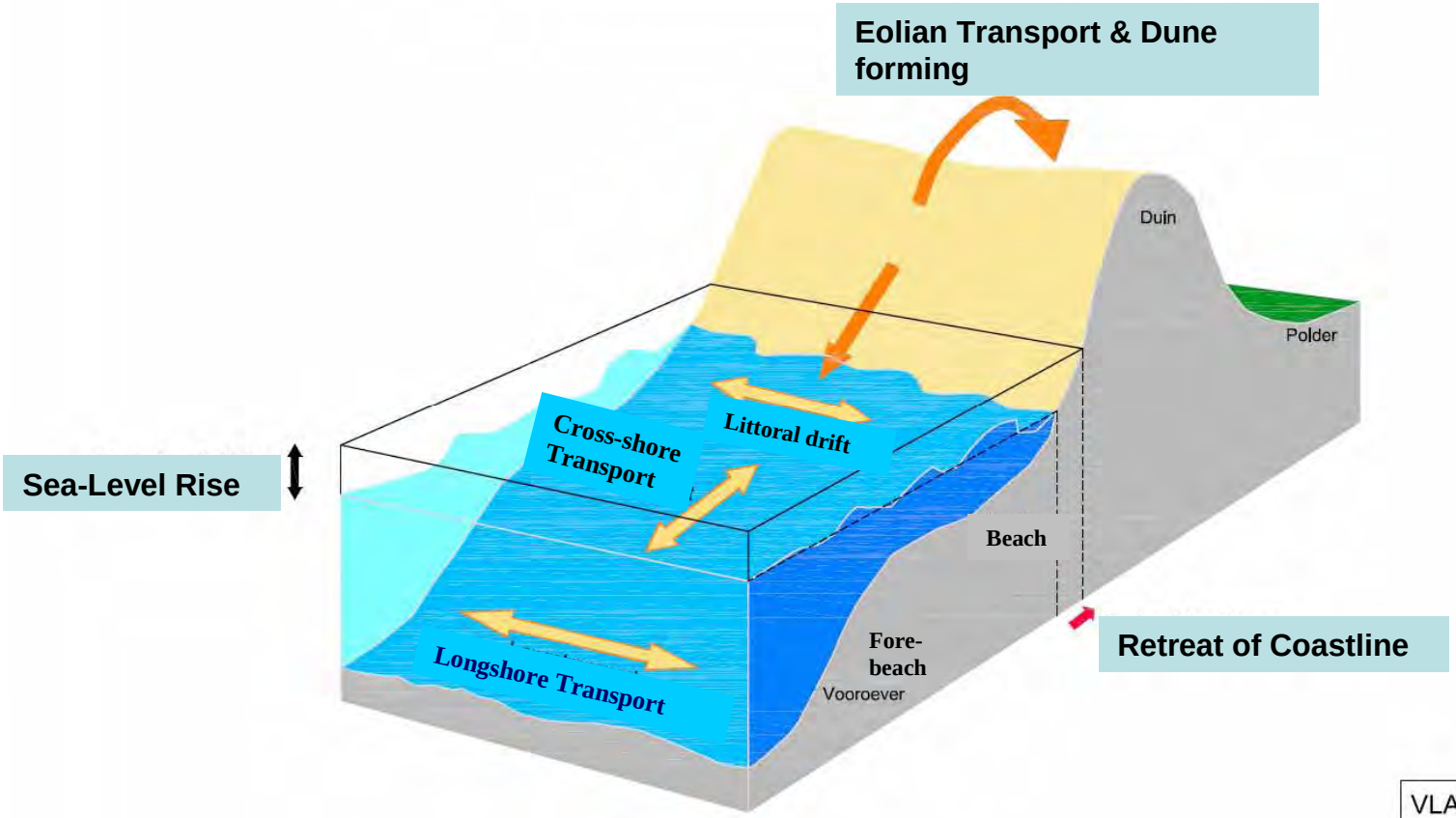
Low steepness waves on steep sloping beaches $\xi 0 > 3,3$



$$\xi_0 = \mathrm{Tan}\beta . (H_0/L_0)^{-0,5}$$

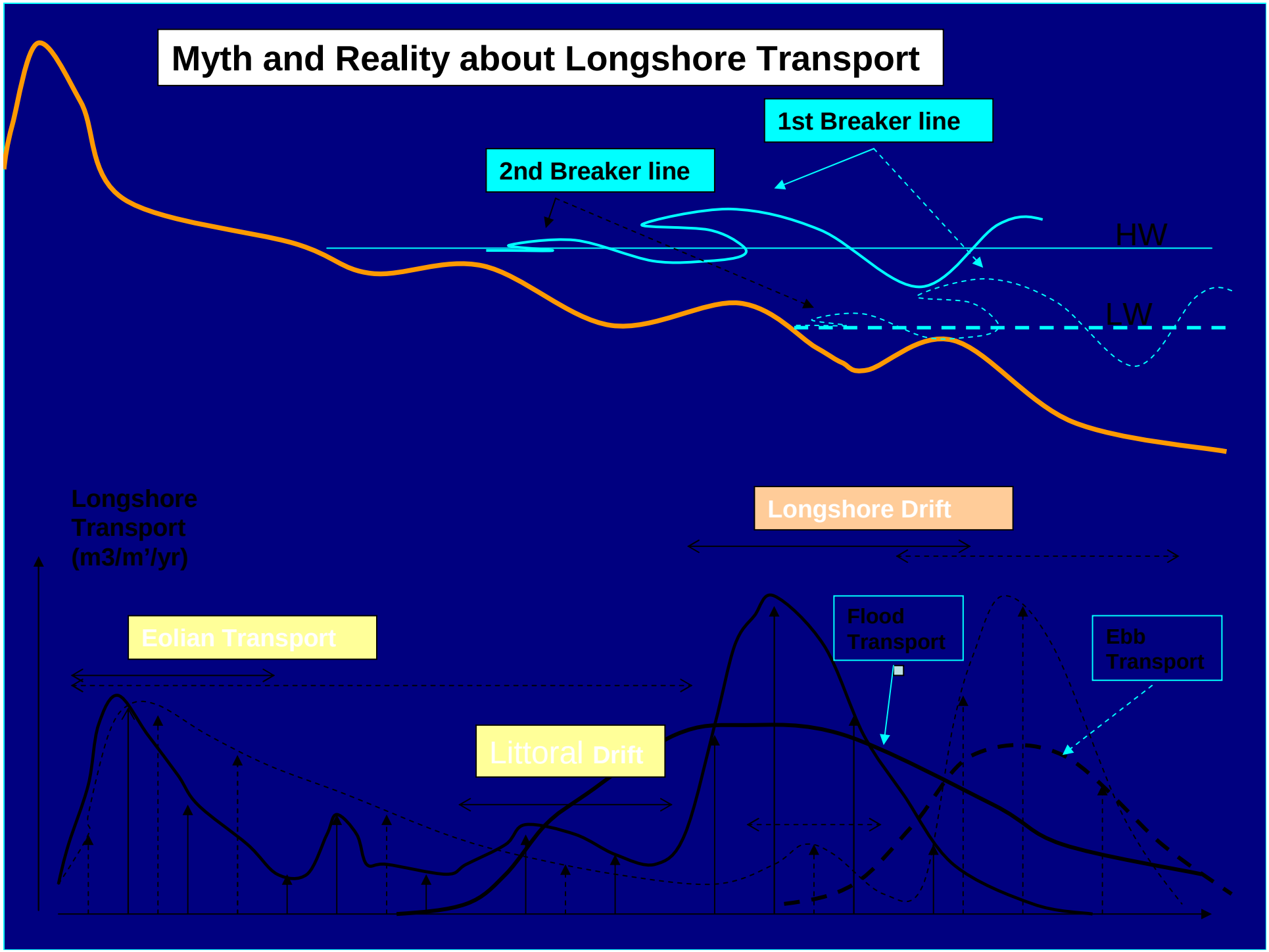
Surf similarirt parameter: Irribaren 1949

Sand-Transport Mechanisms in Coastal Systems

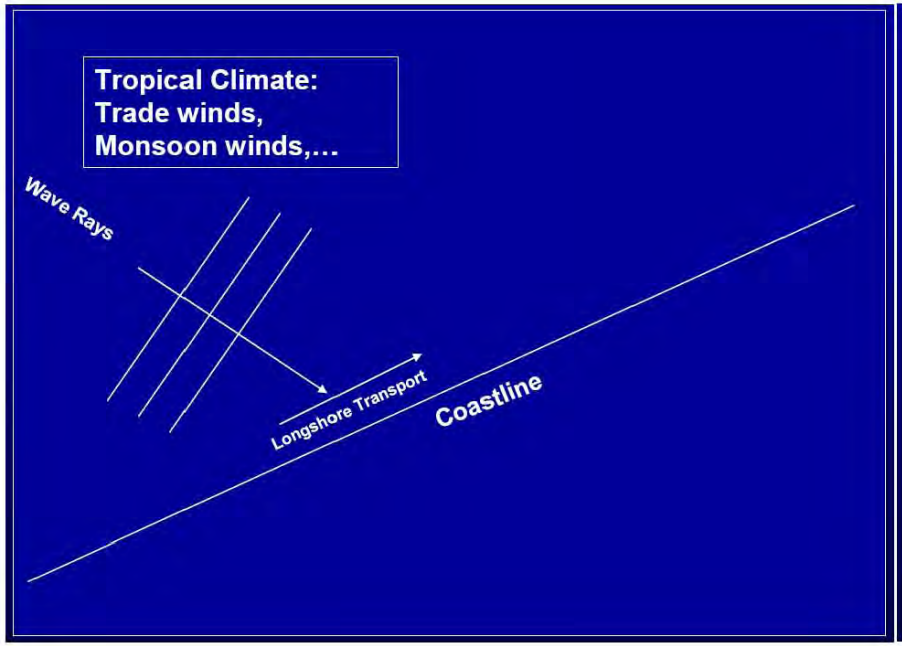


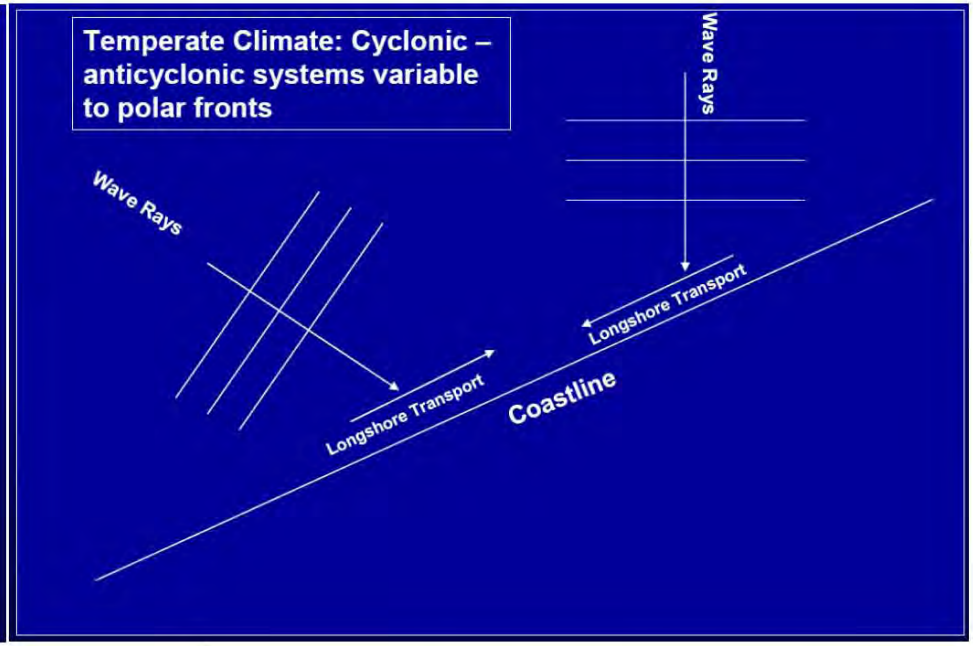
VLAAMSE BAAIEN 2100		
PROFIEL ZEESPIEGELSTIJGING		
SCHAAL	DATUM	ONTWERP
niet op schaal (A4)	10/05/10	RYS
mx	PLANNUMMER: VLAB-2-CS-003 REV.0	

Myth and Reality about Longshore Transport



Littoral drift and Longshore Transport



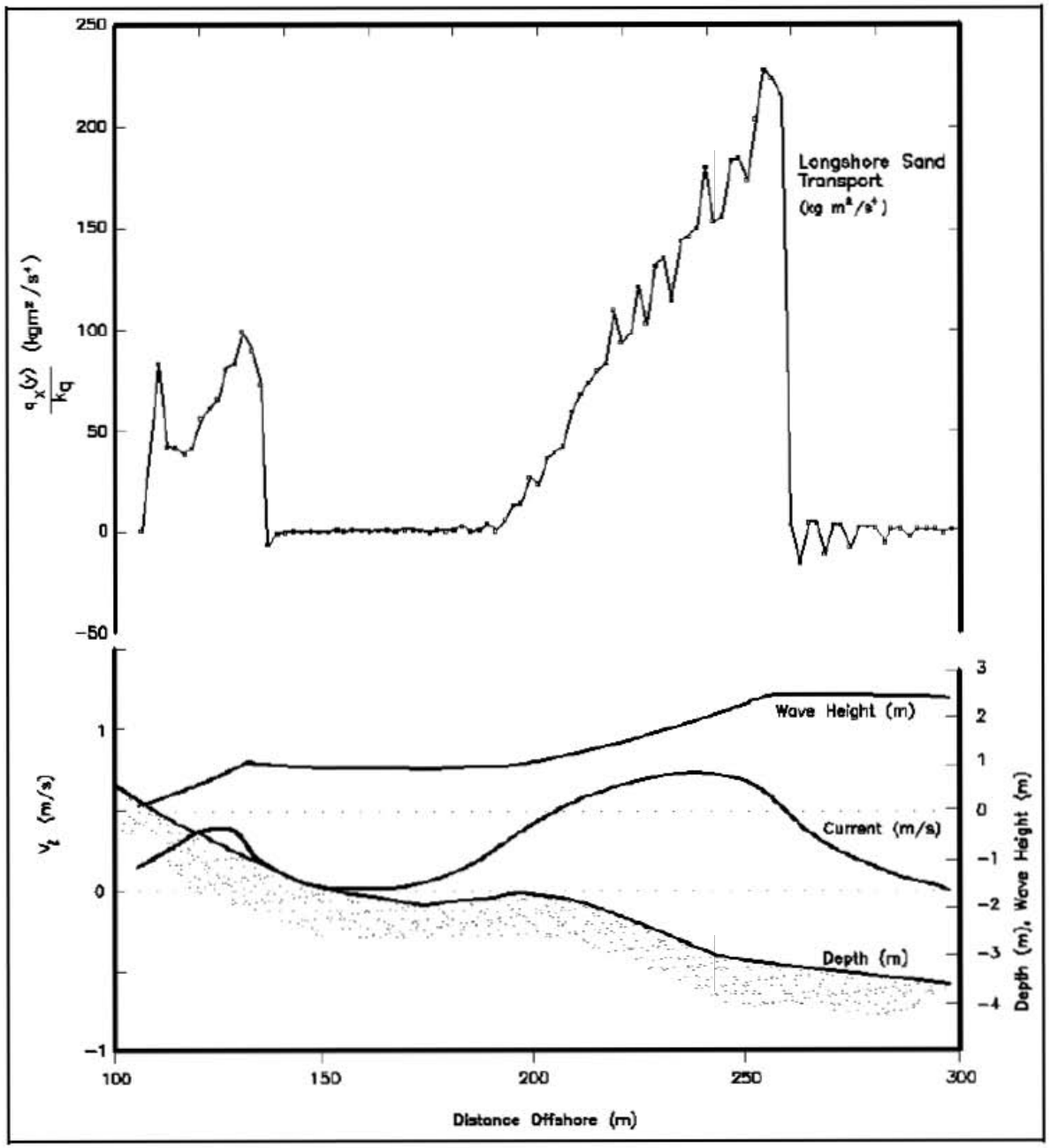


Cfr CERC, EM 2002

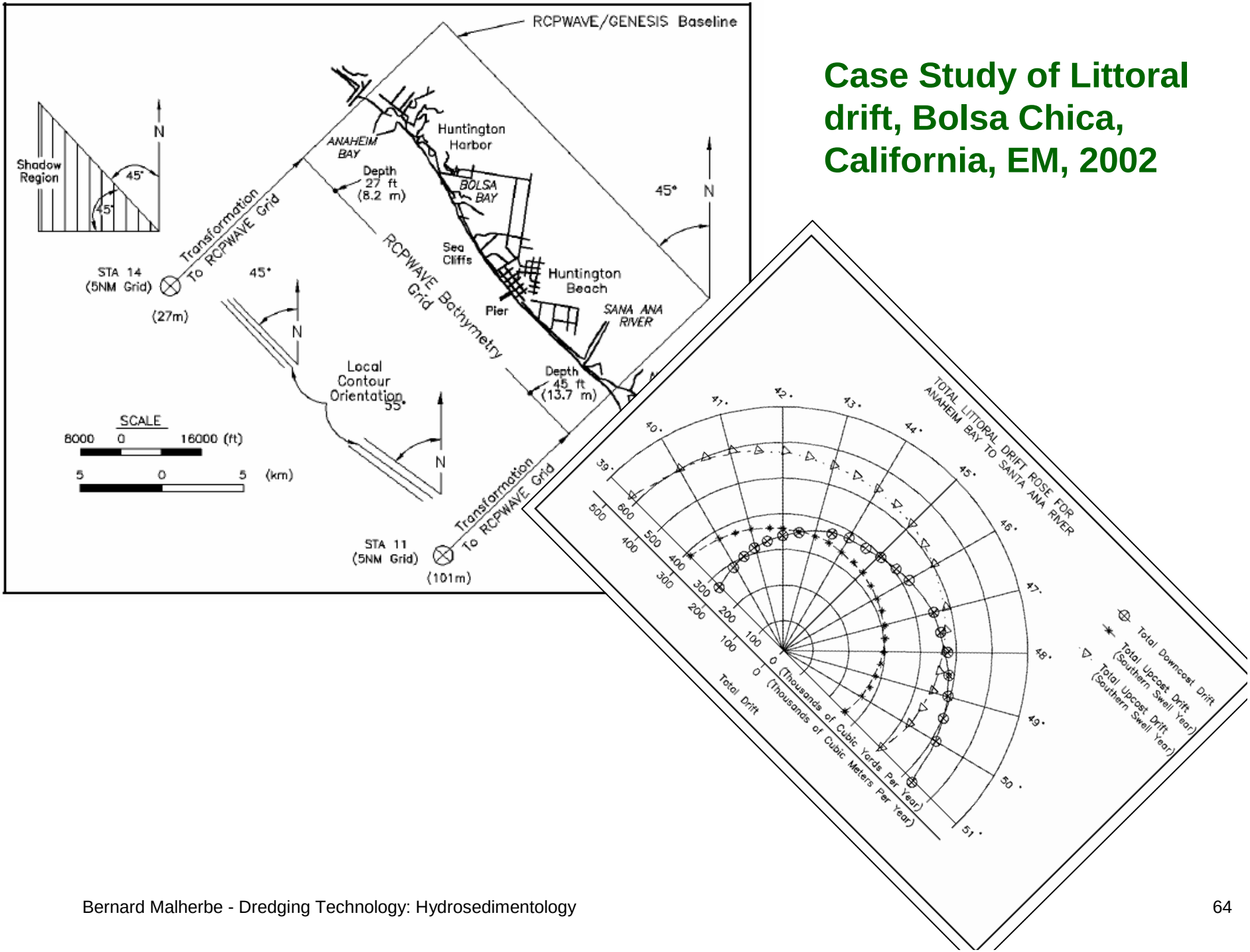
$$Q_\ell = K \left(\frac{\rho \sqrt{g}}{16\ \kappa^{\frac{1}{2}}\ (\rho_s - \rho)\ (1 - n)} \right) H_b^{\frac{5}{2}}\ \sin(2\alpha_b)$$

α_b	Wave breaker angle relative to the shoreline [deg]
κ	Breaker index H_b/d_b [dimensionless]
K	Empirical proportionality coefficient [dimensionless]
n	In-place sediment porosity (≈ 0.4) [dimensionless]
ρ	Mass density of water (salt water = 1,025 kg/m^3
ρ_s	Mass density of sediment grains (2,650 kg/
H_b	Wave height at breaking [length]

Example of Longshore current cq. Transport (ref EM, 2002)



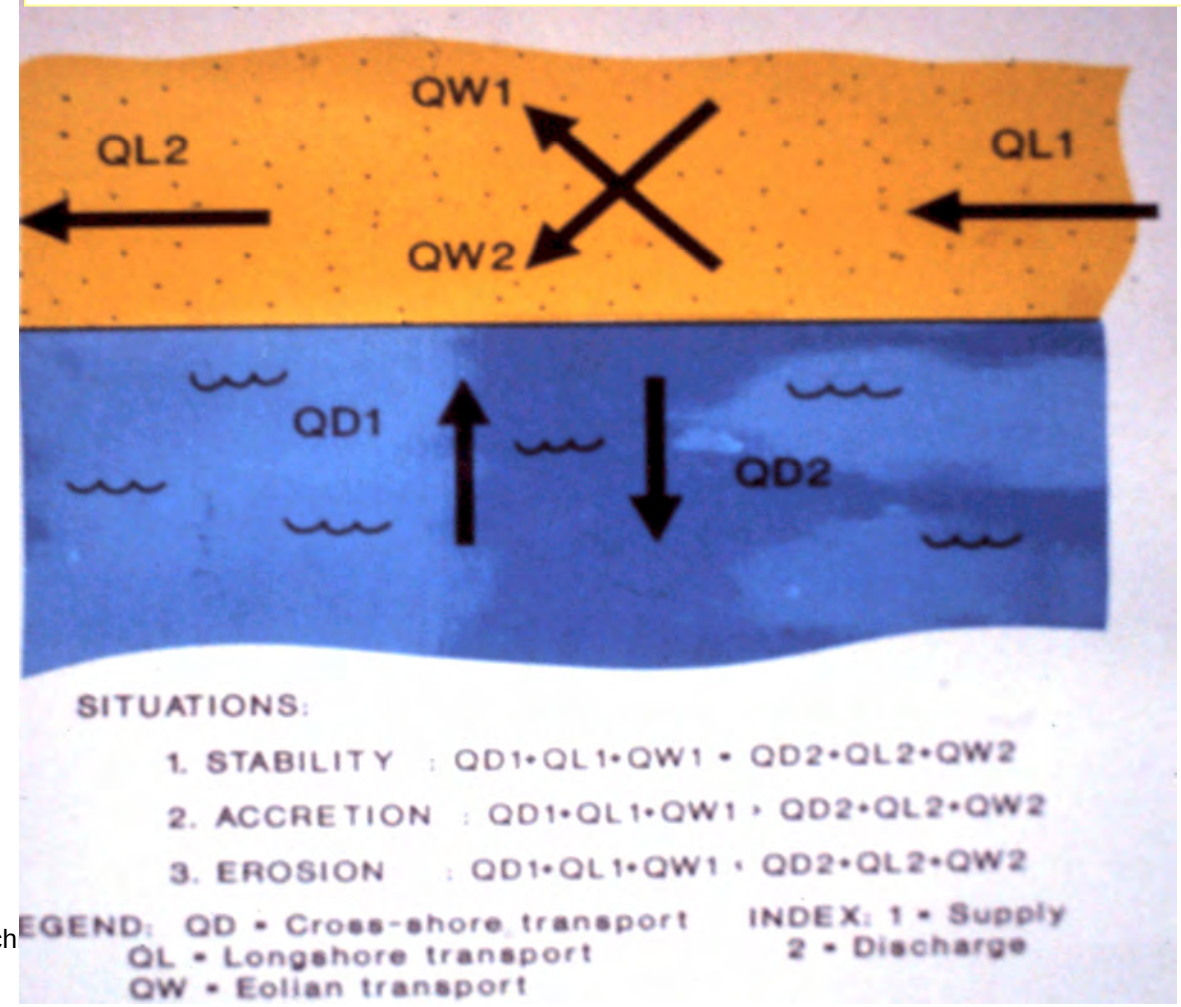
Case Study of Littoral drift, Bolsa Chica, California, EM, 2002



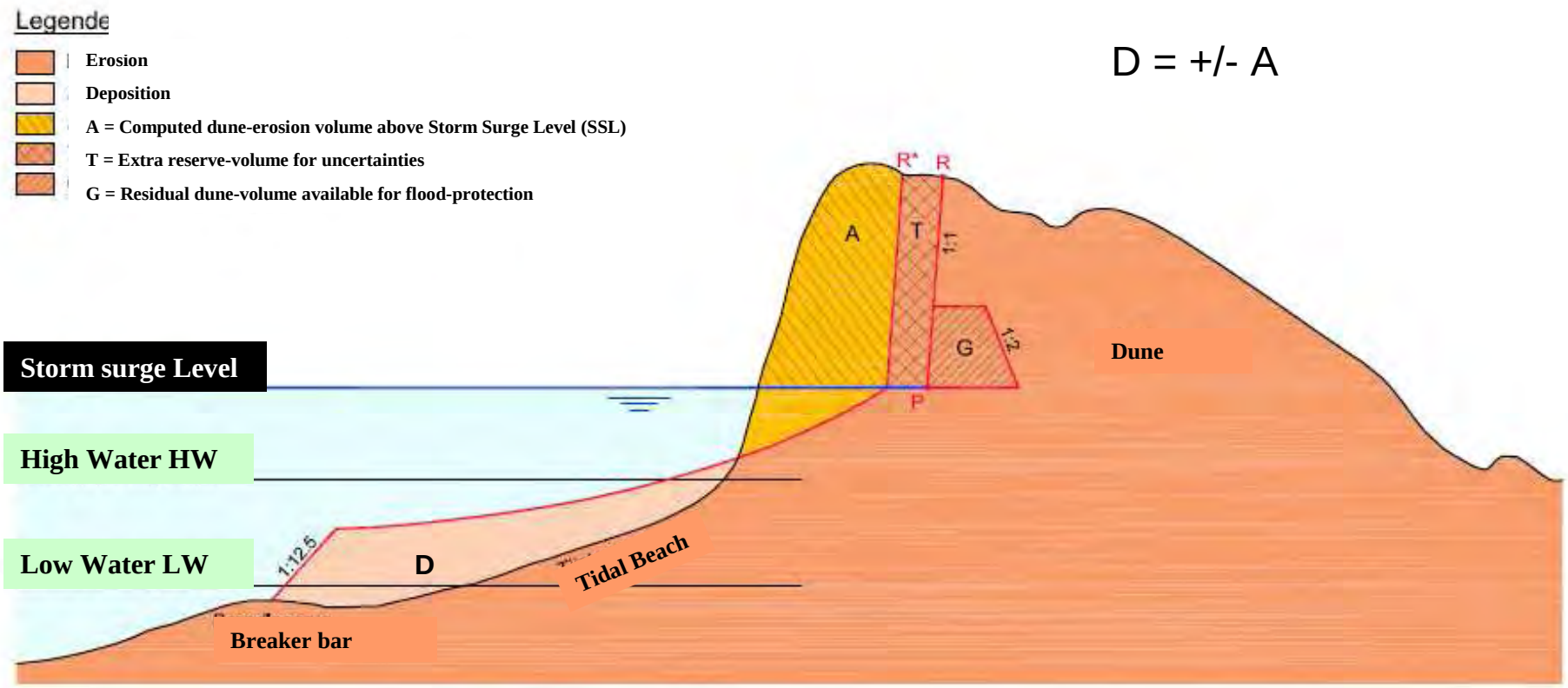
Temperate Climate with equilibrated longshore transport

Dynamic stability principle of a beach-dune system

A beach-dune sandbar is always a dynamic equilibrium between sand supply and sand-discharge



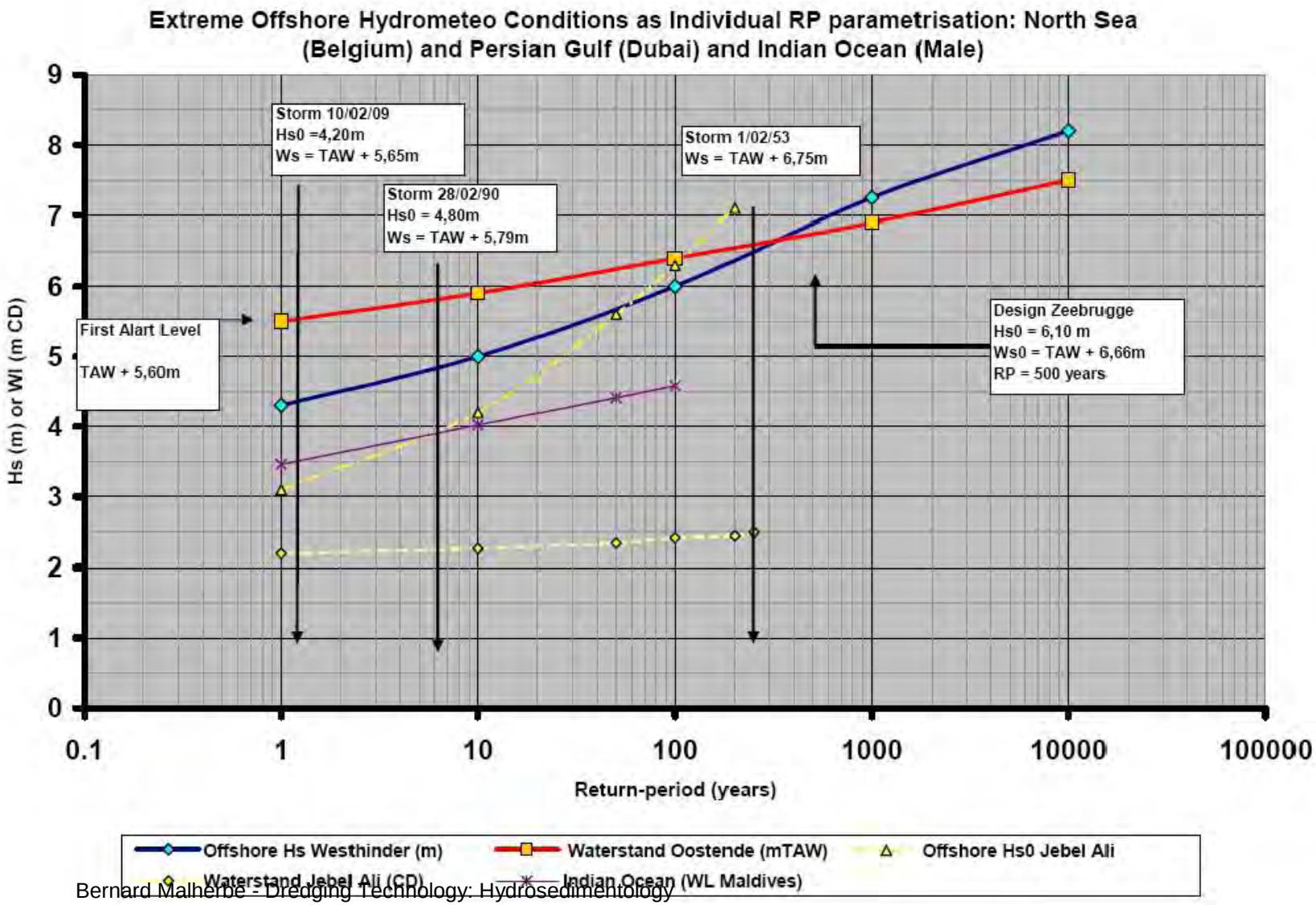
Cross-shore response of dune/beach systems to extreme events



Major causes of beach & dune erosion ?

- **desequilibrium between sand-supply and sand discharge: the system suffers a sand shortage**
- **beach erosion is most critical and visible when hard structures – sea-dikes, groynes, breakwaters – are constructed…because they are unflexible versus the morphodynamics**
- **hard structures may modify the current and wave pattern…thus affecting the hydrodynamic forces**
- **Sea-level rise and global changes ?**

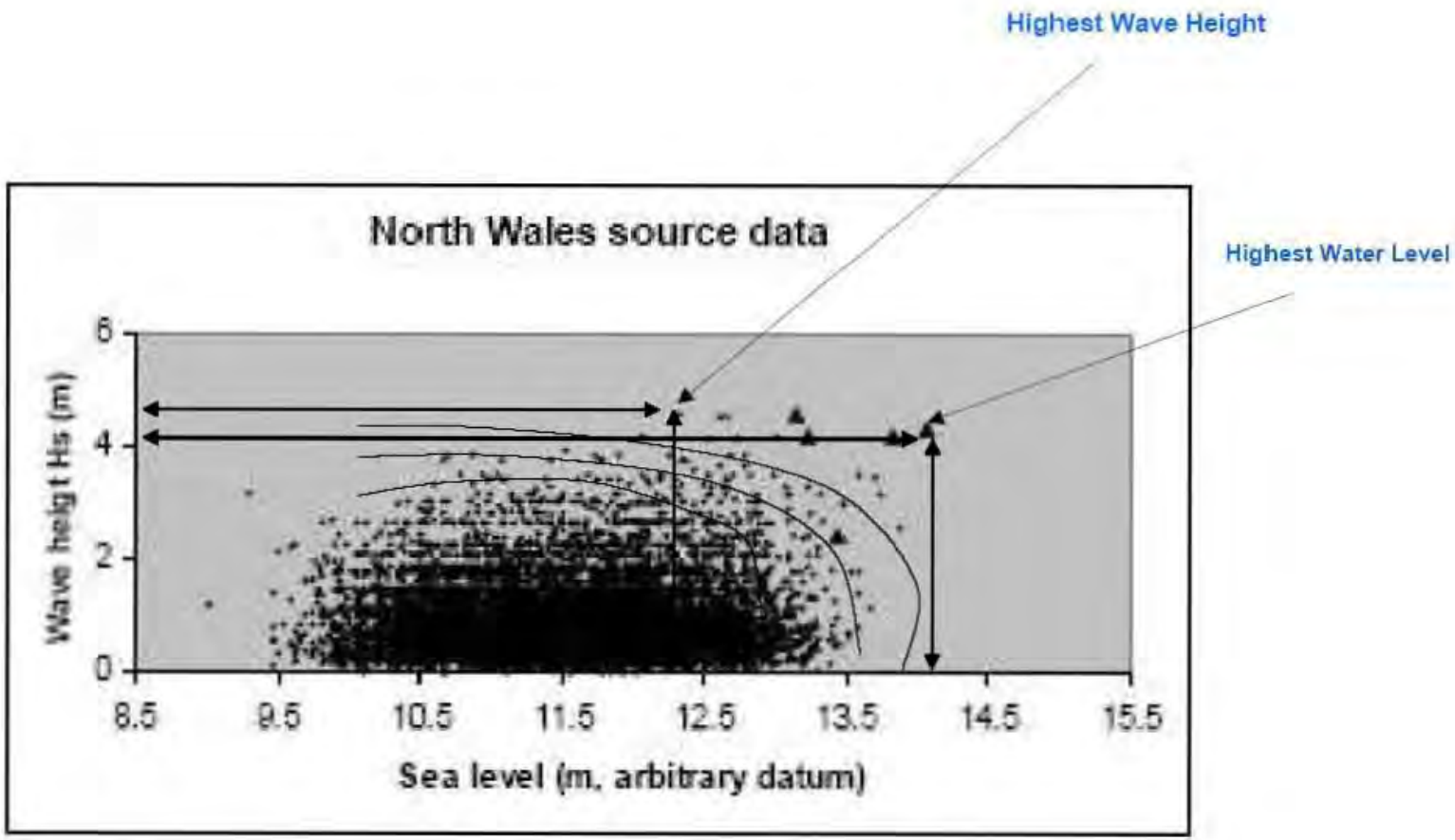
Deduction of Extreme Hydro-Meteo Design Conditions



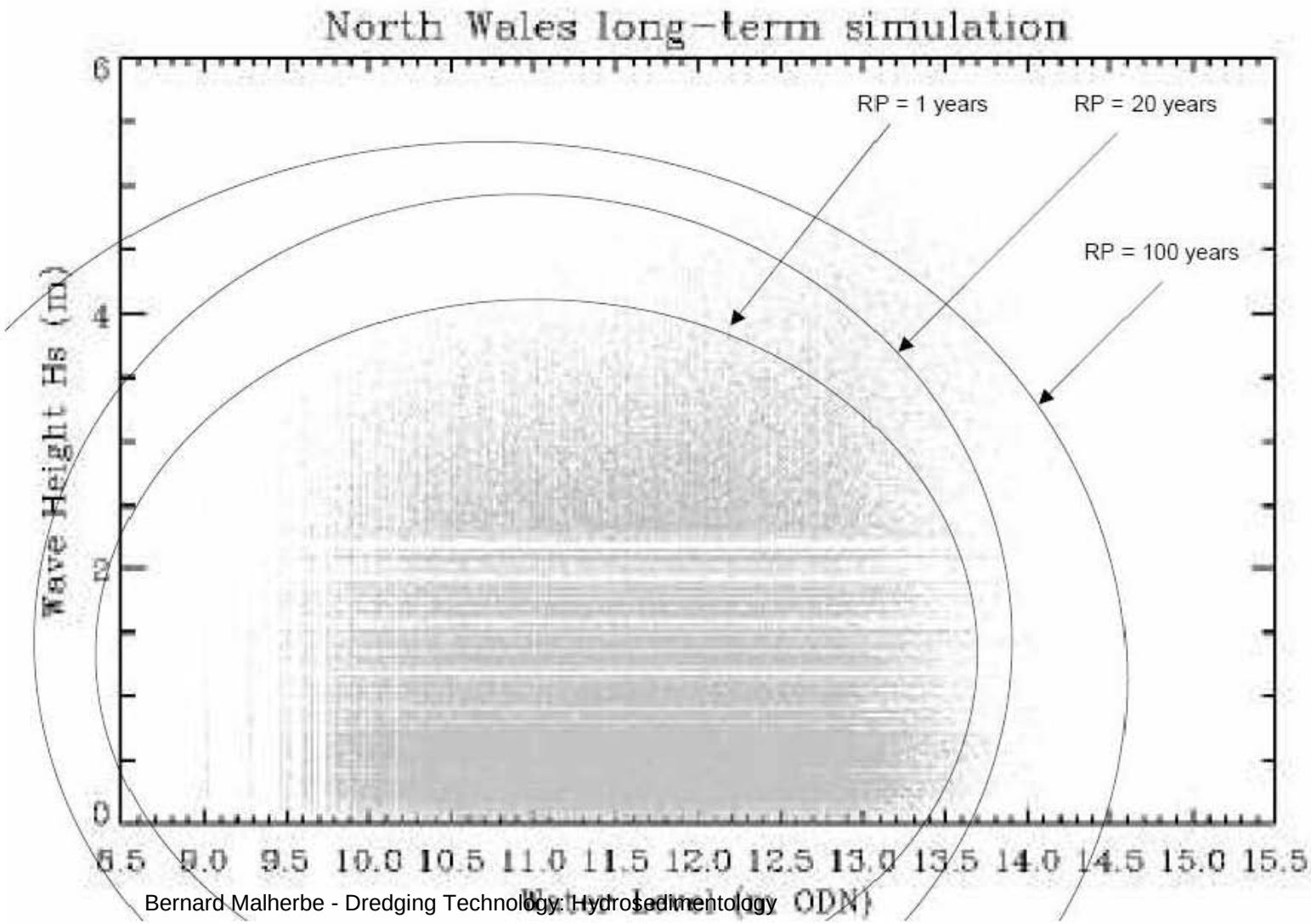
Storm events along the Coast

Picture by Stefaan Ghyssens, 2009

Joint Probability Analysis of extreme Hydro-Meteo conditions

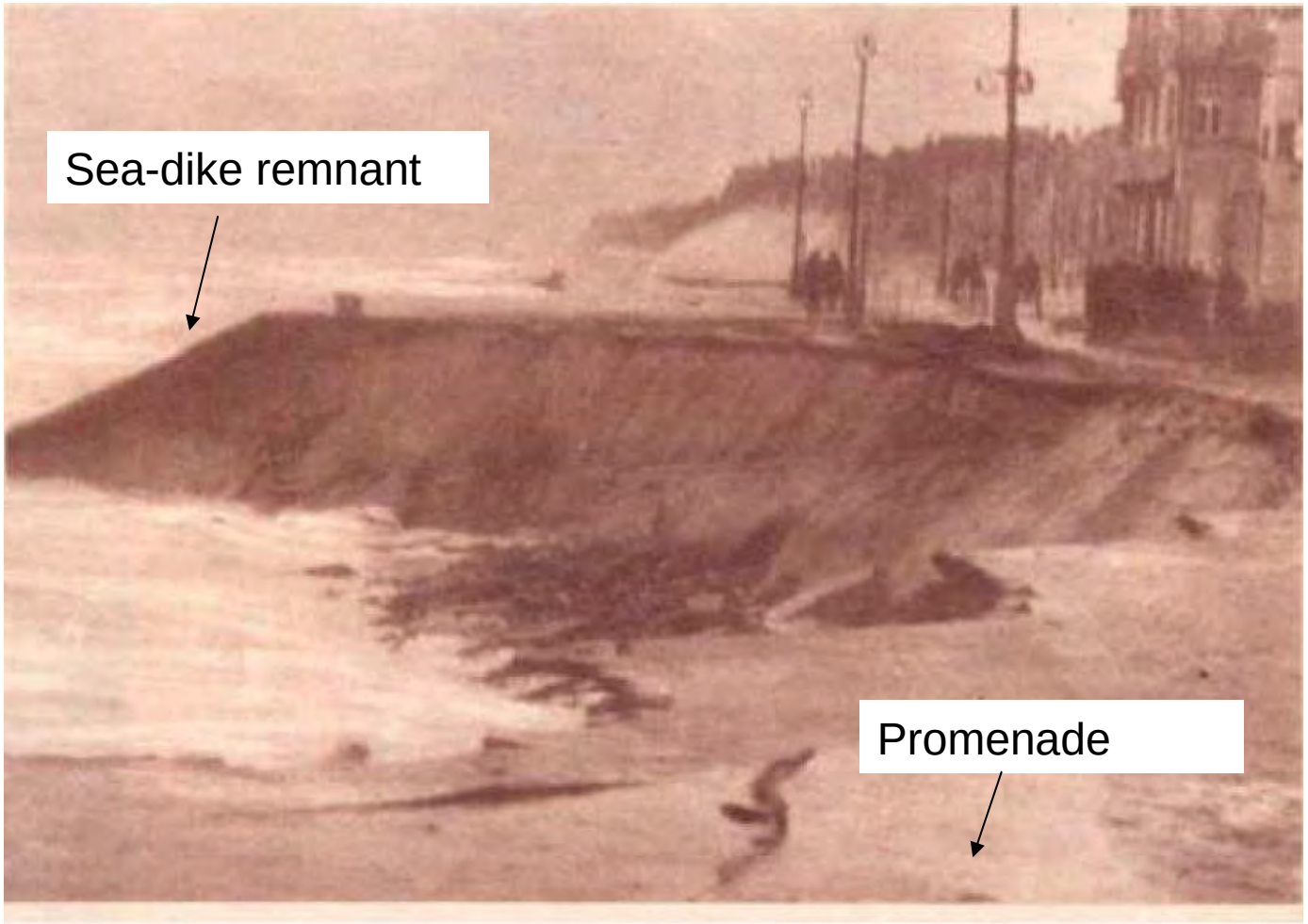


Joint-Probability Analysis of HydroMeteo (ref DEFRA, 2007)



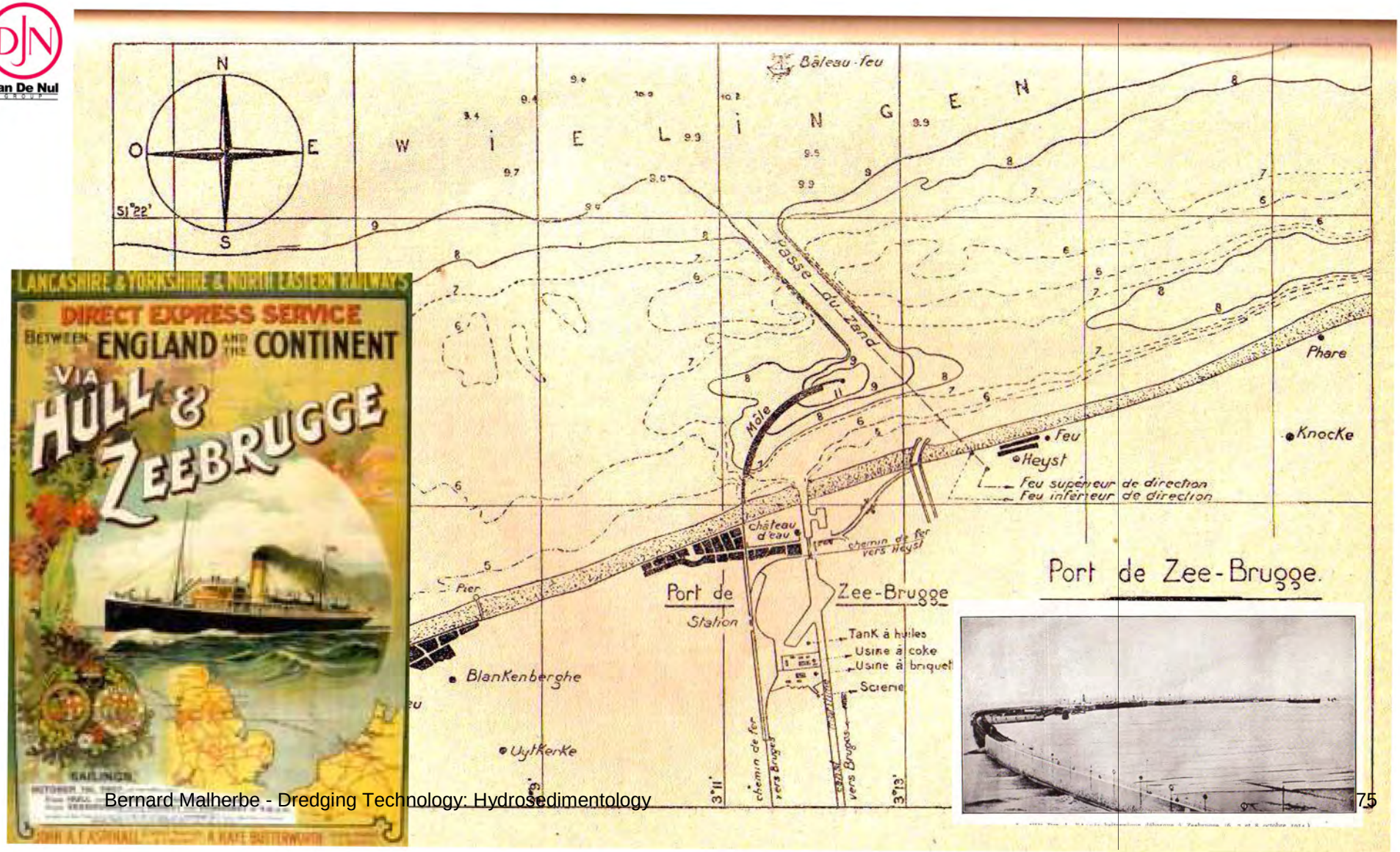
Failure of Sea-Dike structures

Duinbergen, February 1953 (Vandenbossche et al, 2006)



80 years of hard sea-defence – seadike & groyne fields

The Belgian Coastline was almost unhabitated at the turn of the 20th century. The government decided to implement the Port of Zee-Brugge (anno 1898-1903)



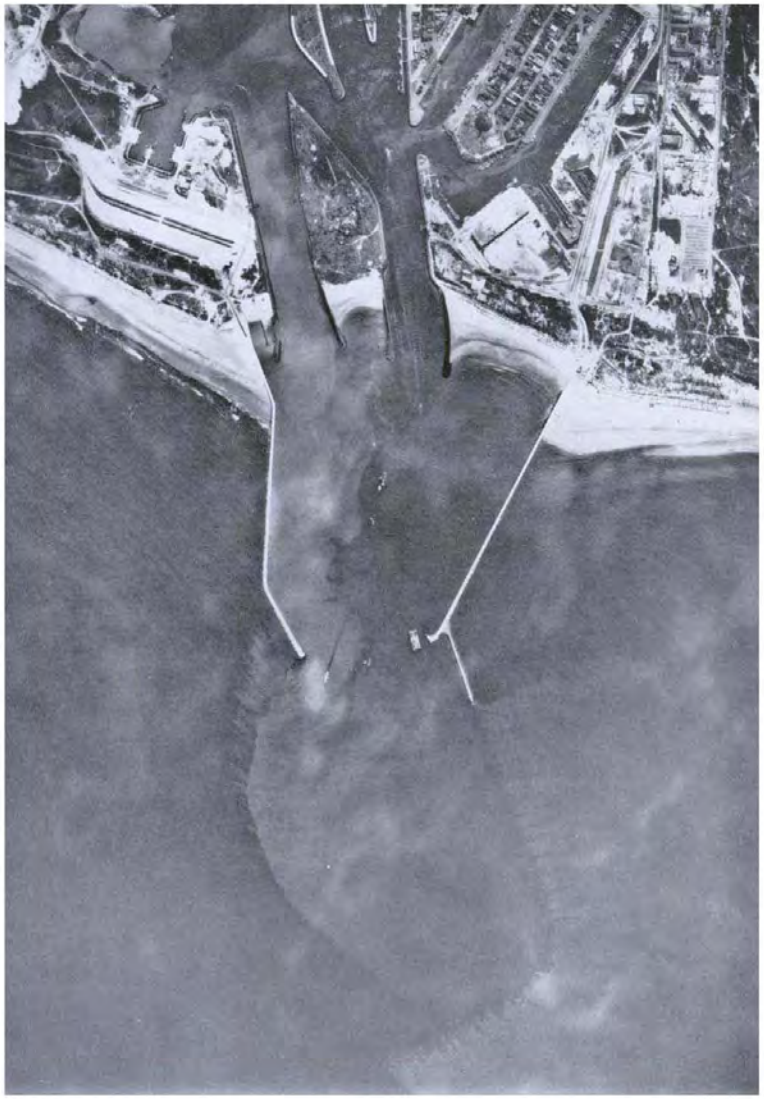
Example of coastal sediment-dynamics in Temperate Climates

Creation of sand-bows between hard spots by cross-shore, longshore transport and eolian transport

Port of Zeebrugge (1906), anno 1970

Port of Zeebrugge , anno 2003

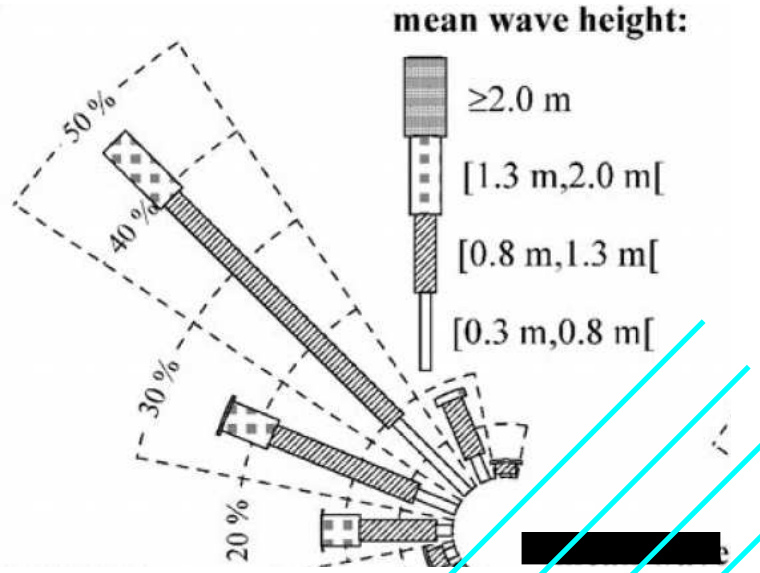
Example of coastal sediment-dynamics in Temperate Climates

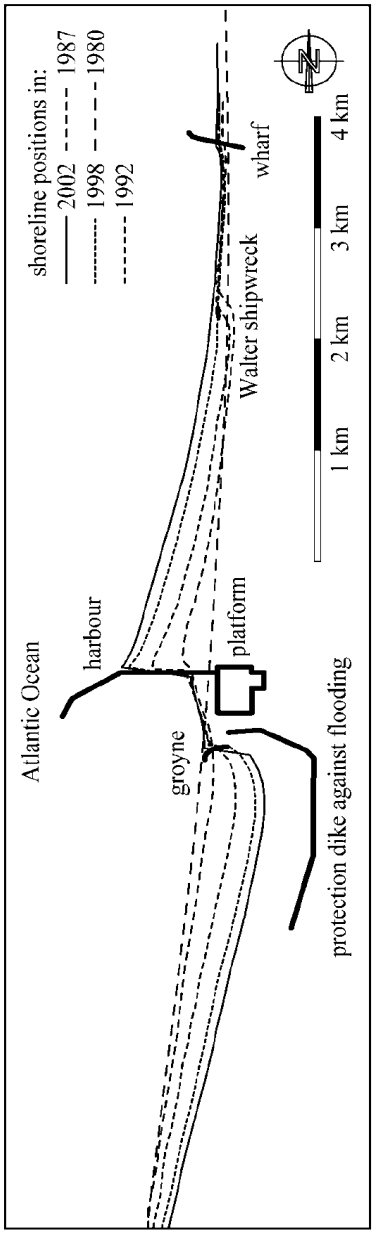


Port of IJmuiden (Nl), anno 1963

Port of IJmuiden (Nl), anno 1995

Longshore transport may become pre-dominant in cases where mono-directional wave propagation prevails : example of Tropical Climates

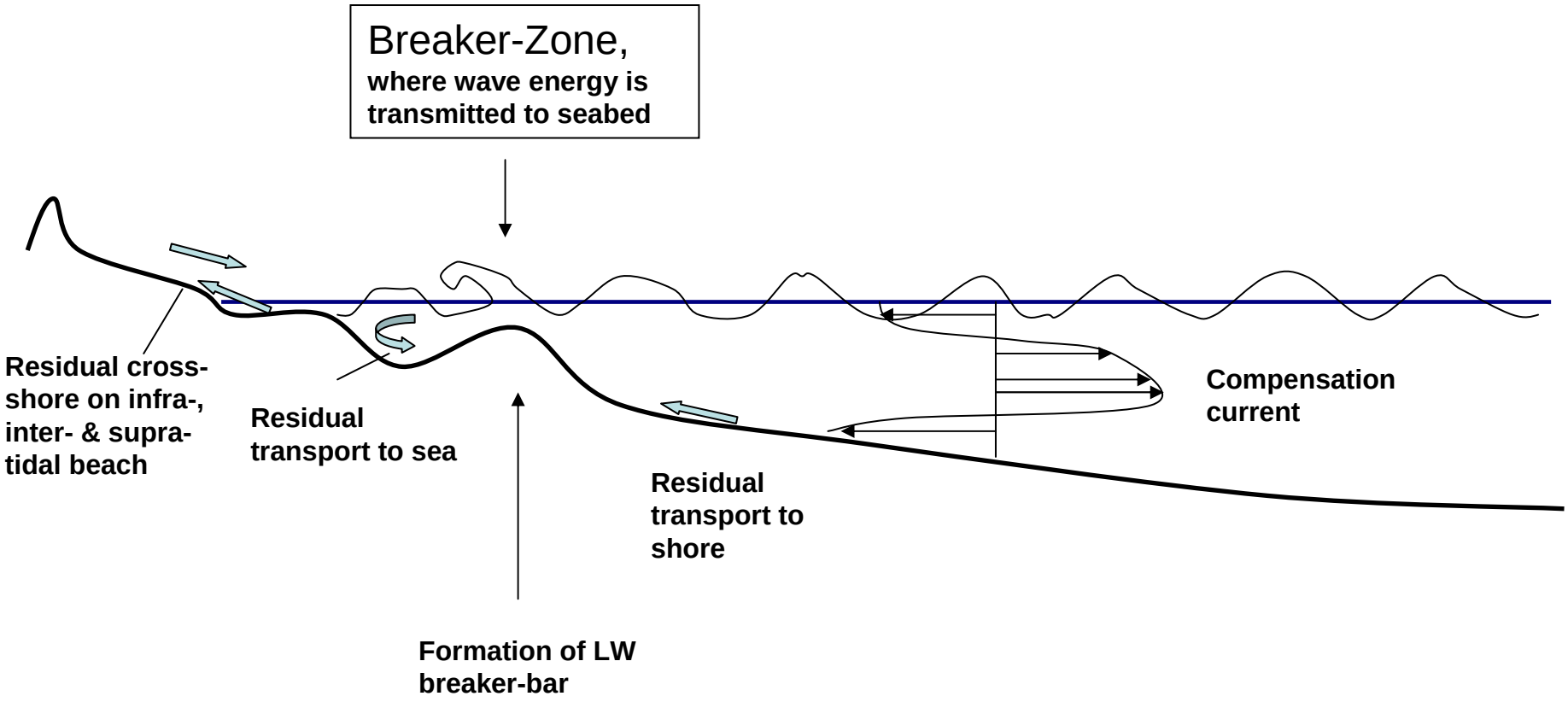




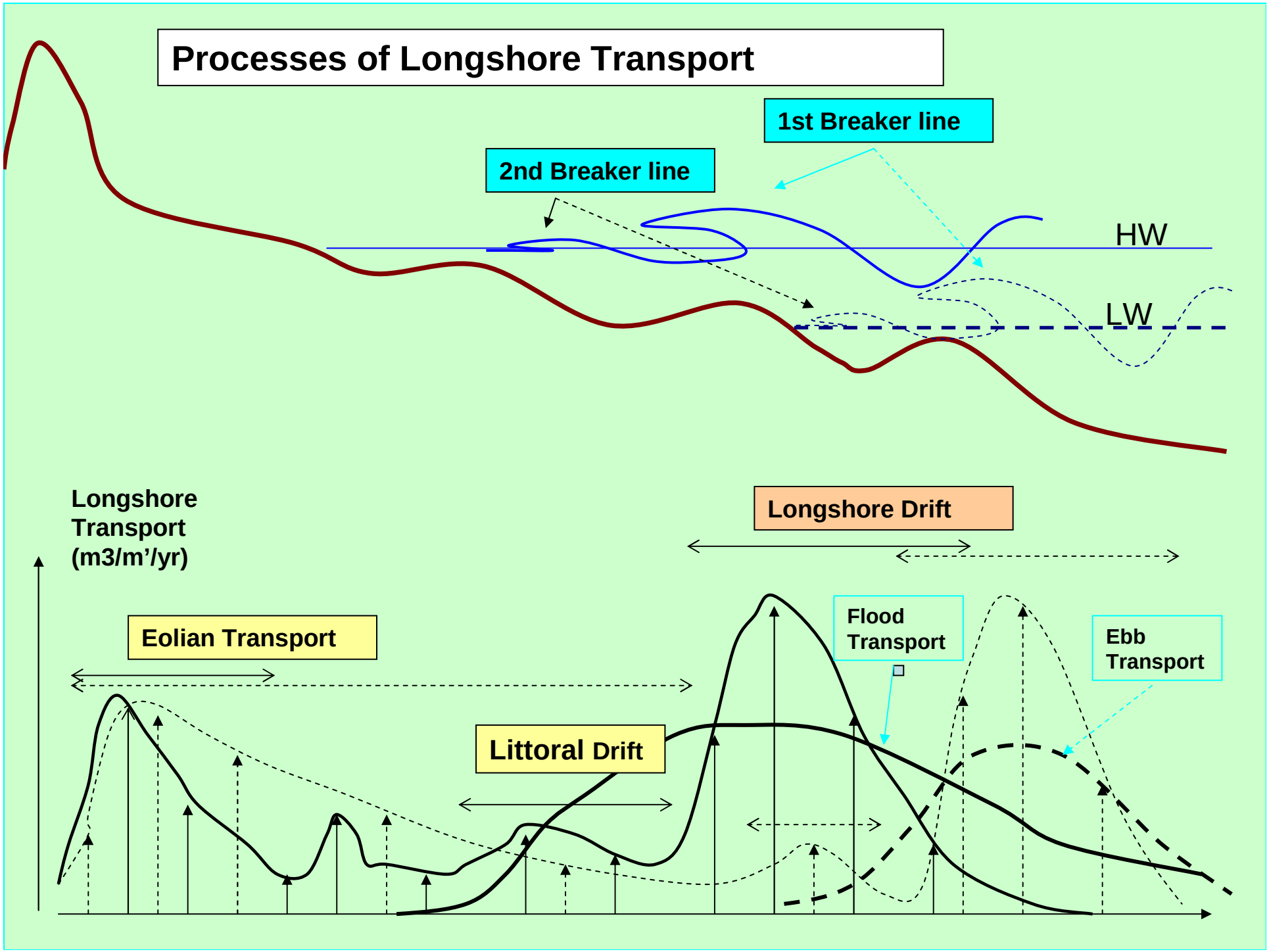
Beach-bow formation between hard spots

Beach-bows between ‘hard spots’

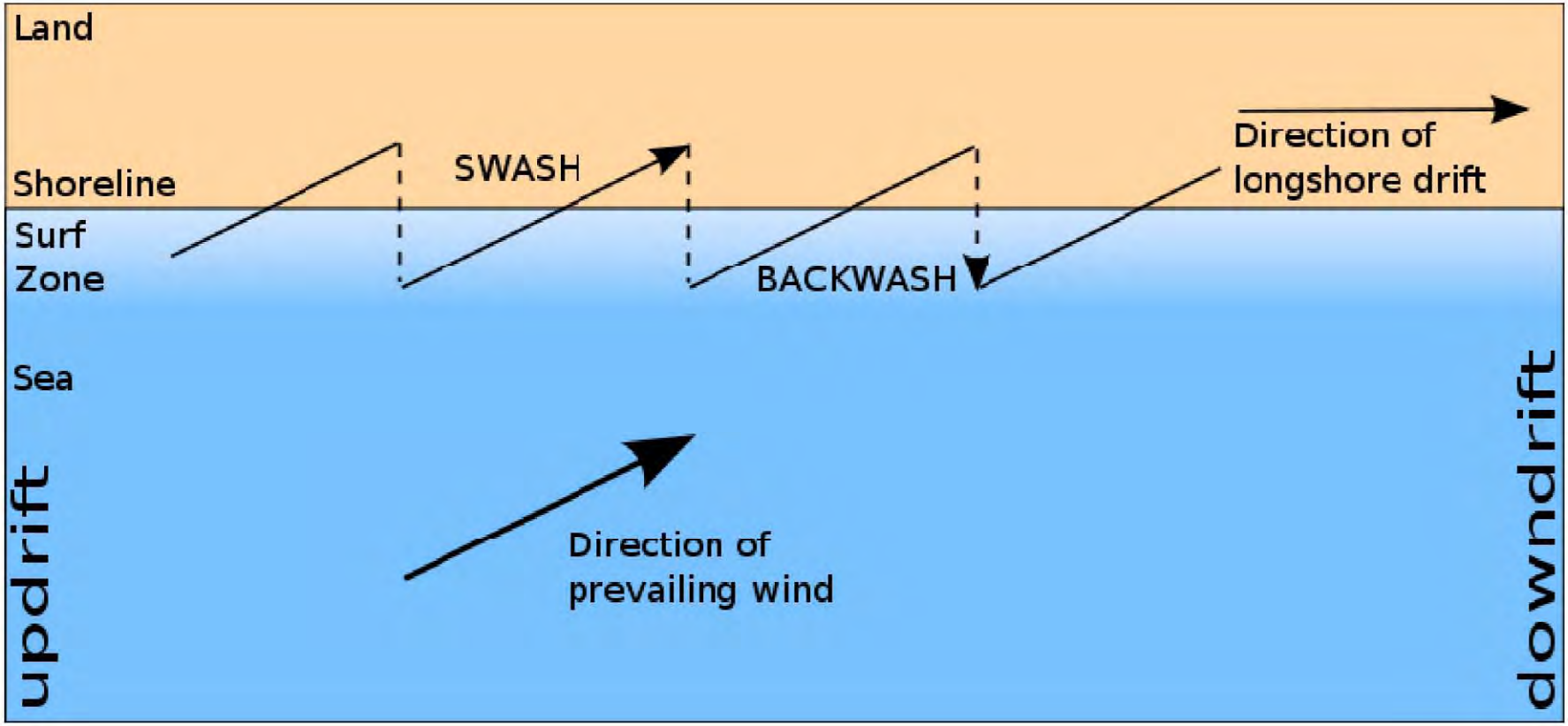
Sediment-transport under wave action in shore-approach



Processes of Longshore Transport



Littoral Drift induced by wash/backwash on Tidal Beach

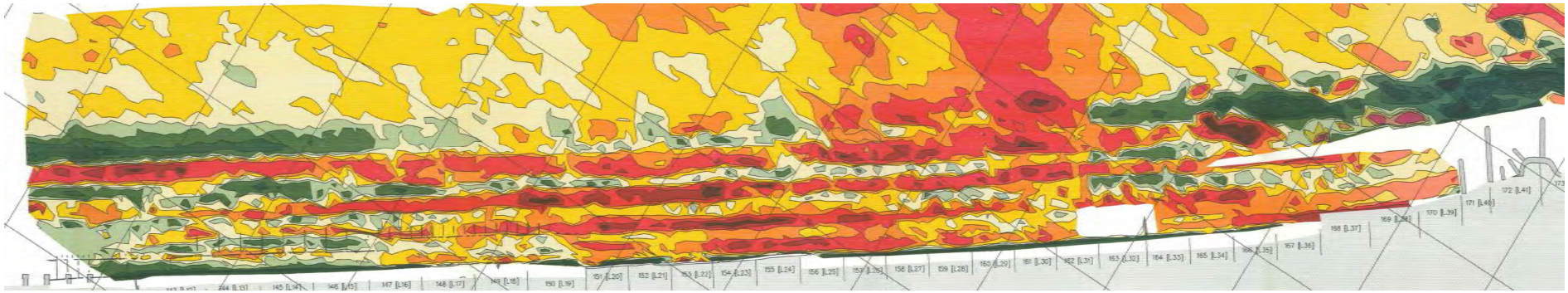


Facts & Figures about Sediment-Transport in Nearshore processes

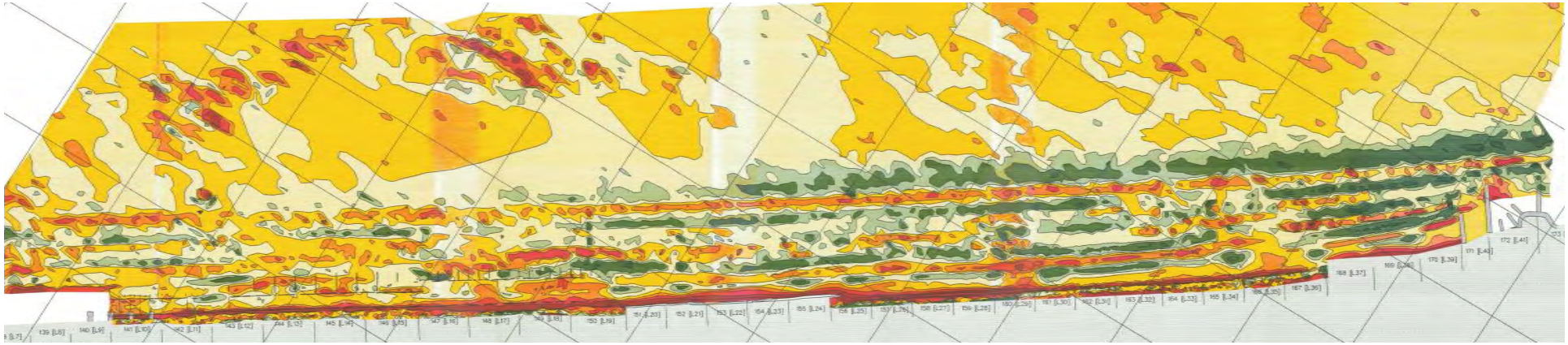
Tools to determine (residual) sediment-transport:

- Differential mapping of submerged, inter-tidal and supra-tidal beach & dune (before and after a storm, over longer periods,…)
- Fluorescent, magnetic, radio-active ,…tracers
- Sediment-capture traps
- Numerical sediment-transport models (prudent use! Difficult to calibrate or to validate)
- Physical models with movable bed: careful use because of difficulty to upscale sand-particles (Froude- similitude)

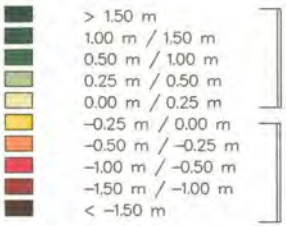
Illustration of Cross-Shore Beach & Dune Dynamics: differential maps (HAECON, 1995)



Coastal Stretch Bredene, Vosseslag, De Haan, Vlissegem, Wenduine: 1976 - 1987



Coastal Stretch Bredene, Vosseslag, De Haan, Vlissegem, wenduine: Nov 1989- March 1990: the result of a 1/63 yr RP storm

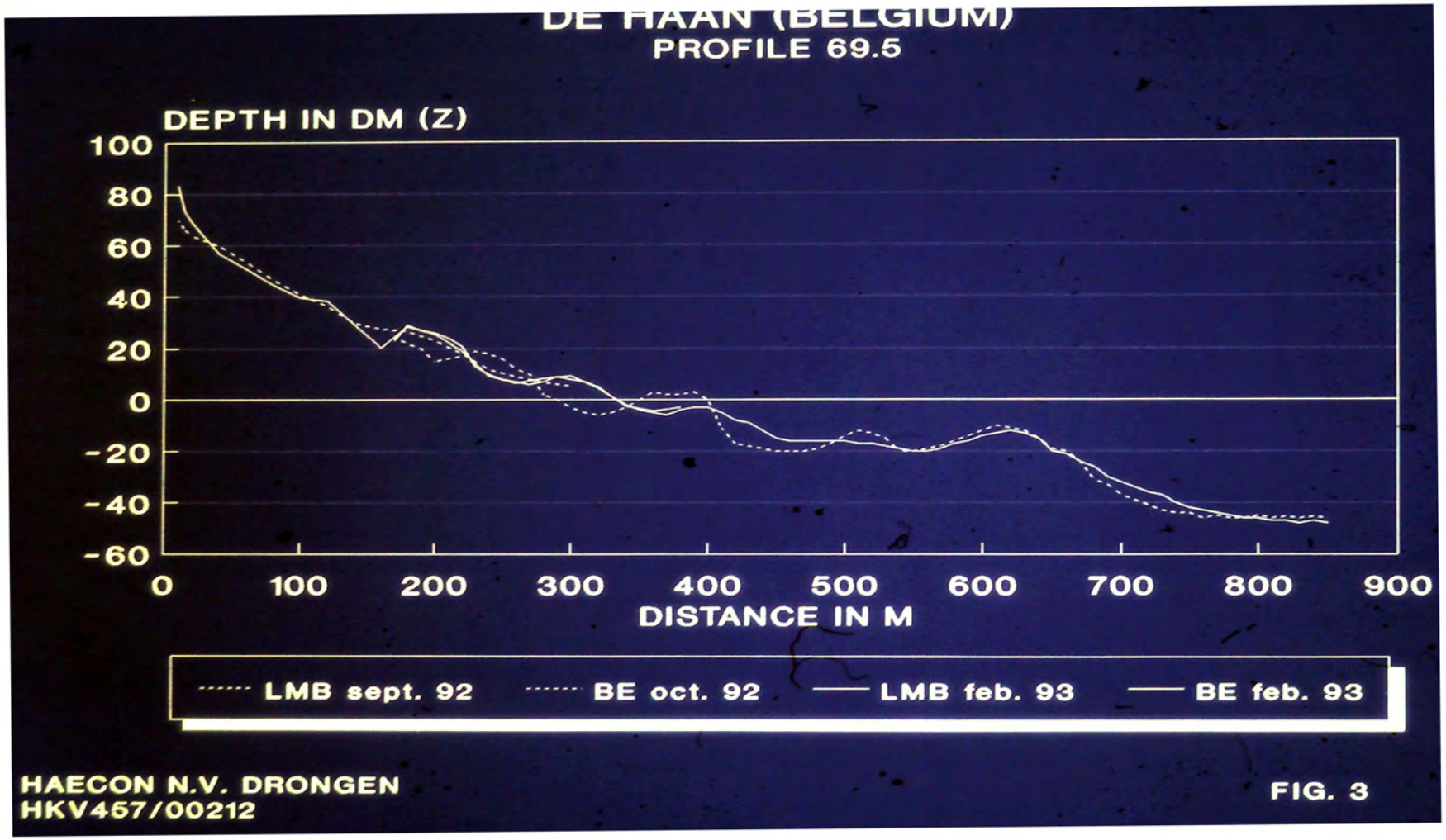


Sedimentation

Erosion

Dominating cross-shore transport reflected in ridge & runnel beach morphology

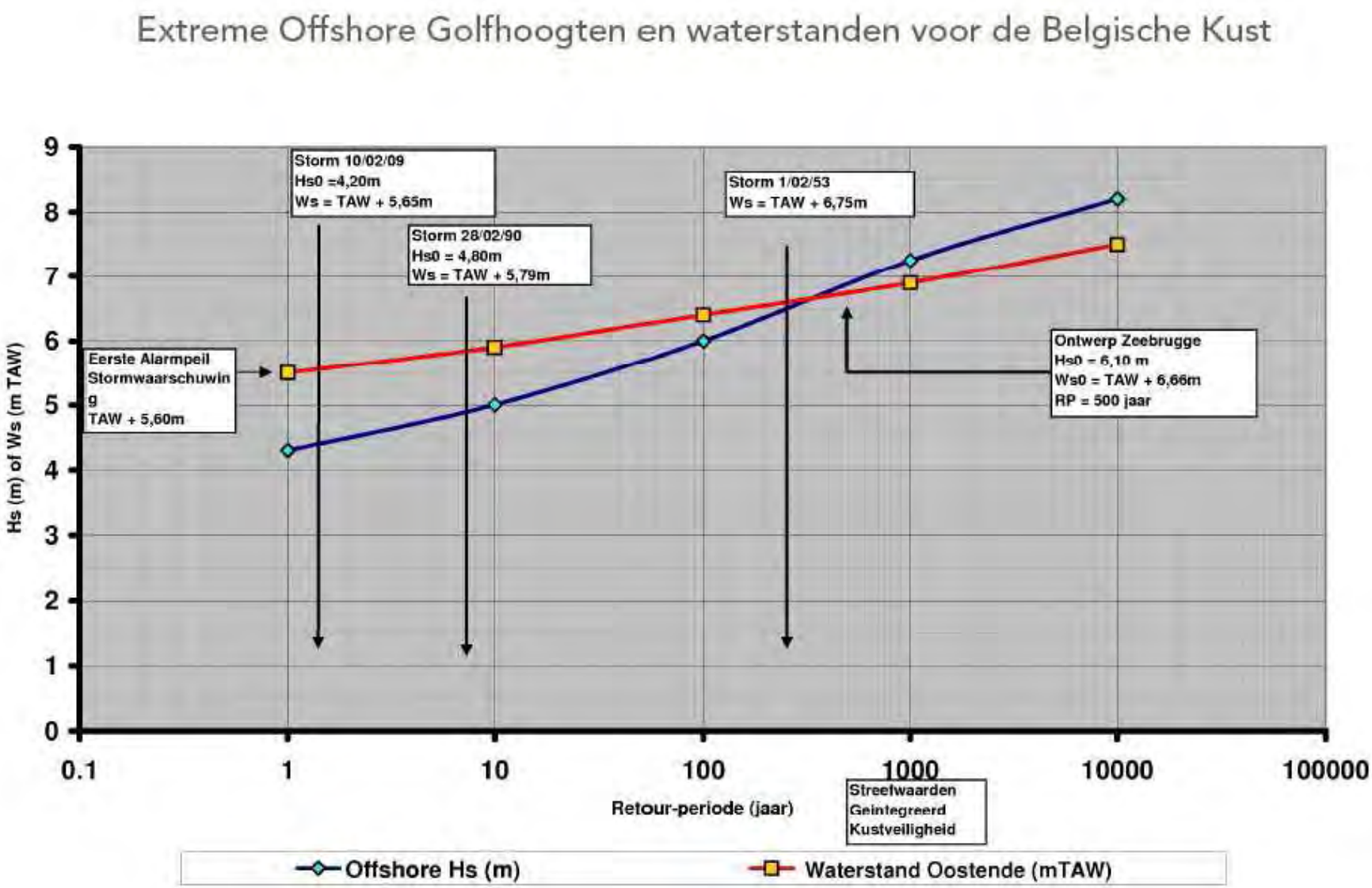
Illustration of crosshore morphodynamics in ridge & runnel beach/dune system



Values of sediment-transport in beach systems:

- **Ridge & runnel beach systems in Temperate Climates (Belgian North Sea Coast):**
  - **Cross-shore transport (determined by differential mapping): 10 - 70 m3/m'/year to 30 -90 m3/m'/event (storm) , with residuals in the order of 20-50m3/m'**
  - **Longshore intertidal beach transport (fluorescent tracers): 0,05 m3/m'/day (year for 300m wide beach: 5.000 to 6.000 m3/year)**
- **Microtidal beach systems in Sub-Tropical Climates:**
  - **Longshore transport: 500.000 – 1.000.000 m3/year**

Extreme hydro-meteorological conditions used for coastal protection



80 years of hard sea-defence – seadike & groyne fields

Beach-bows forming between hard “head-lands”

Regional beach-Bows: Southern Bight of North Sea

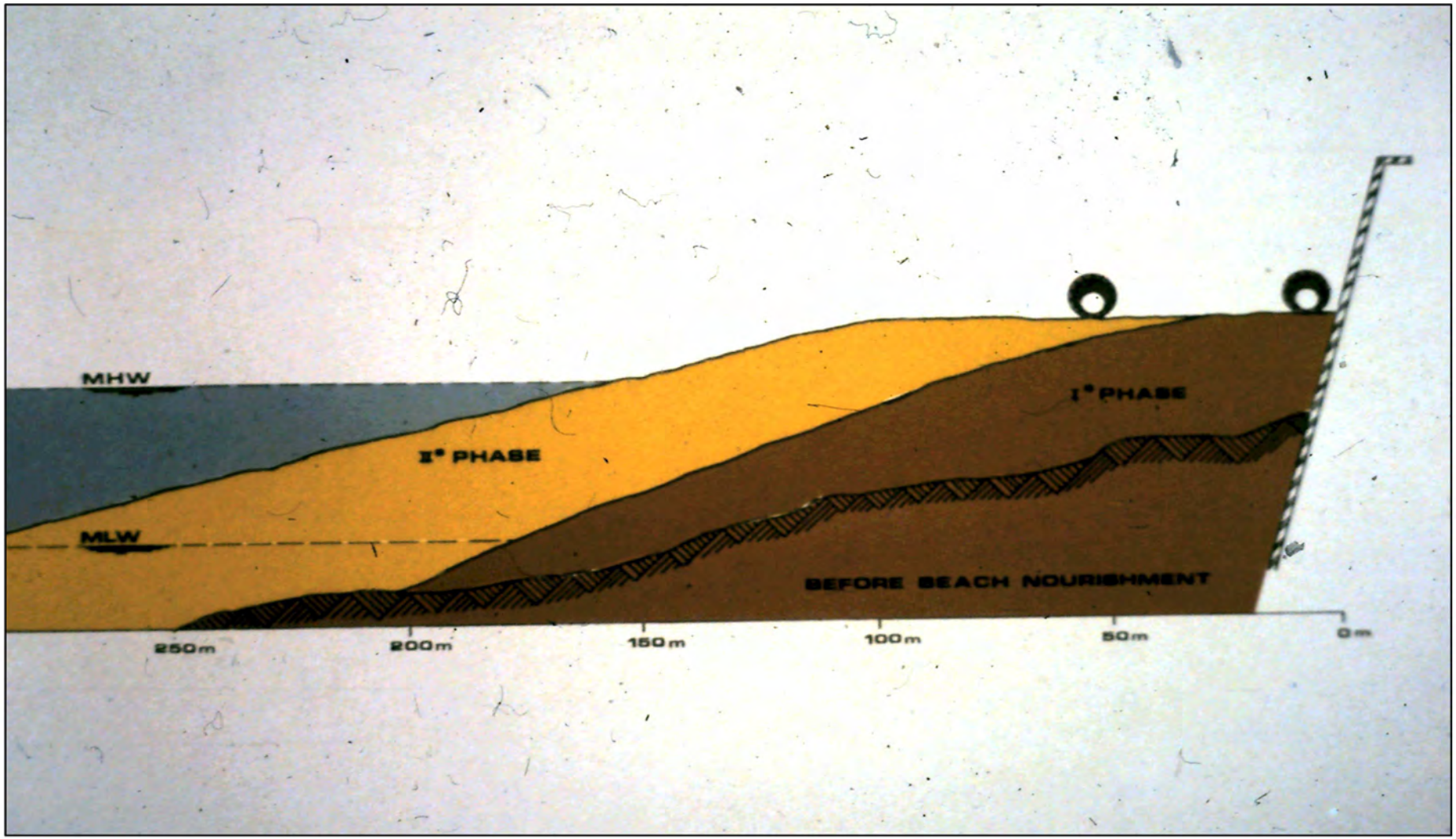
Beach-bows between ‘hard spots’

Coastal Protection by Beach-Reclamation

Knokke, anno 1962

Knokke, anno 1979

Knokke-Heist Beach rehabilitation scheme (1978/1979): about 1.000 m3/m' fill-density



Island of Sylt, Germany: beach & coastal protection rehabilitation scheme

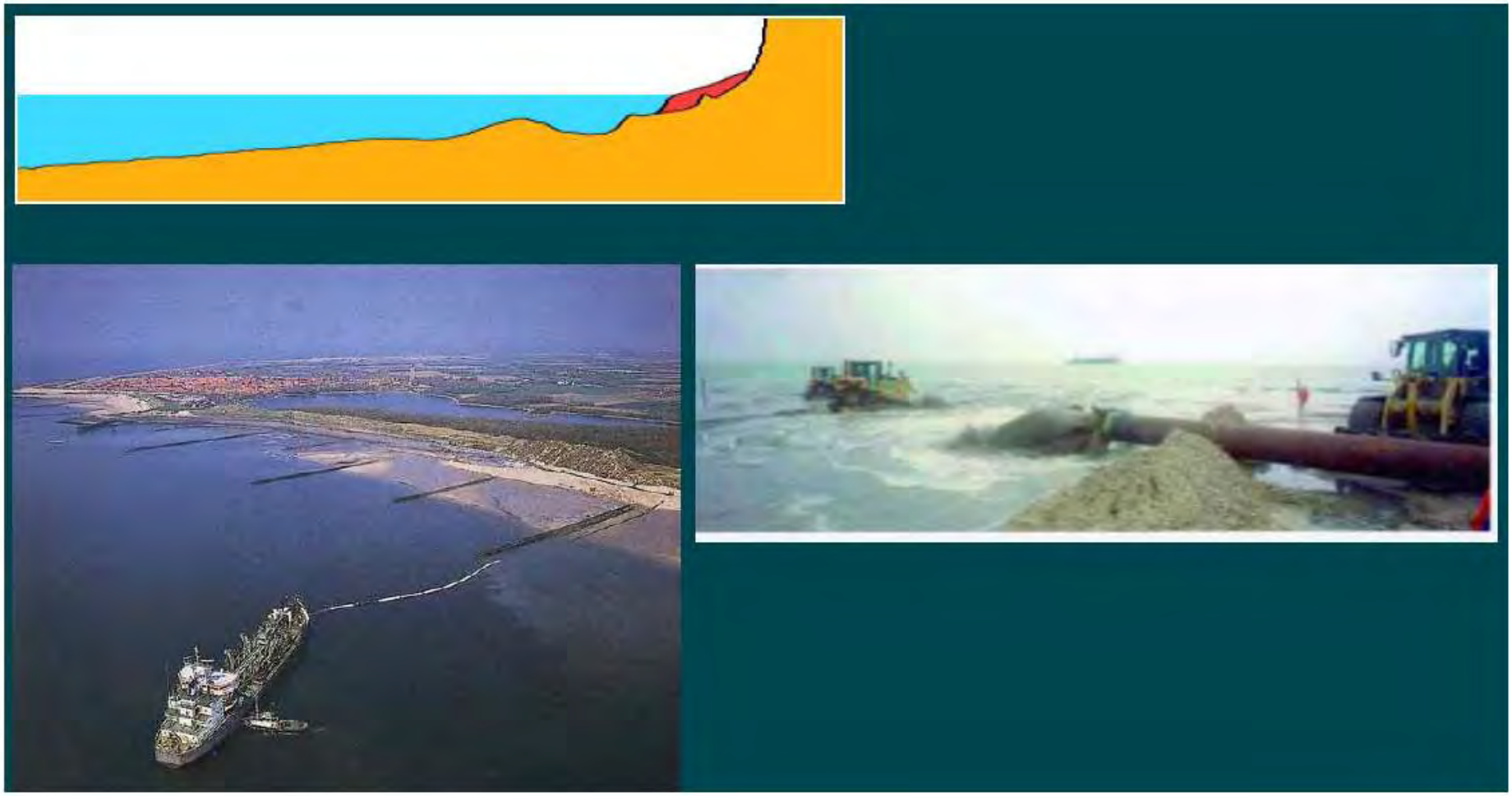
Hydraulic fill of the supratidal beach (750 m3/m') and…

…tidal-beach profiling to install natural beach-slopes

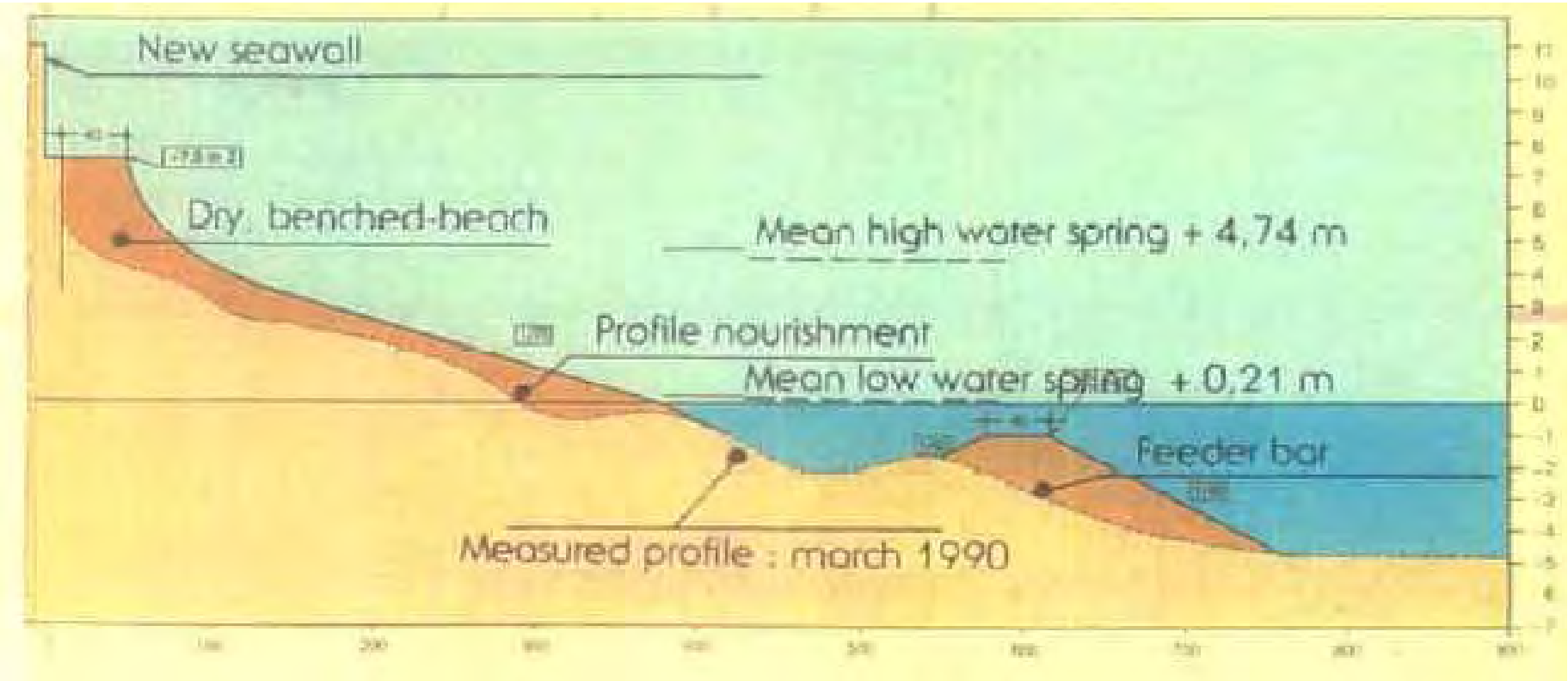
End-Result:

- **a wider supratidal beach acting as a buffer for extreme conditions**
- **a bigger volume of sand available in the inter-tidal and sub-tidal beach for dynamic response**

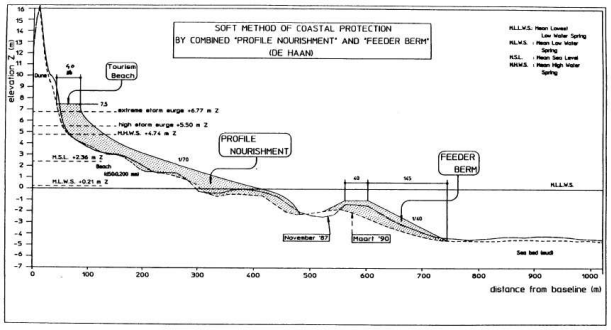
Classic Beach Replenishment: reclaiming supratidal beach



Profile Nourishment and Feeder Berm for “soft” coastal protection at De Haan, Belgium: a “morphological” beach restauration



De Haan Coastal Protection Works: a major pioneering achievment. Less than 5 % losses per year

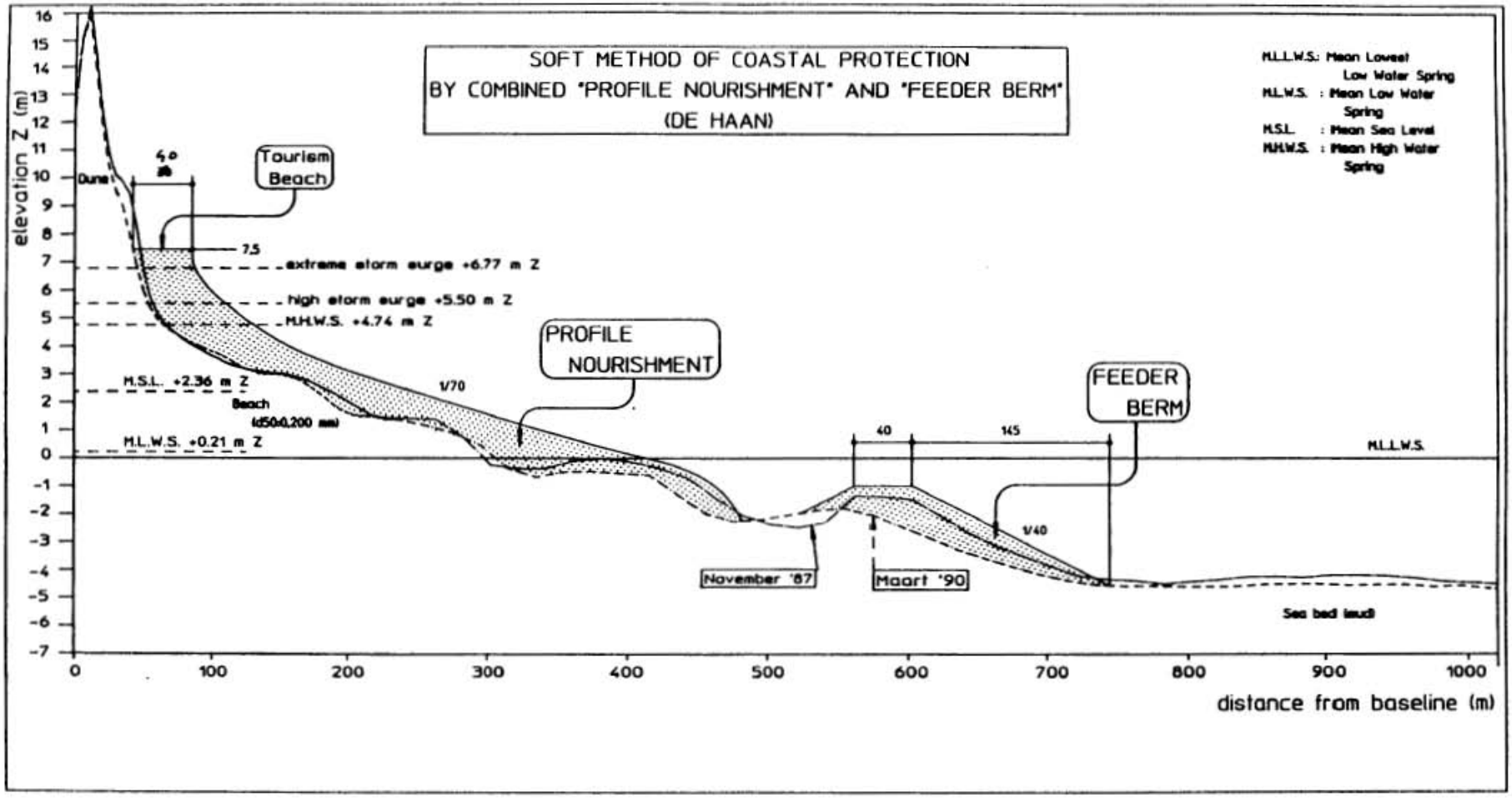


Belgian Expe
By
Jan De Nul G

Beach restauration requires large quantities of sand: between 300 and 1.000 m3/m'.

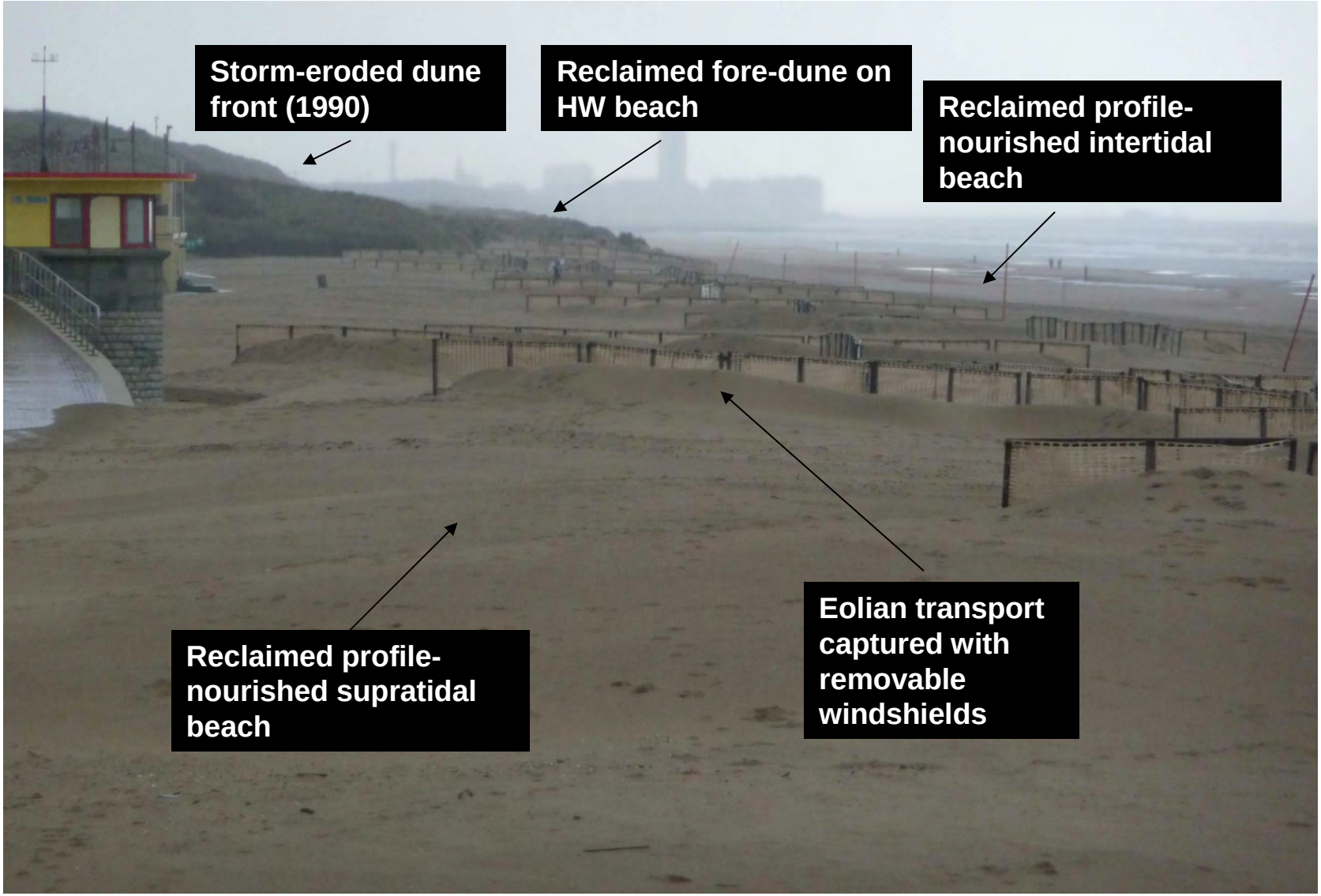
Hence hydraulic reclamation is generally technically and economically the most attractive solution.

Morphological beach-reclamation, De Haan, Belgium (1992)

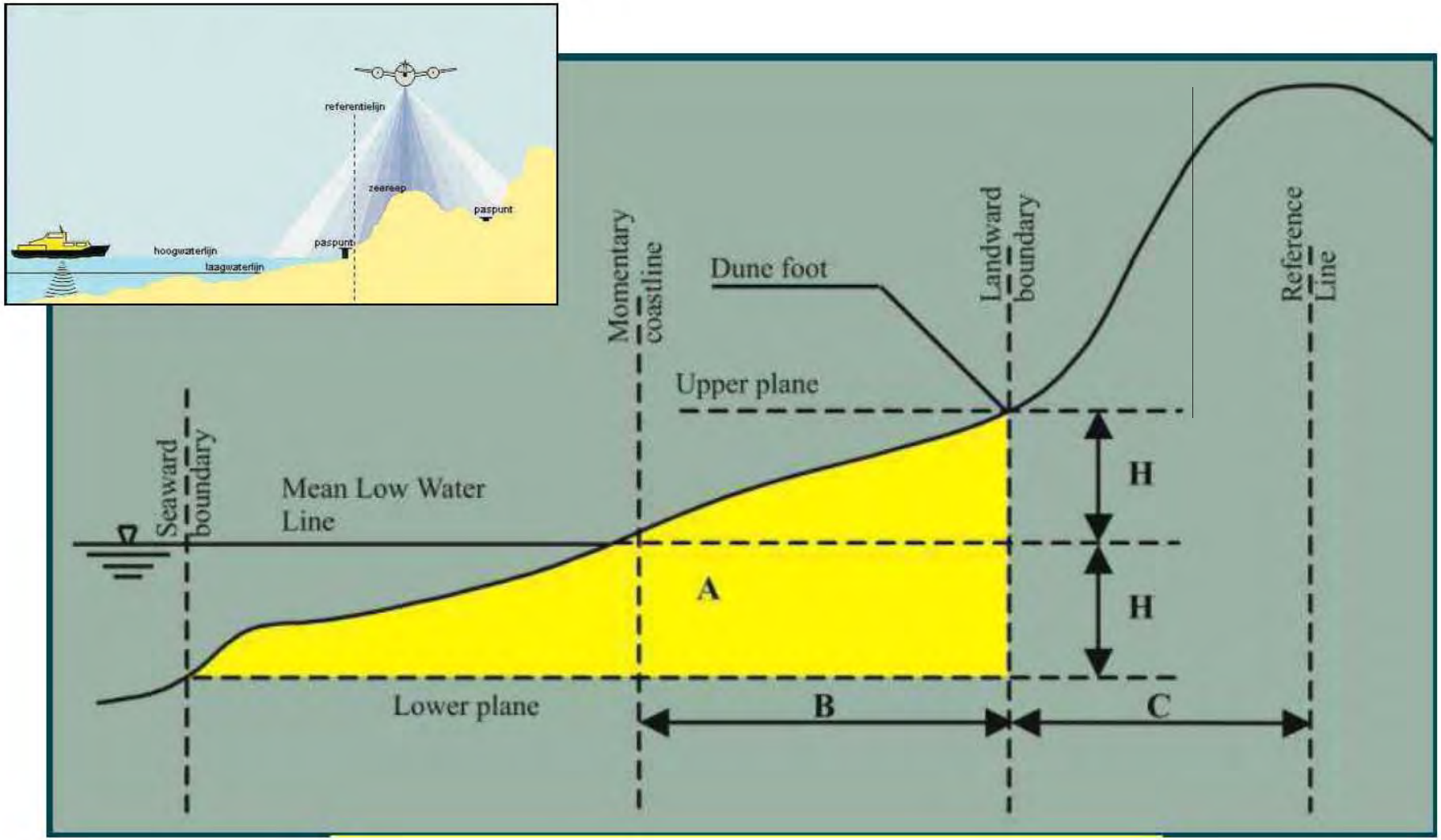


Feeder-Berm Beach Rehabilitation, Westkapelle, The Netherlands

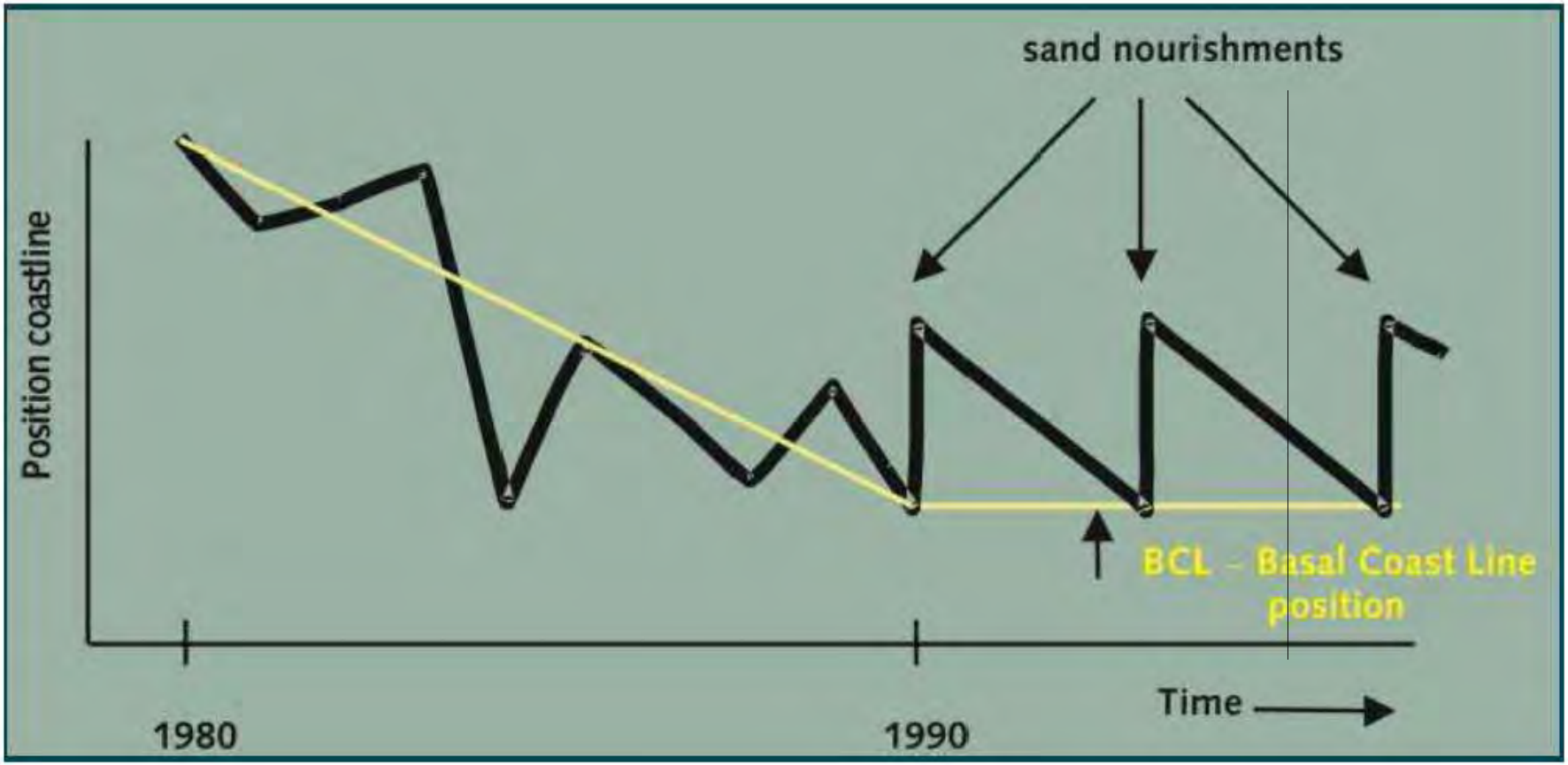
Result of a Soft Method of Coastal Protection



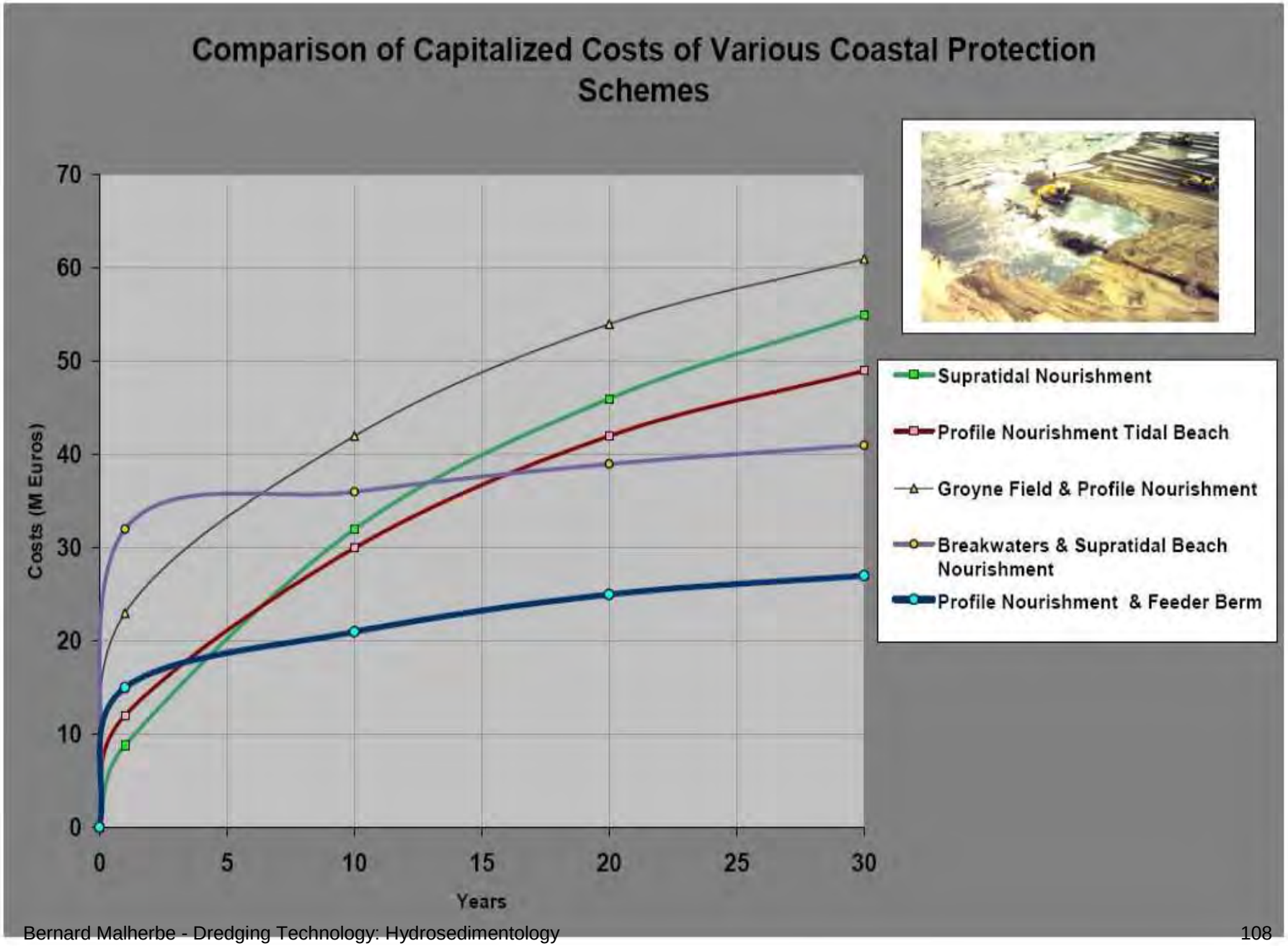
Management of Coastal Protection by Dune/Beach belts



Planning sand-supply : case of Rijkswaterstaat, The Netherlands



Cost-comparison of various coastal protection measures



Case Study Koniambo Coast, New Caledonia (ref CAPSE, 2007)

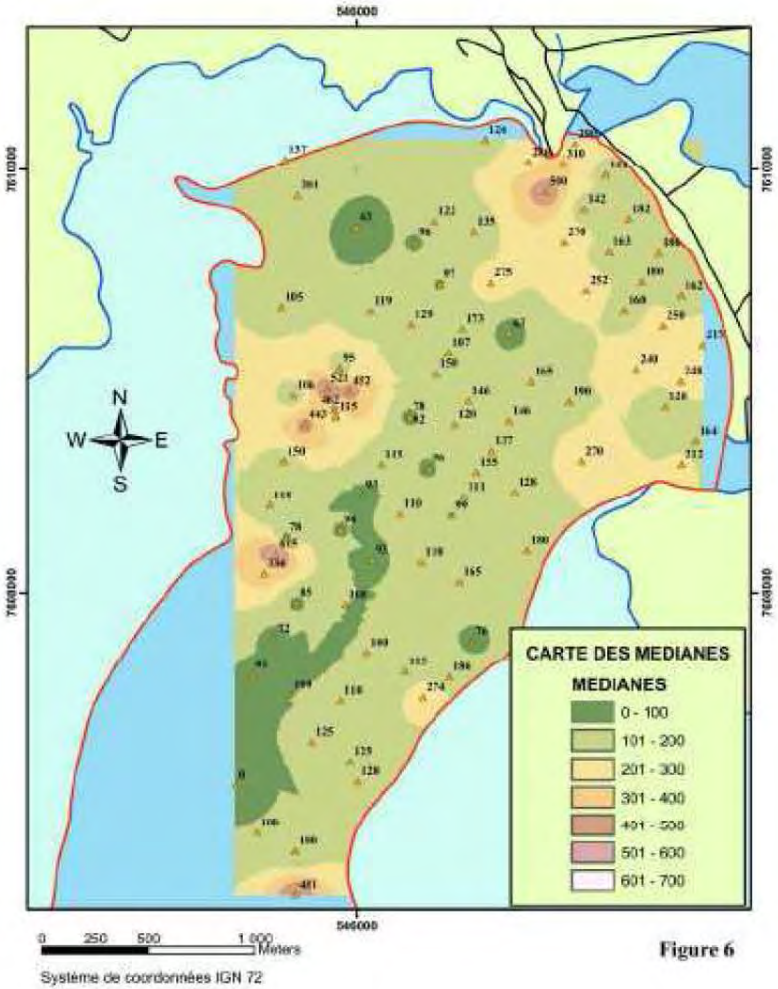
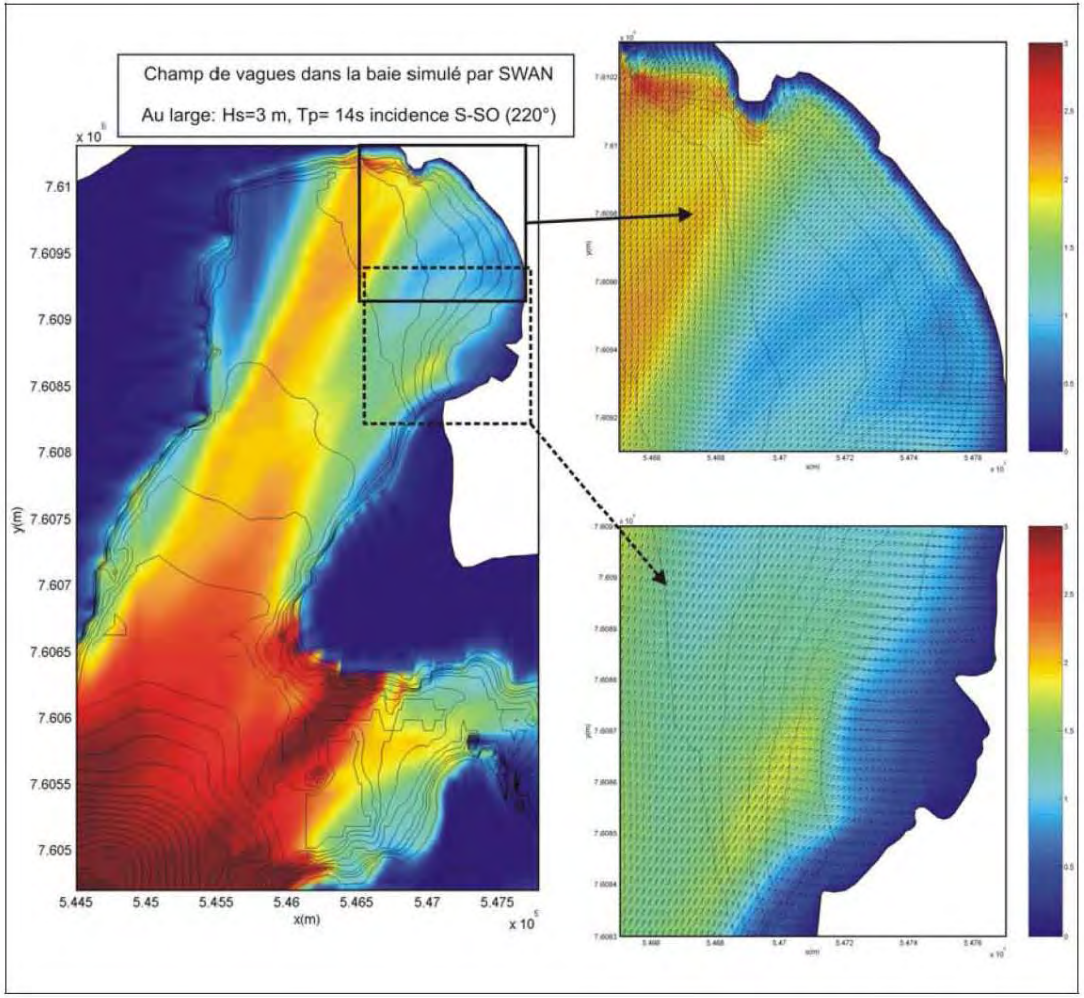
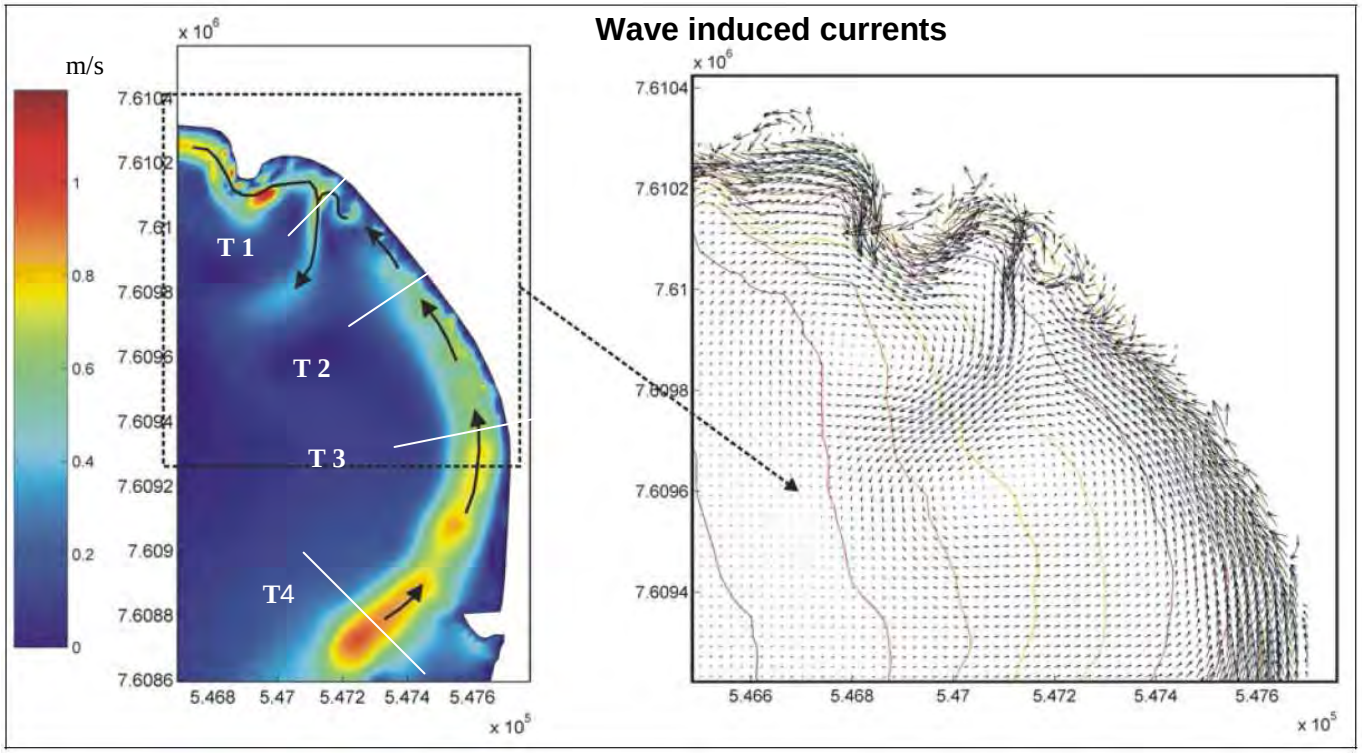


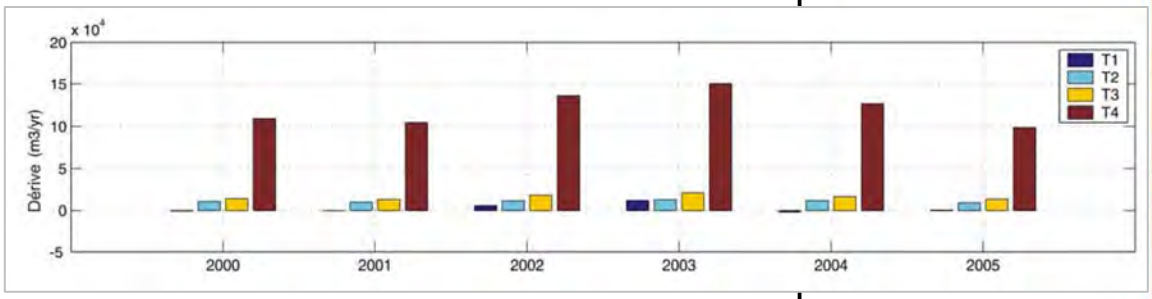
Figure 6

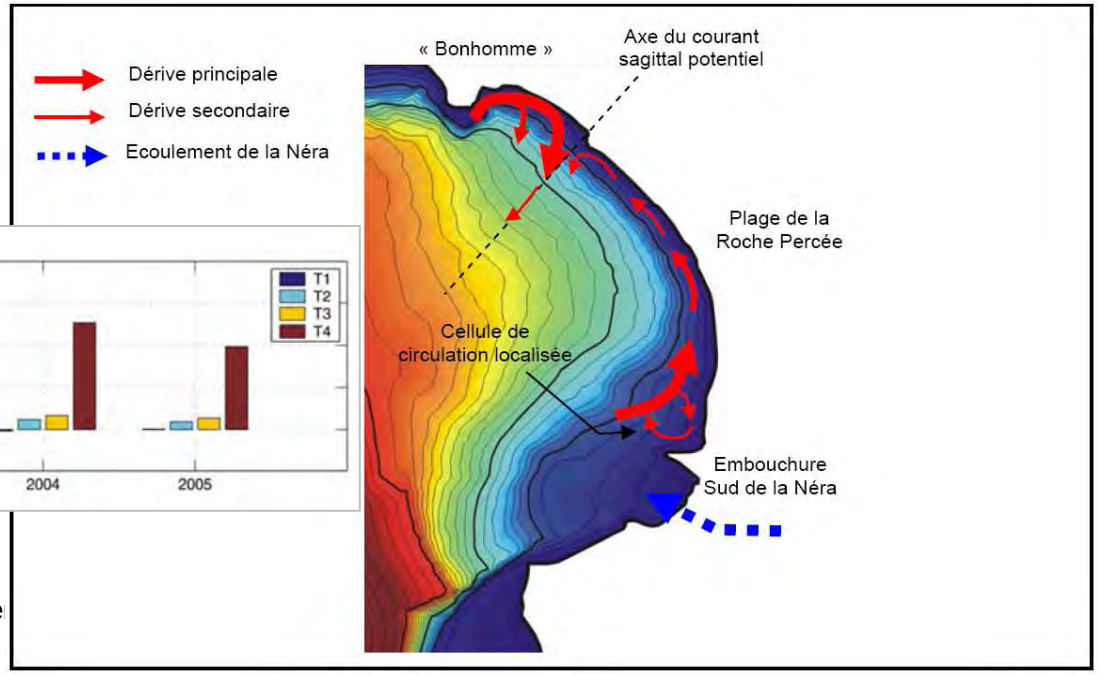


Koniambo, Littoral Processes simulated by numerical models

ref: CAPSE, 2007

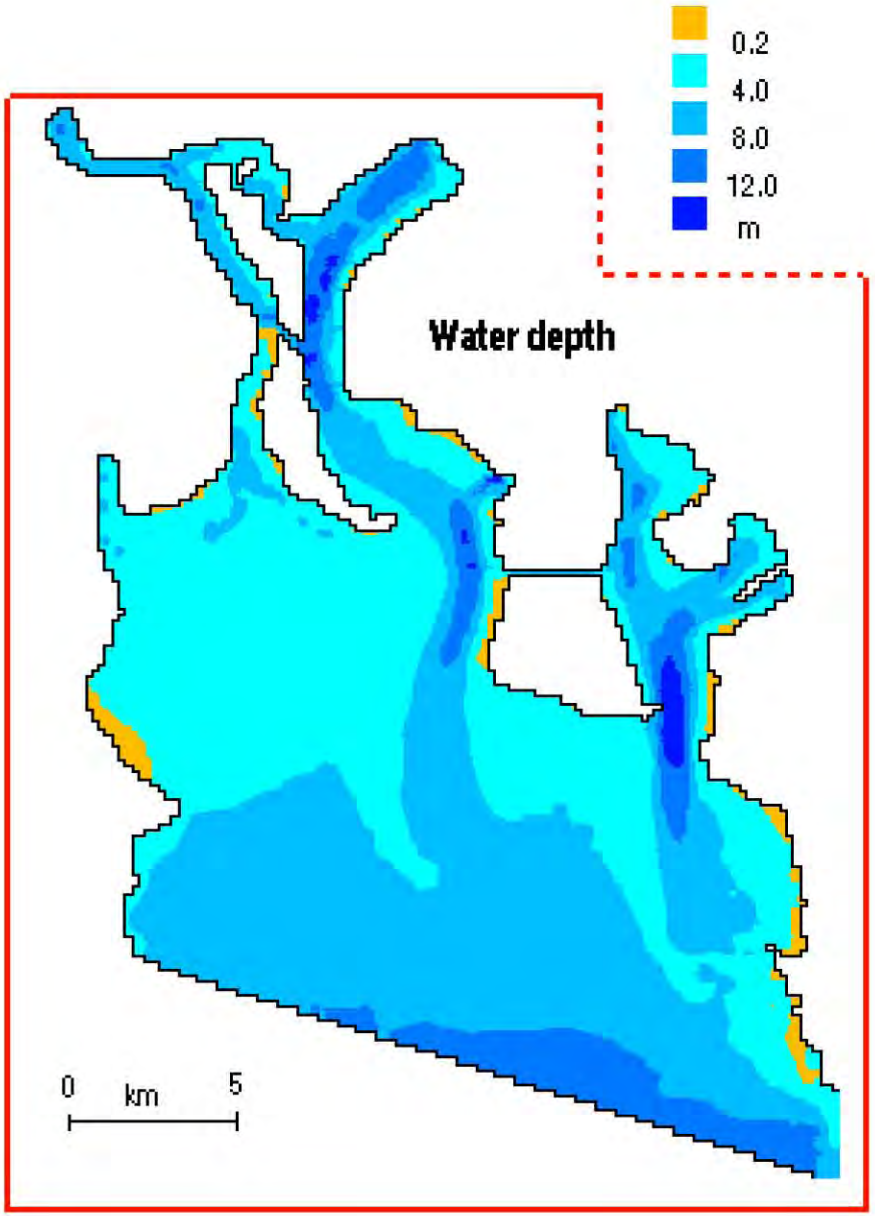


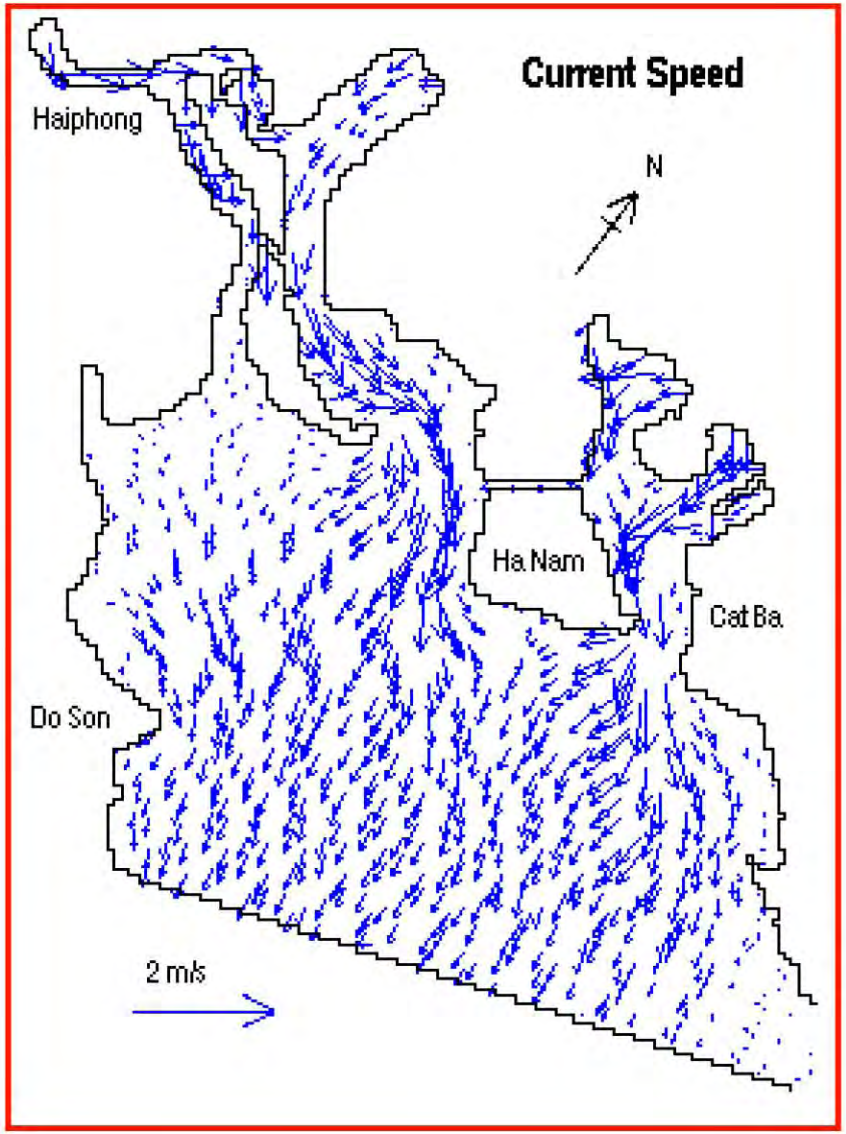


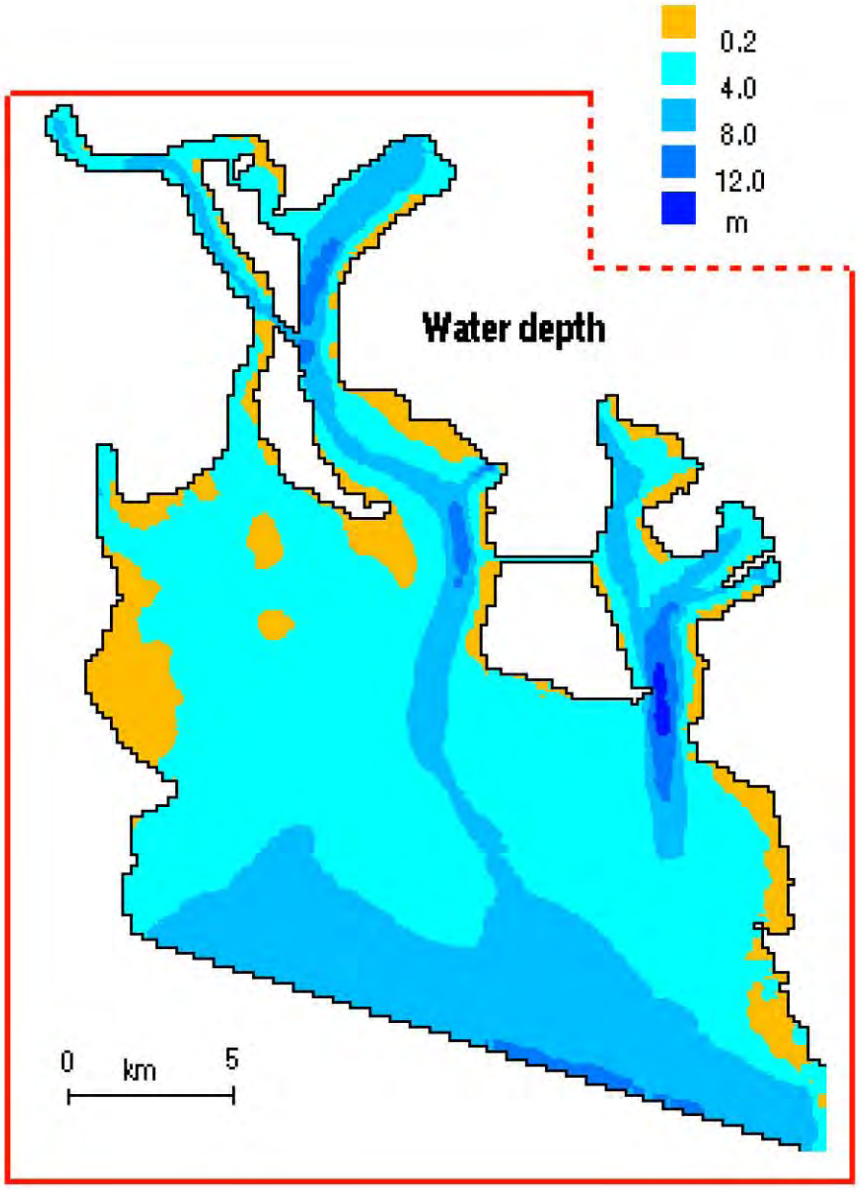


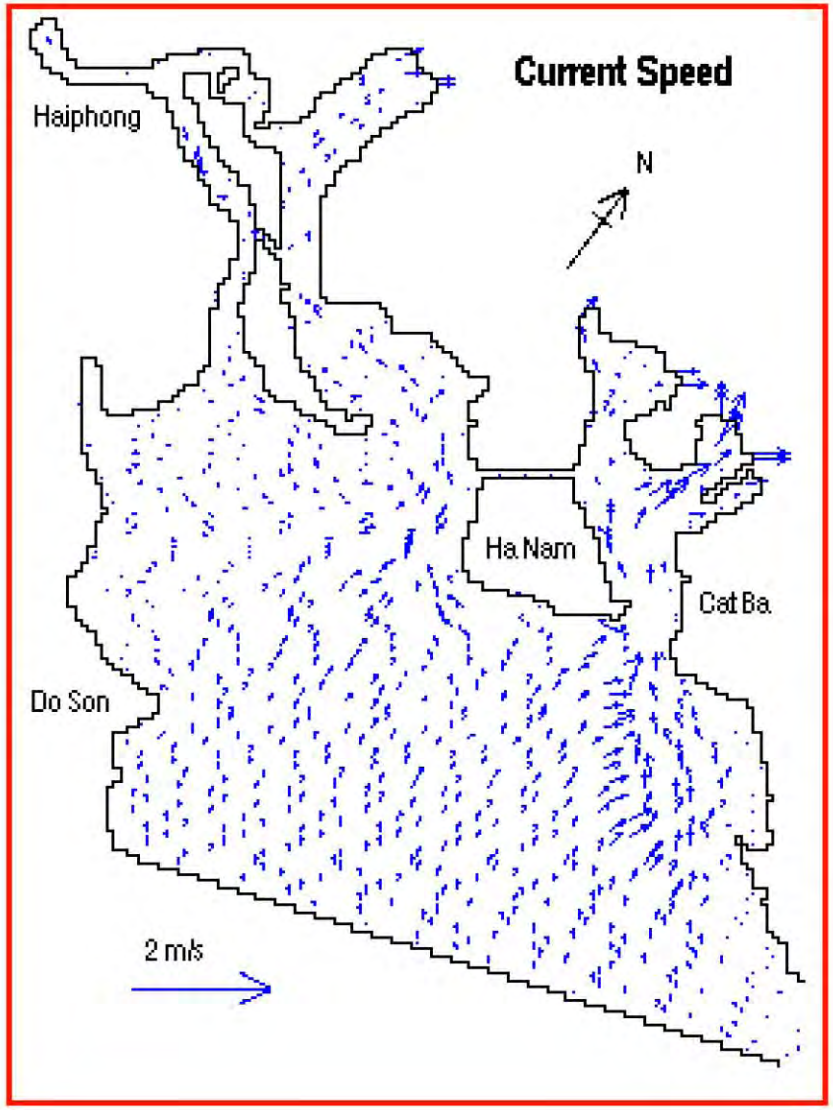
Actions of Currents on Sediments

Tidal flood current at Pointe de Raz, Bretagne, France


0.2
4.0
8.0
12.0
m
Water depth
0
km
5


Current Speed
Haiphong
N
Ha Nam
Cat Ba
Do Son
2 m/s


0.2
4.0
8.0
12.0
m
Water depth
0
km
5


Current Speed
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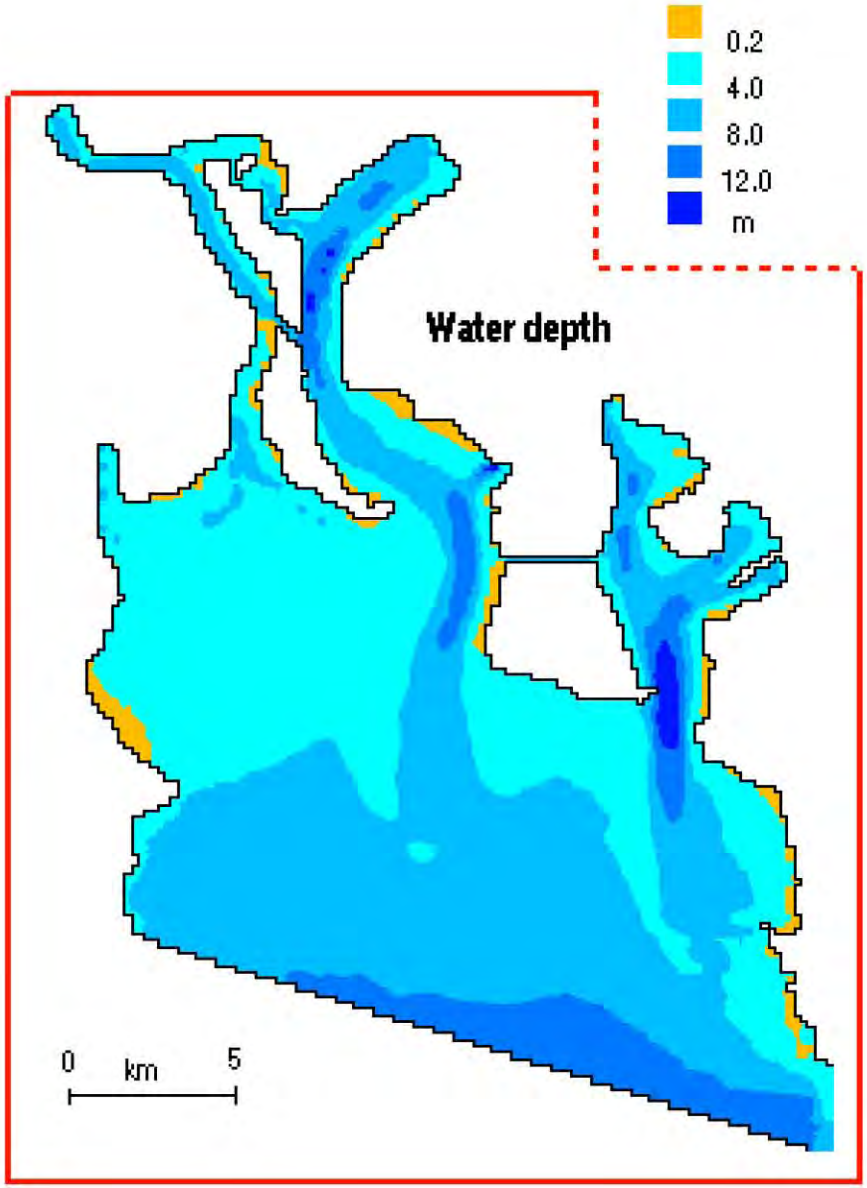
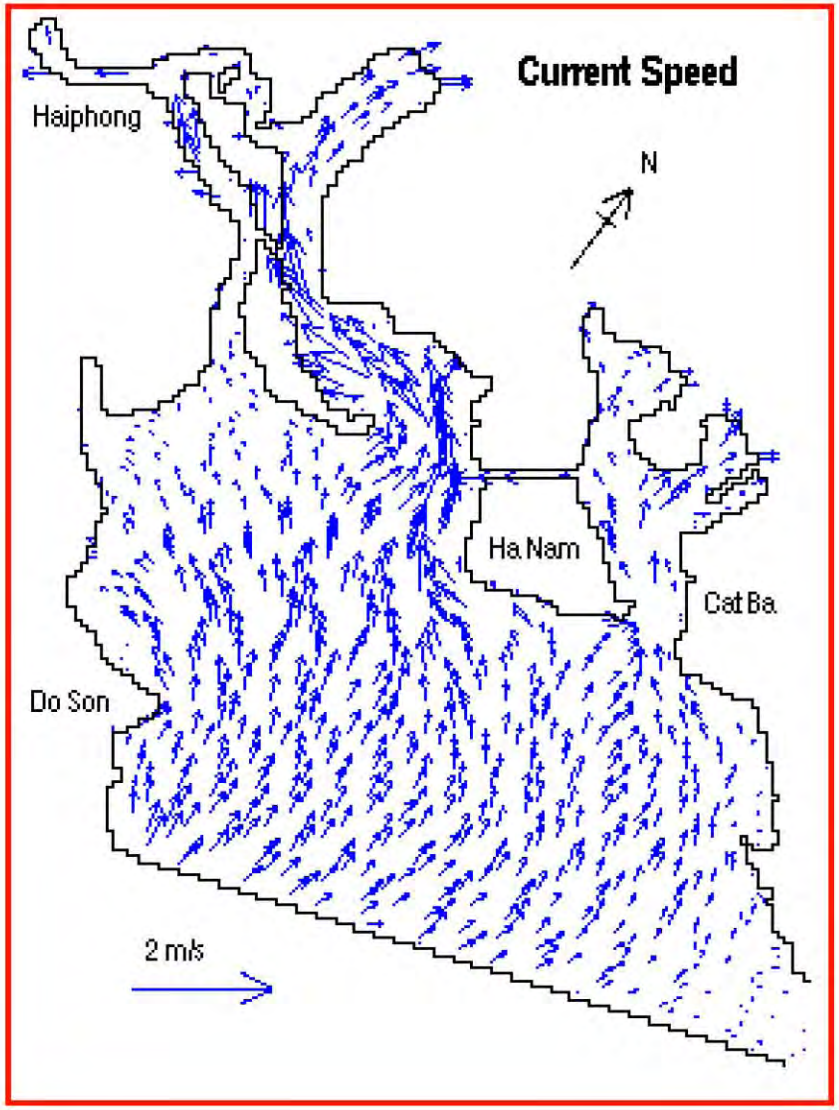
N
Ha Nam
Cat Ba
Do Son
2 m/s

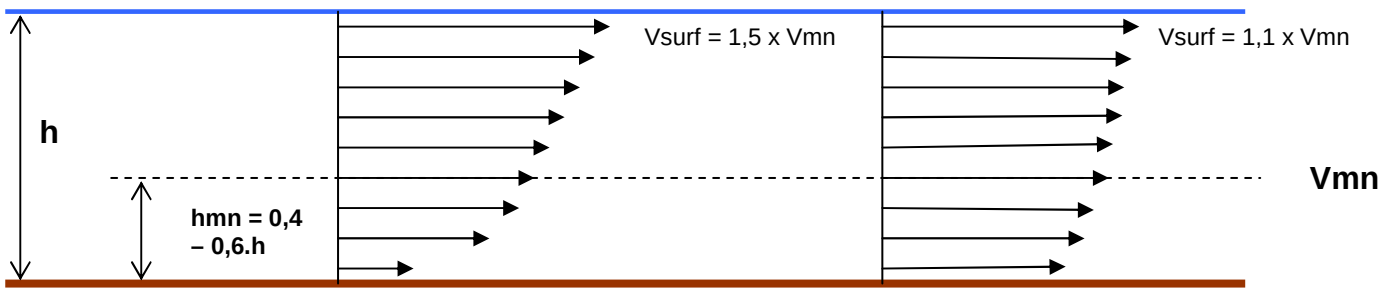

0.2
4.0
8.0
12.0
m
Water depth
0
km
5


Current Speed
Haiphong
N
Ha Nam
Cat Ba
Do Son
2 m/s

Hydrology of free-surface flows

Prandtl: approximation of the velocity-profile in the river or tidal sea.

Velocity determines sediment-segregation and transport of sediments ν



Hydraulic Rough **Hydraulic Smooth**

J. Van Veen (1947)

$Vh = V1m \,.\, (h)^{exp1/5}$

>> parabolic profile

Shear- stress on bed

$\tau = .\, \nu\, \rho.\, dv/dz$

waarbij:

- ν = kinematic viscosity of water (ca. 1,5 x 10^{-6} m^2/sec)
- ρ = volume-mass of water (ca 1.000 kg/m3)
- dv/dz = nearbed velocity- gradient

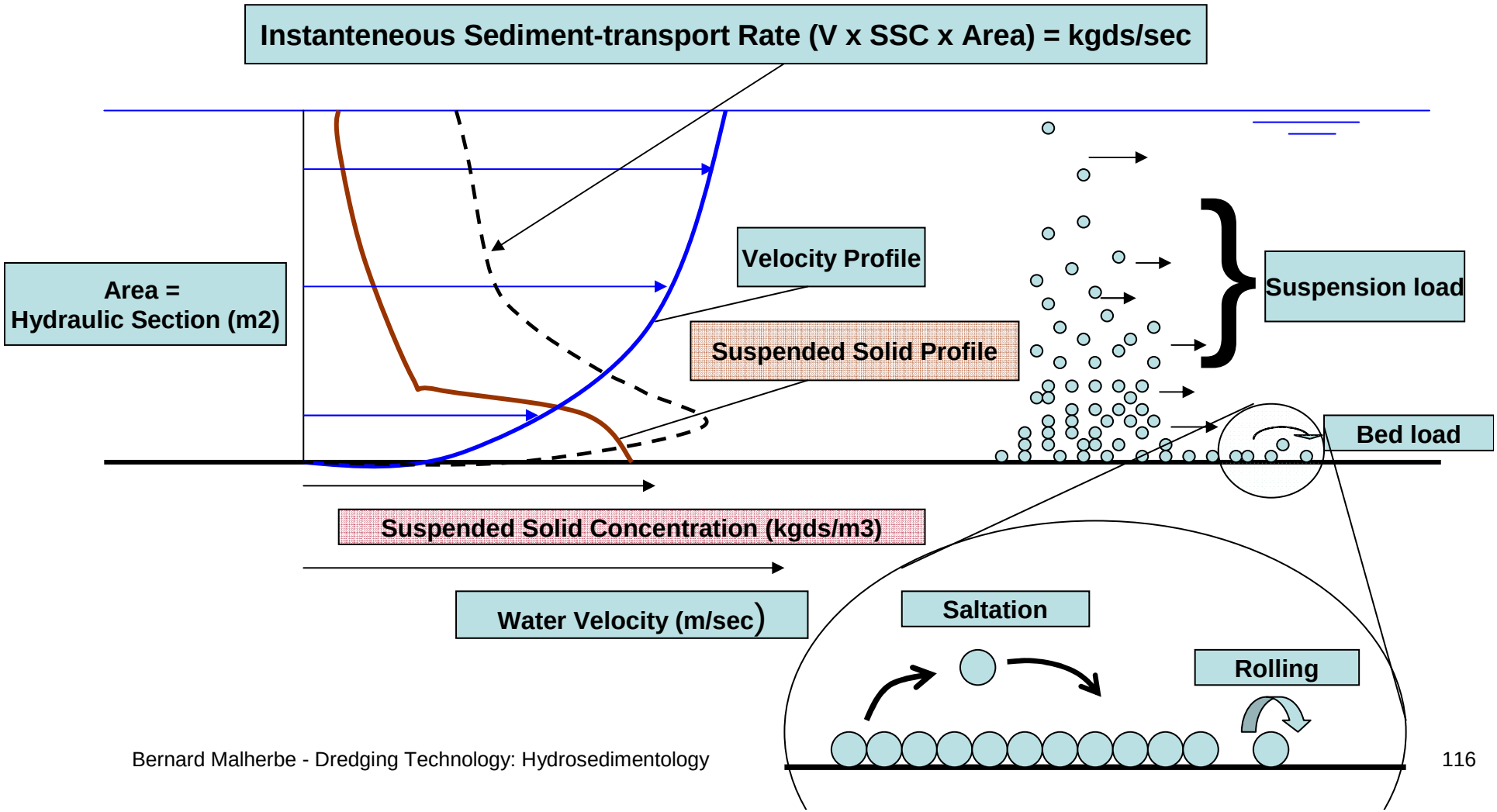
$\tau o = \rho \,.\, u^{*2}$

$u^* = Vh \,/\, (5{,}5 + 5{,}75.\, \log (h \,.\, u^* / \nu)$ Prandtl – von Karman

waarbij:

- Vh = velocity at height h above bed
- u* = von Karman shear-stress velocity

MODES OF SEDIMENT-TRANSPORT



SEDIMENT TRANSPORT

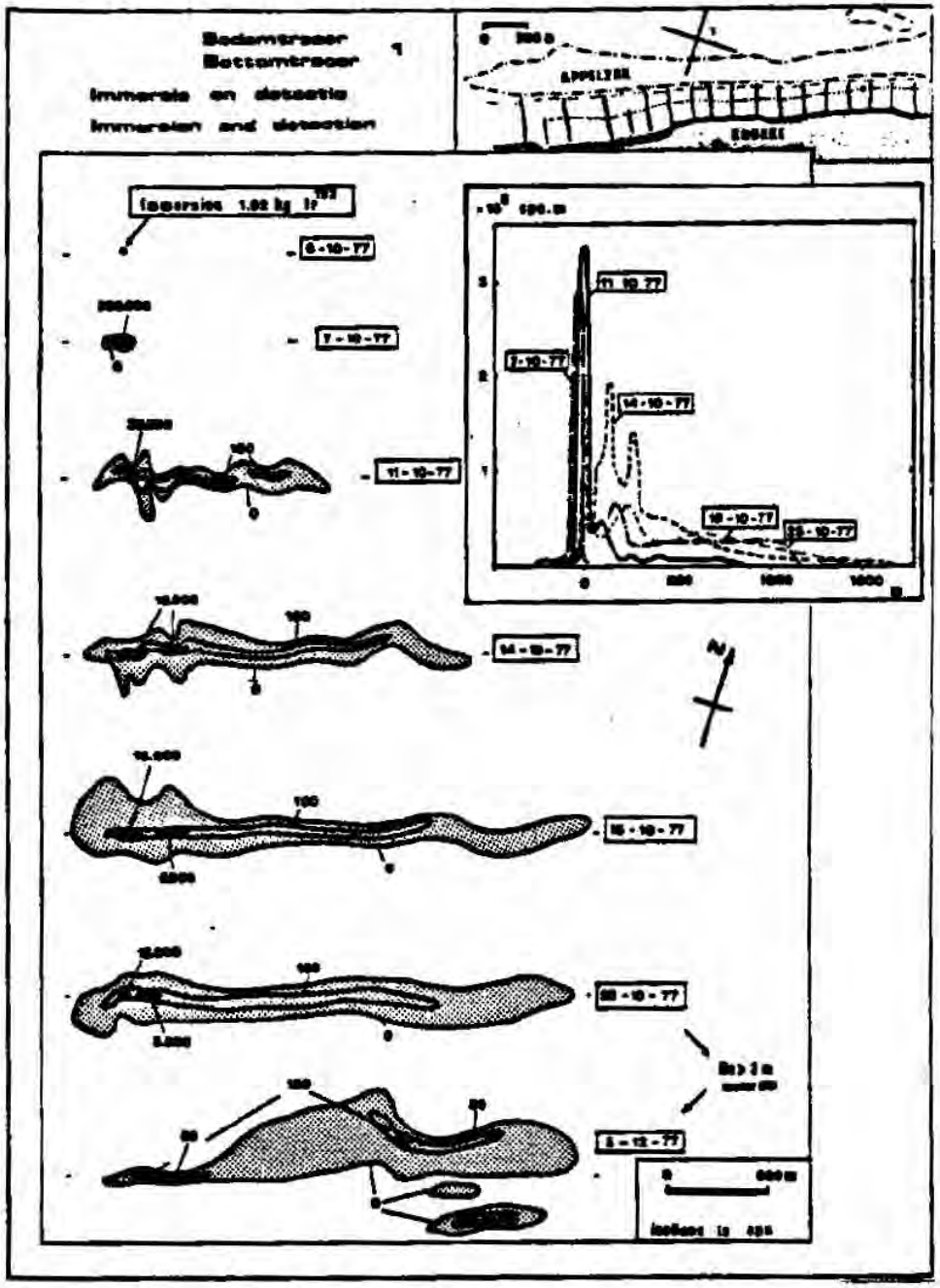
Order of magnitudes(shallow tidal seas):

- **Suspension-Load Transport**
  - **SSC = 0,050 – 5 kgds/m3 (kg of dry solids)**
  - **V = 0,5 – 5 m/sec**
  - **h = 4 – 10m**

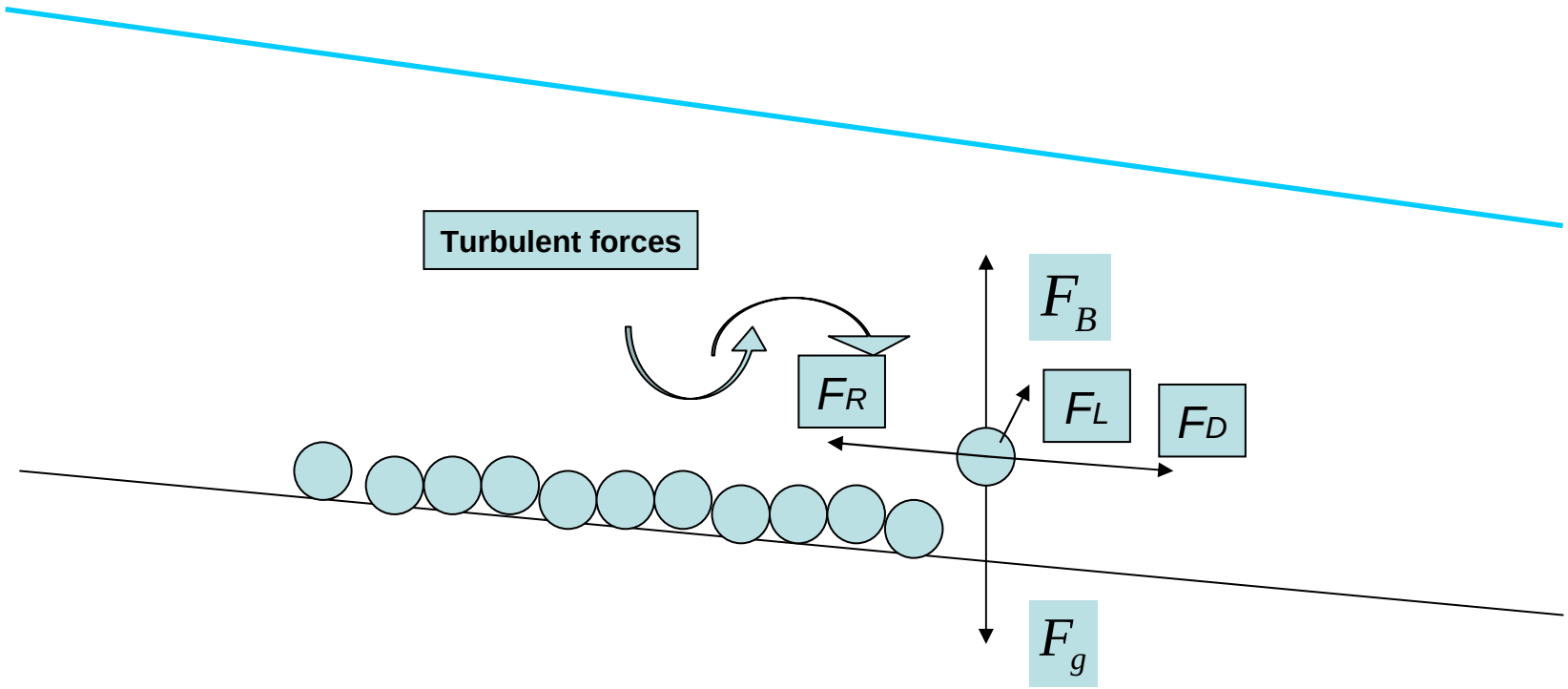
    >>Ssi = 0,1 – 250 kgds/sec/m' (m' = cross linear meter)
- **Bed-Load Transport**
  - **V = 0,5 – 35 m/day (!)**
  - **h = 0,02 – 0,10 m (!)**

    >> Sbi = 3 – 3500 kgds/day/m' (!)

Measurement of residual bed-load transport with medium-life radio-active tracers



Basic principles of sediment-dynamic physics



Forces exerted on spherical particles in water

Forces exterted on particle:

- **Gravitational force**

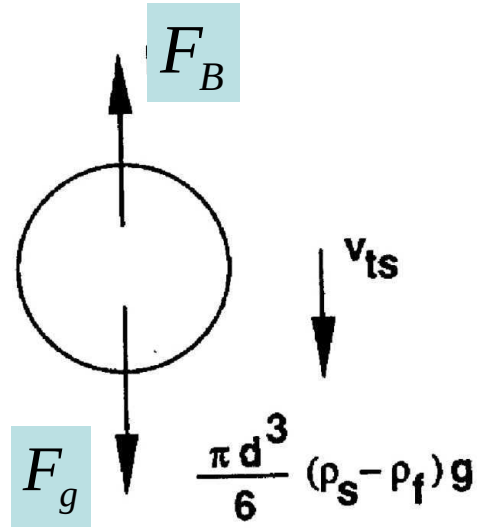
$$F_g = \rho_s V_s g$$

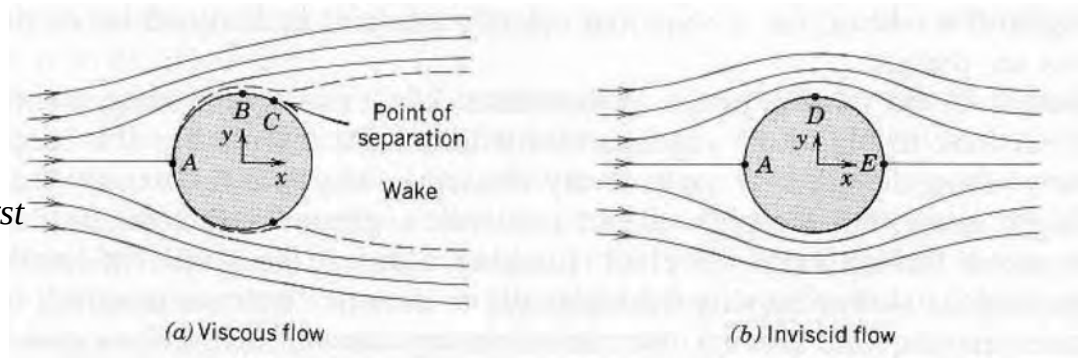
- **Buoyancy force (Archimedes)**

$$F_B = \rho_w V_s g$$

- **Flow-resistance forces**
  - **Wall-friction**
  - **Drag-resistance**

$$F_D = \frac{1}{2} C_D \rho_w v^2 A_{st}$$

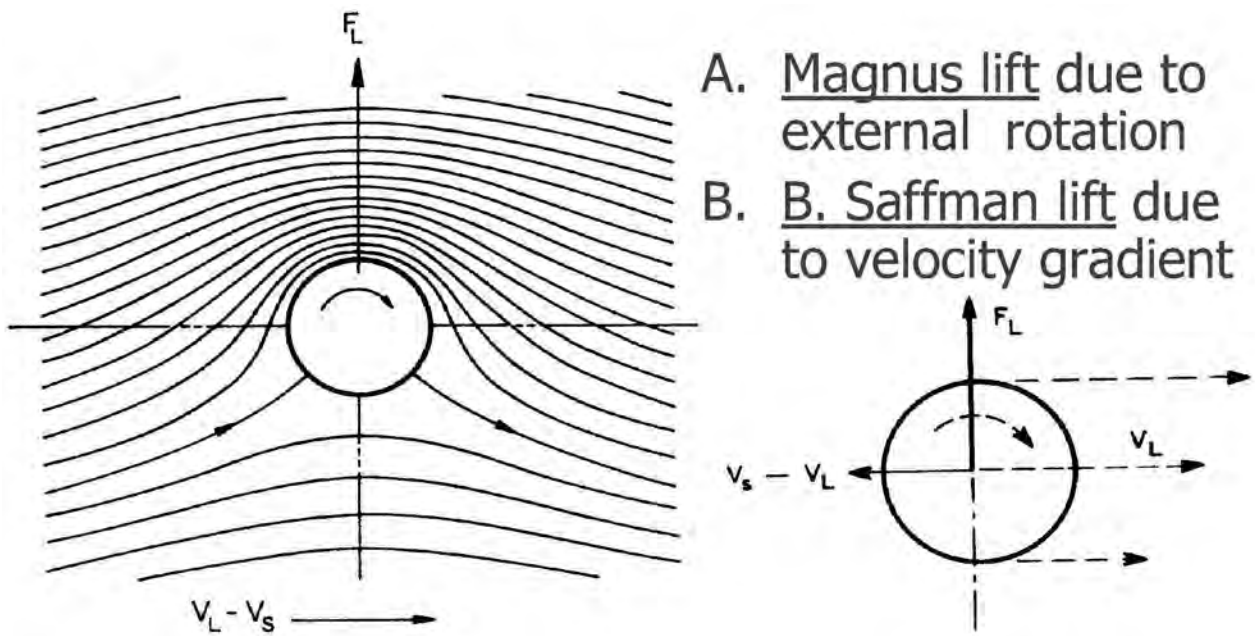




Forces exerted on non –spherical particles in flowing water

- **Gravitational forces**
- **Buoyancy forces**
- **Flow-resistance forces**
- **Lift-forces due to velocity gradients, particle geometry, particles settled on the bed,….**
- **Turbulent forces (accelerations,…)**

$$F_L = \frac{1}{2} C_L \rho_w v^2 A_{st}$$



Hydraulic transport of particles in flowing water: Phenomenon and physics of slip

$$v_p = v_w - v_{slip} \qquad f_S = \frac{v_s}{v_m}$$

Slip-velocity is dependent upon hydraulic regime

- **Particle in suspension:** $v_{slip} \approx 0$
- **Particle in sliding bed:** $0 < v_{slip} < v_w$
- **Particle in vertical flow:** $v_{slip} \approx 0$

Governing factors:

- **Contact-surface between particle and fluid**
- **Specific density of particles wrt fluid**

	Slipfactor fs
Silt and clay	0,9 - 1
Fne sand	0.8-1
Coarse sand	0.7-0.9
Gravel	0.65-0.85
Boulders	0.4-0.65

Hydraulic transport of sediments: conservation of mass

- **Law of mass-conservation of fluid:**

$$\rho . v_{in} . A_{in} = \rho . v_{out} . A_{out}$$

- **Law of mass-conservation of sediments:**

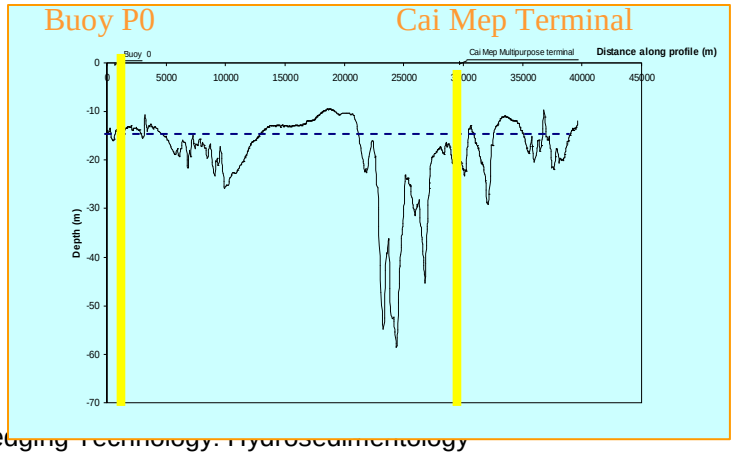
$$\rho d . v_{in} . A_{in} = \rho d . v_{out} . A_{out} + \delta S / \delta t$$

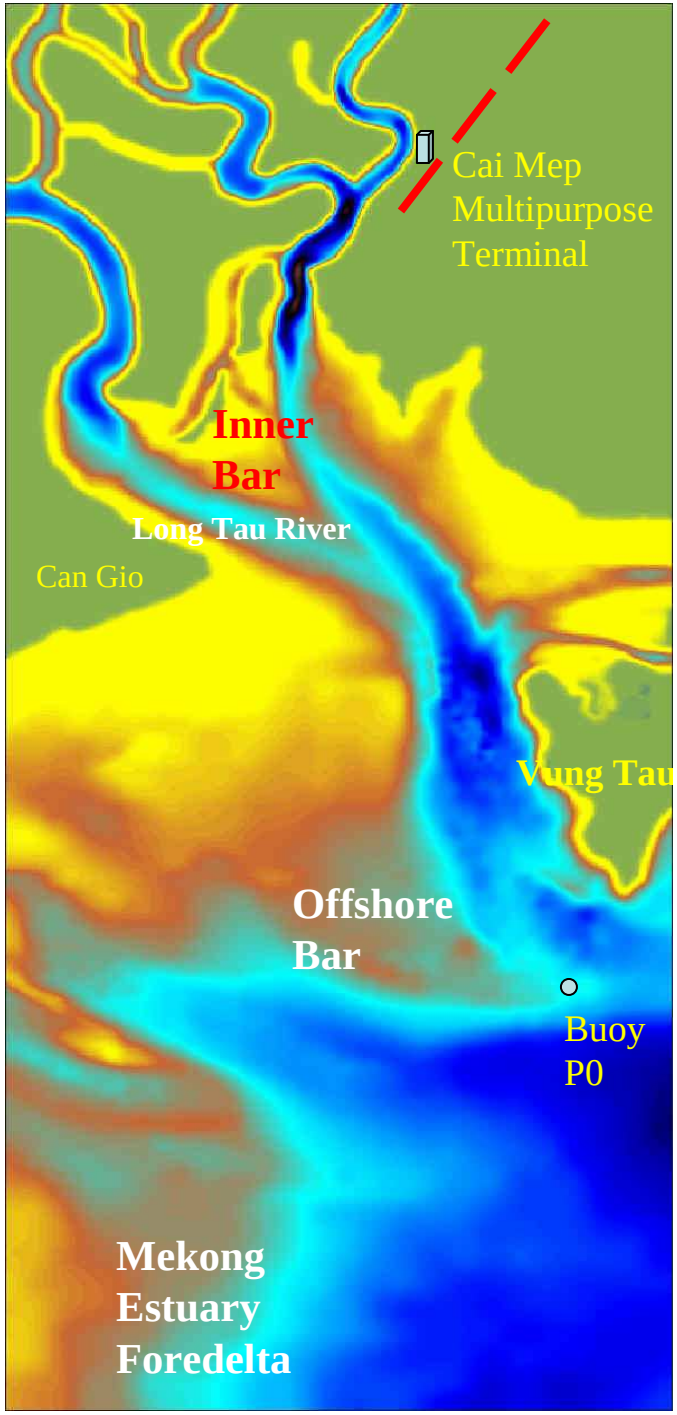
In which:

- ρd = dry volume-mass of sediments (kg d.s. / m3)
- v = velocity (m/sec)
- A = hydraulic section (m2)
- t = time along streamline (sec)
- S = Erosion/sedimentation flux between in and out (kg d.s./m2)

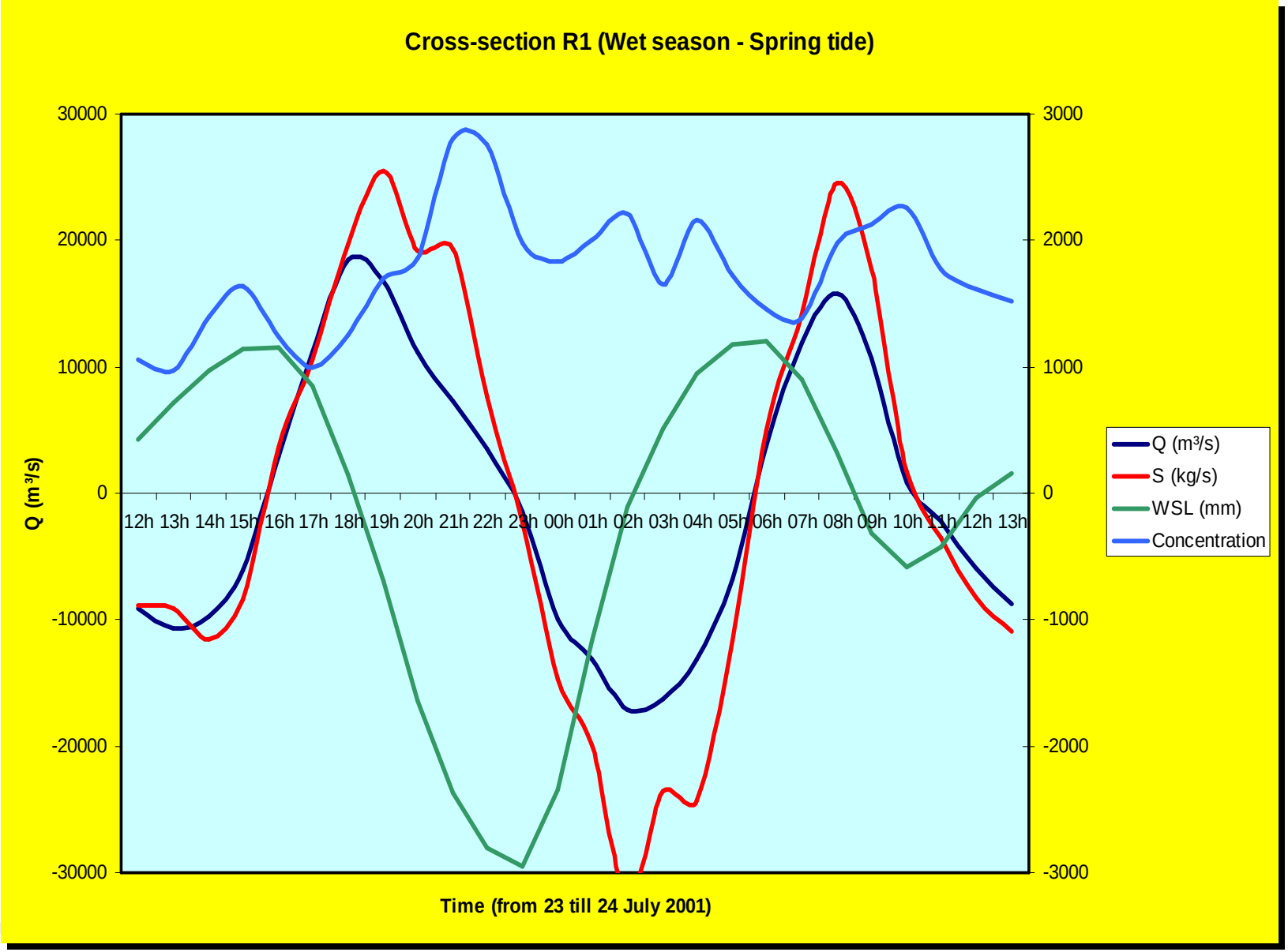
Hydrosedimentological and Environmental Impact Study for the Access channel to Sai Gon Port and to the Cai Mep/Thi Vai River and the Cai Mep Multipurpose Terminal

Long Sectional View along the Access-Channel

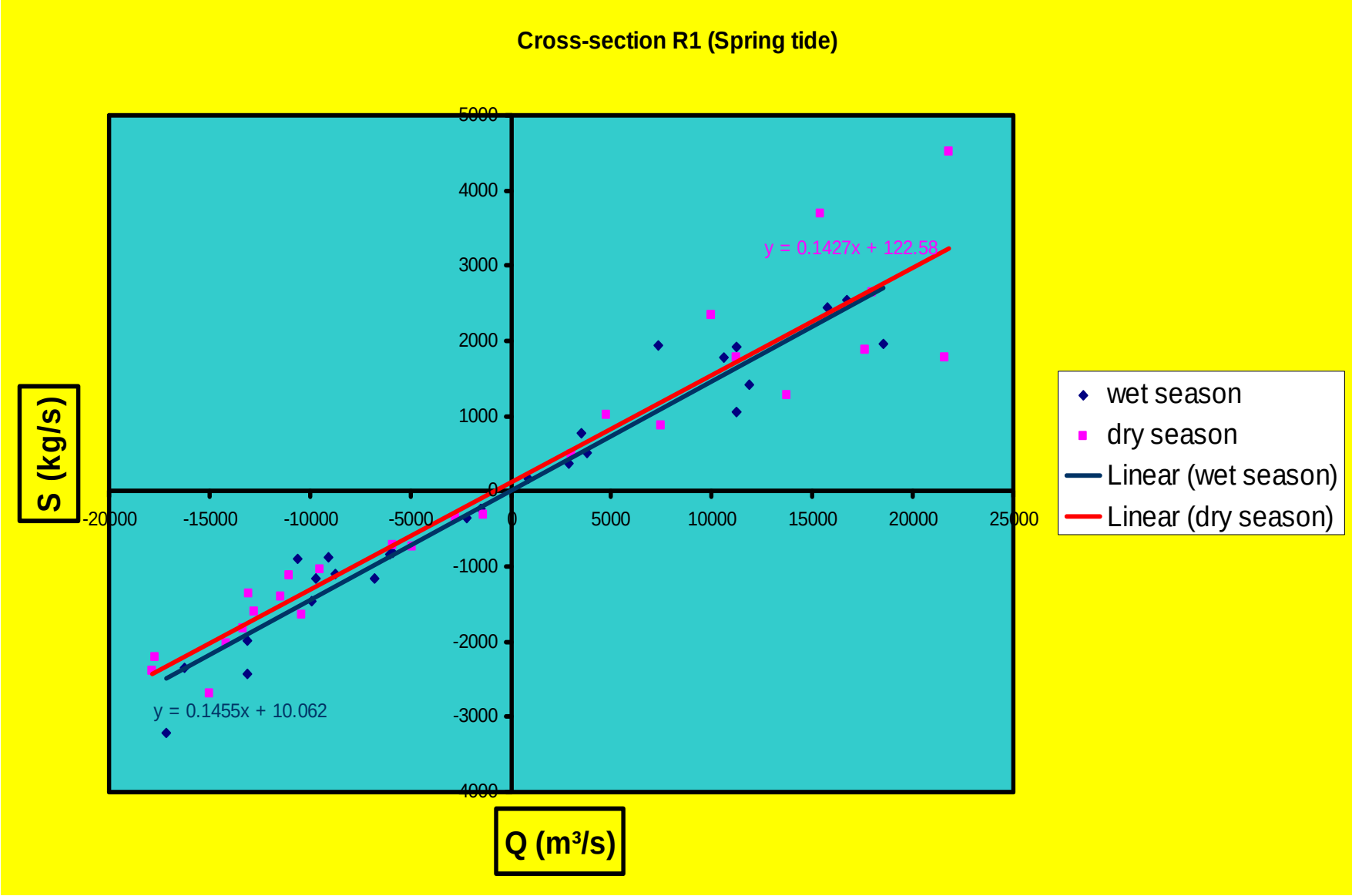




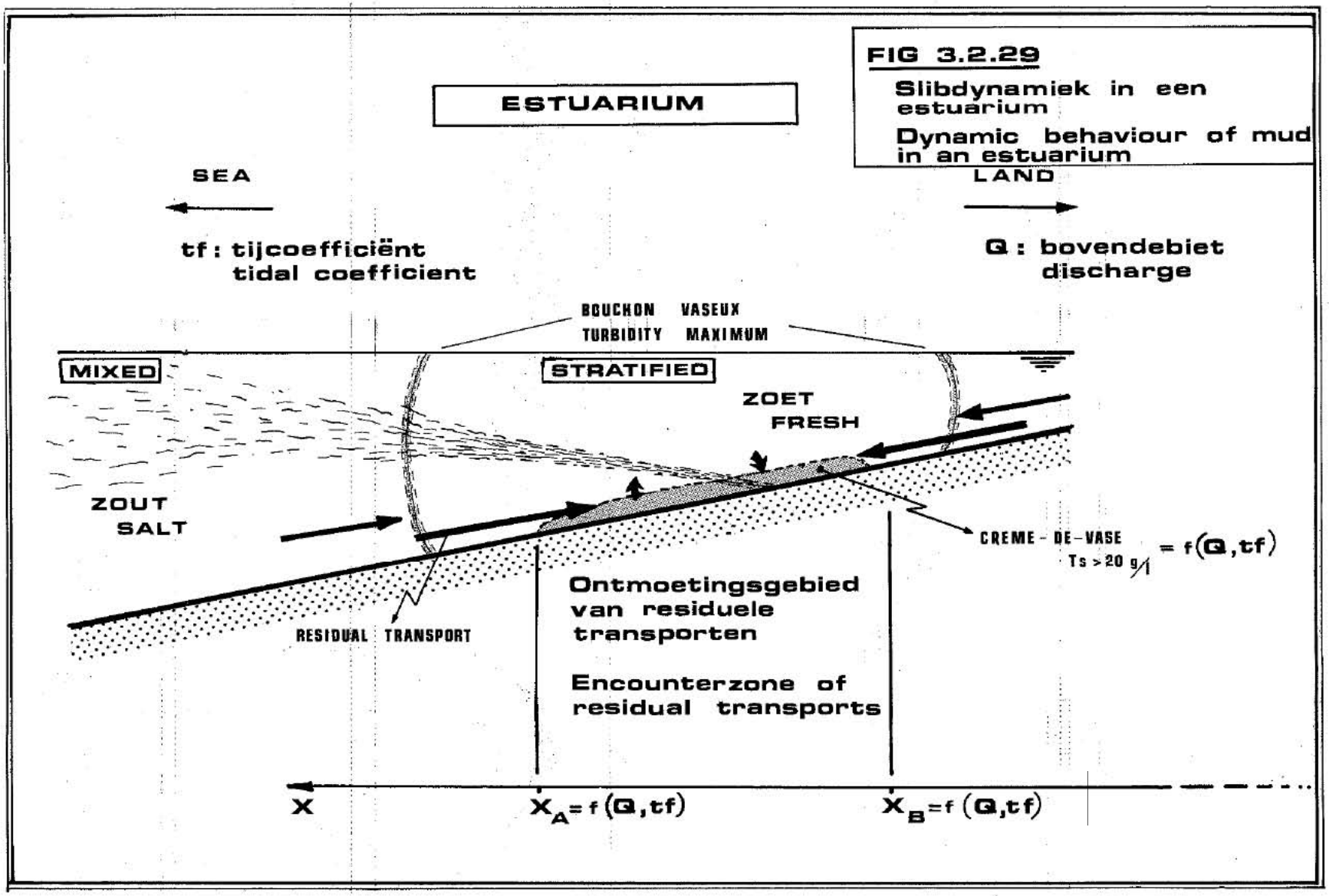
Results of fixed Station Profilings in the Cai Mep River Transect



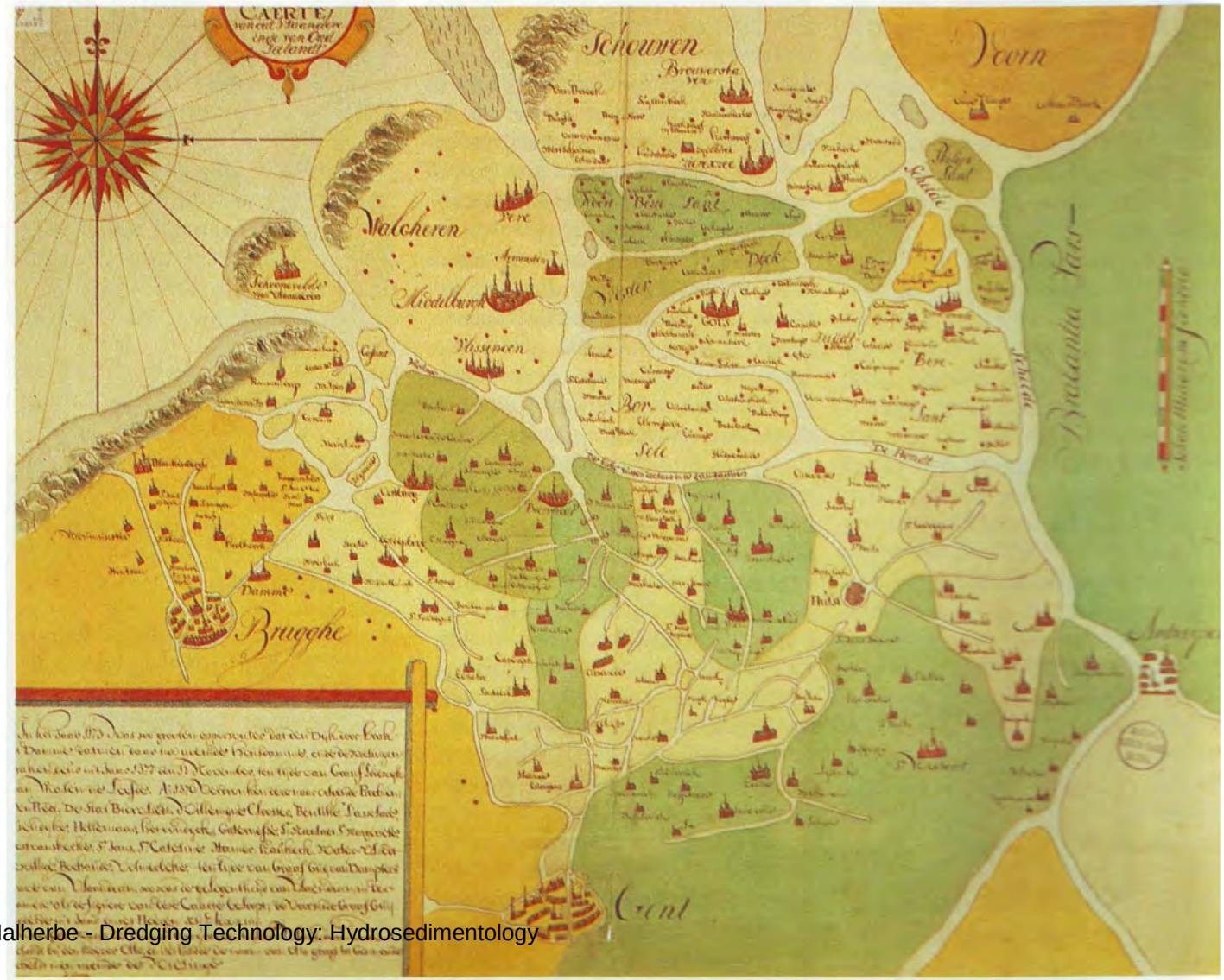
Correlation graph between Discharge and suspended Sediment Transport



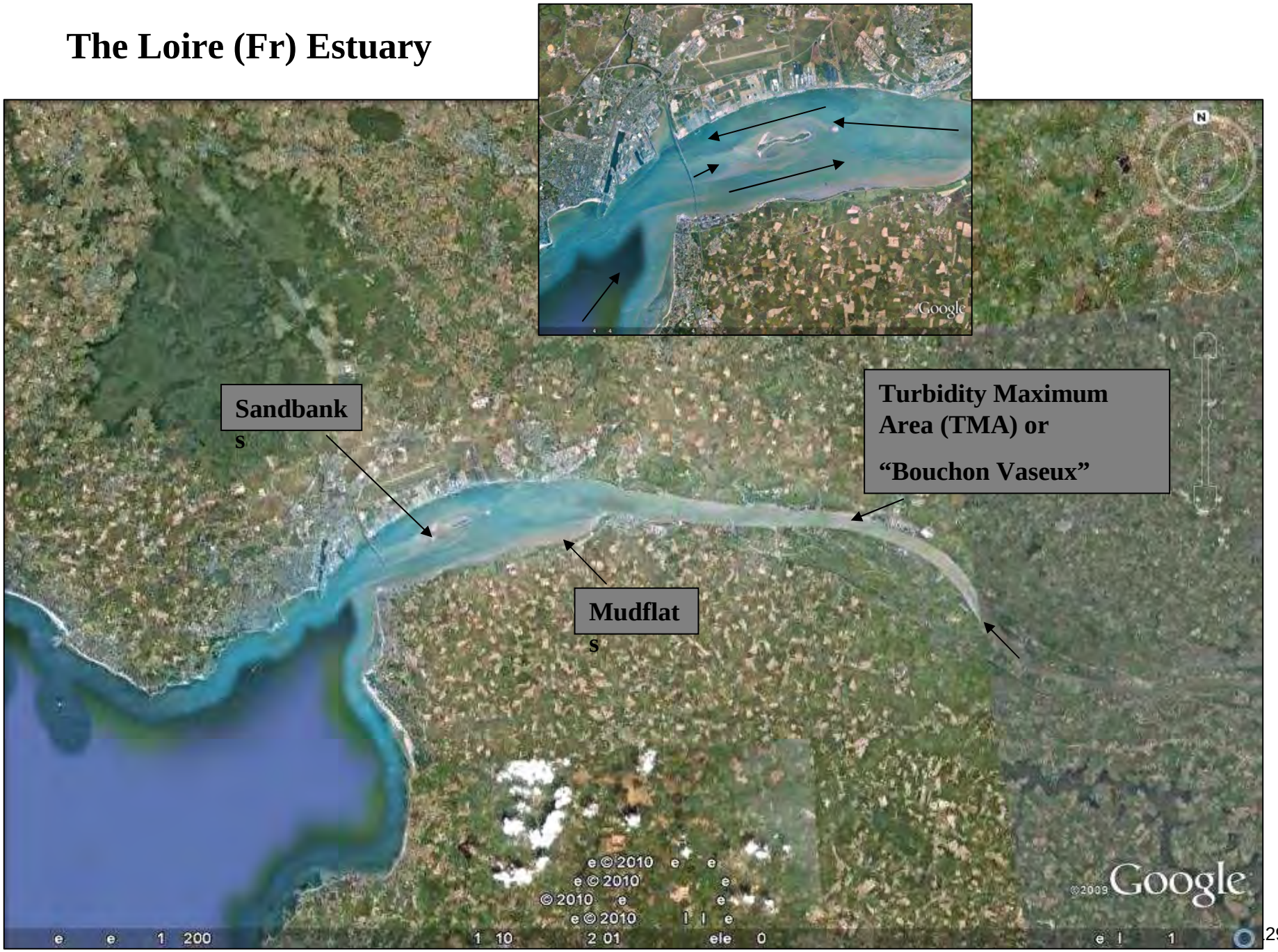
Dynamics of fine sediments in an estuary (Bernard Malherbe, PhD thesis)



The early trade-settlements of man were often developed along river or estuary-banks

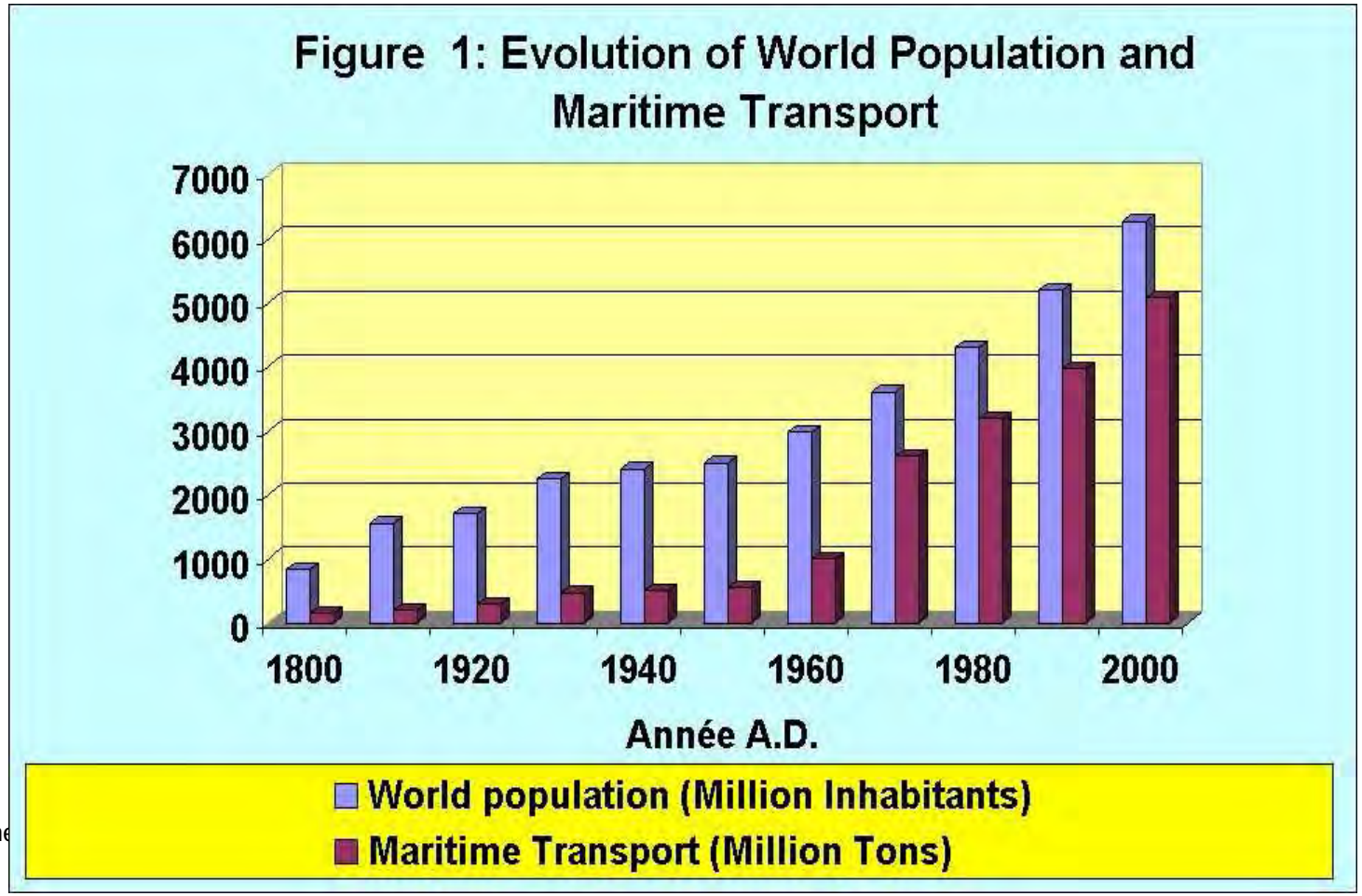


The Loire (Fr) Estuary



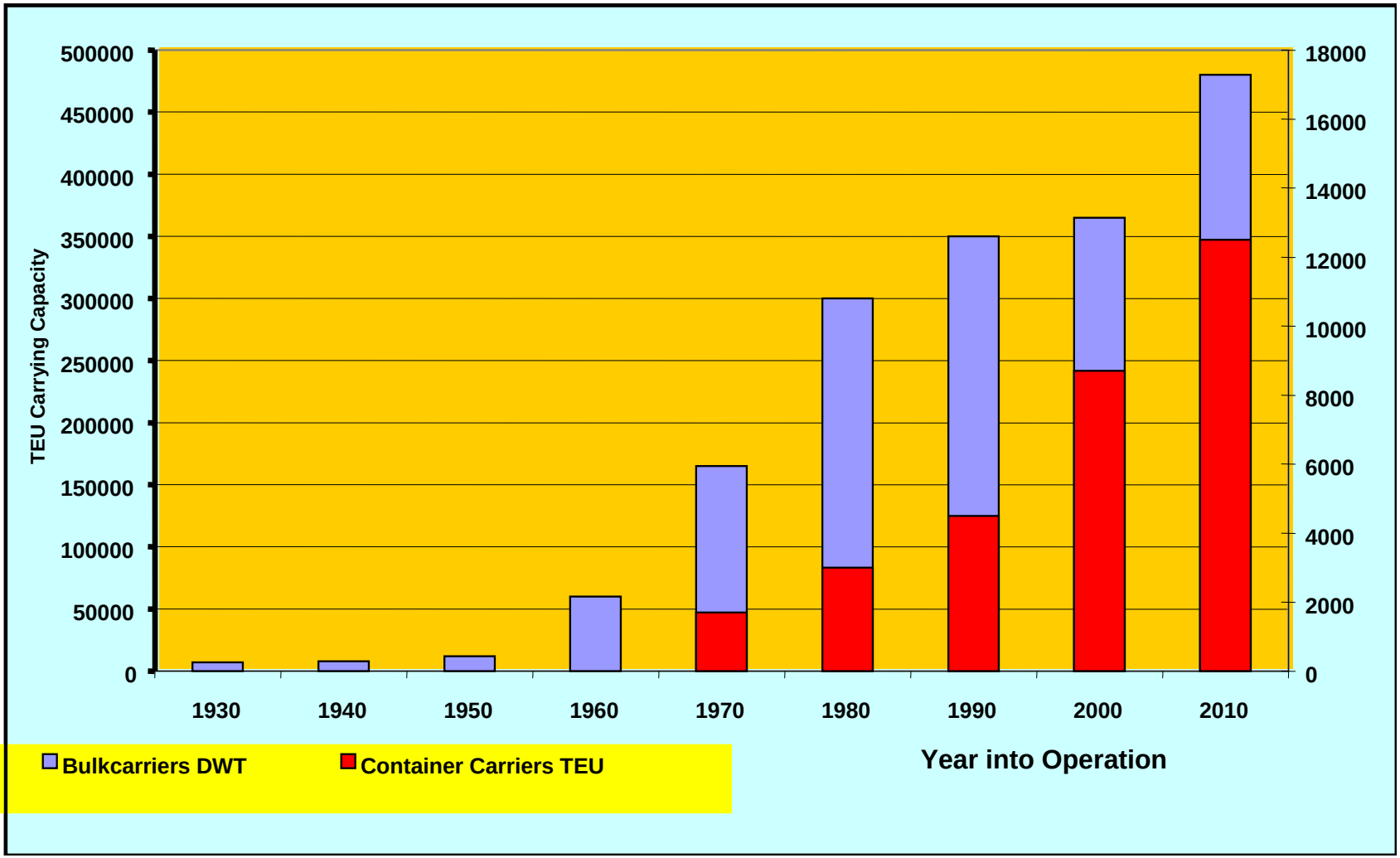
INTERNATIONAL TRADE IS GROWING FAST…

MARITIME TRANSPORT IS GROWING EVEN FASTER



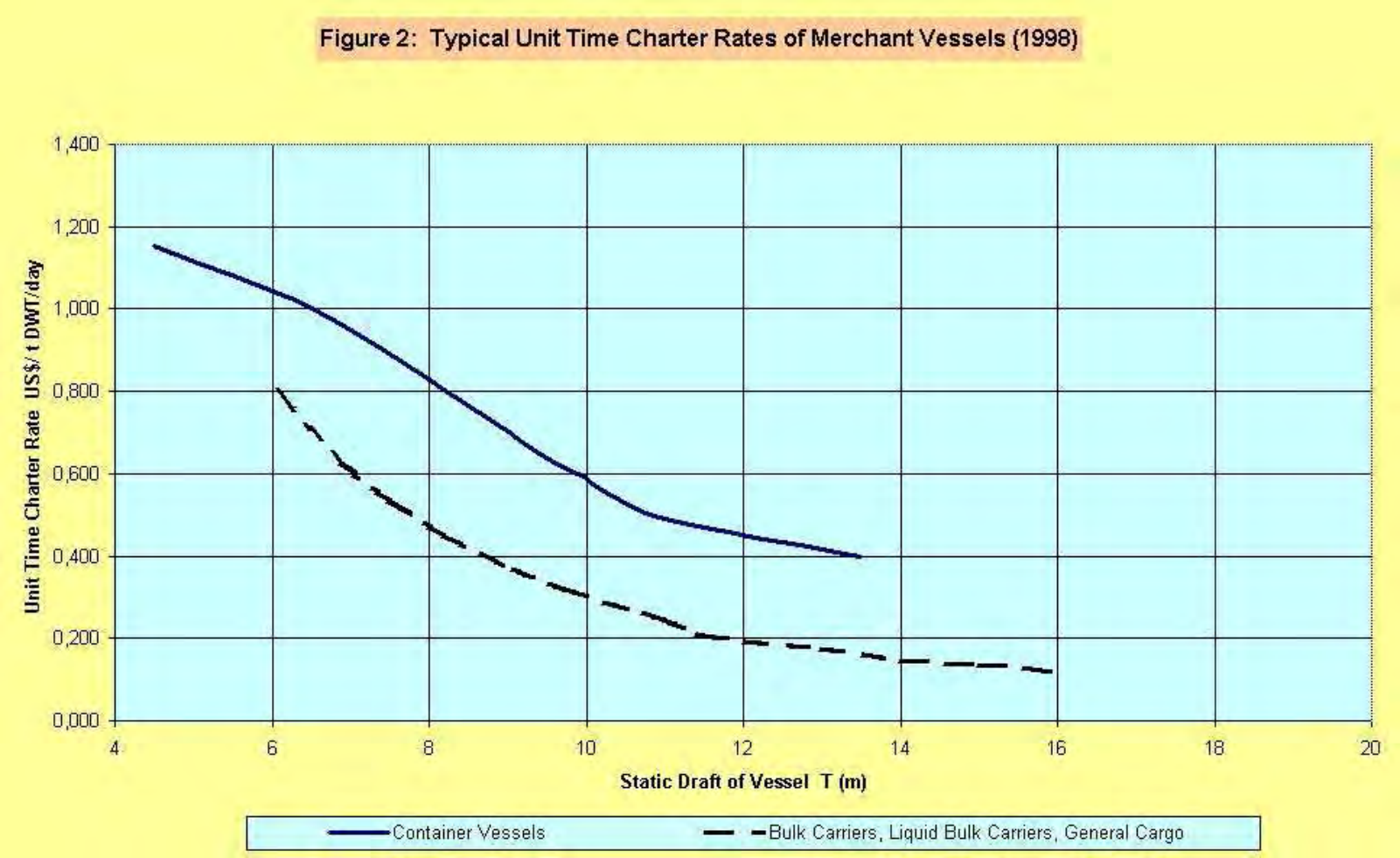
ECONOMY OF SCALE :

EVER INCREASING SHIP'S SIZES



Berna

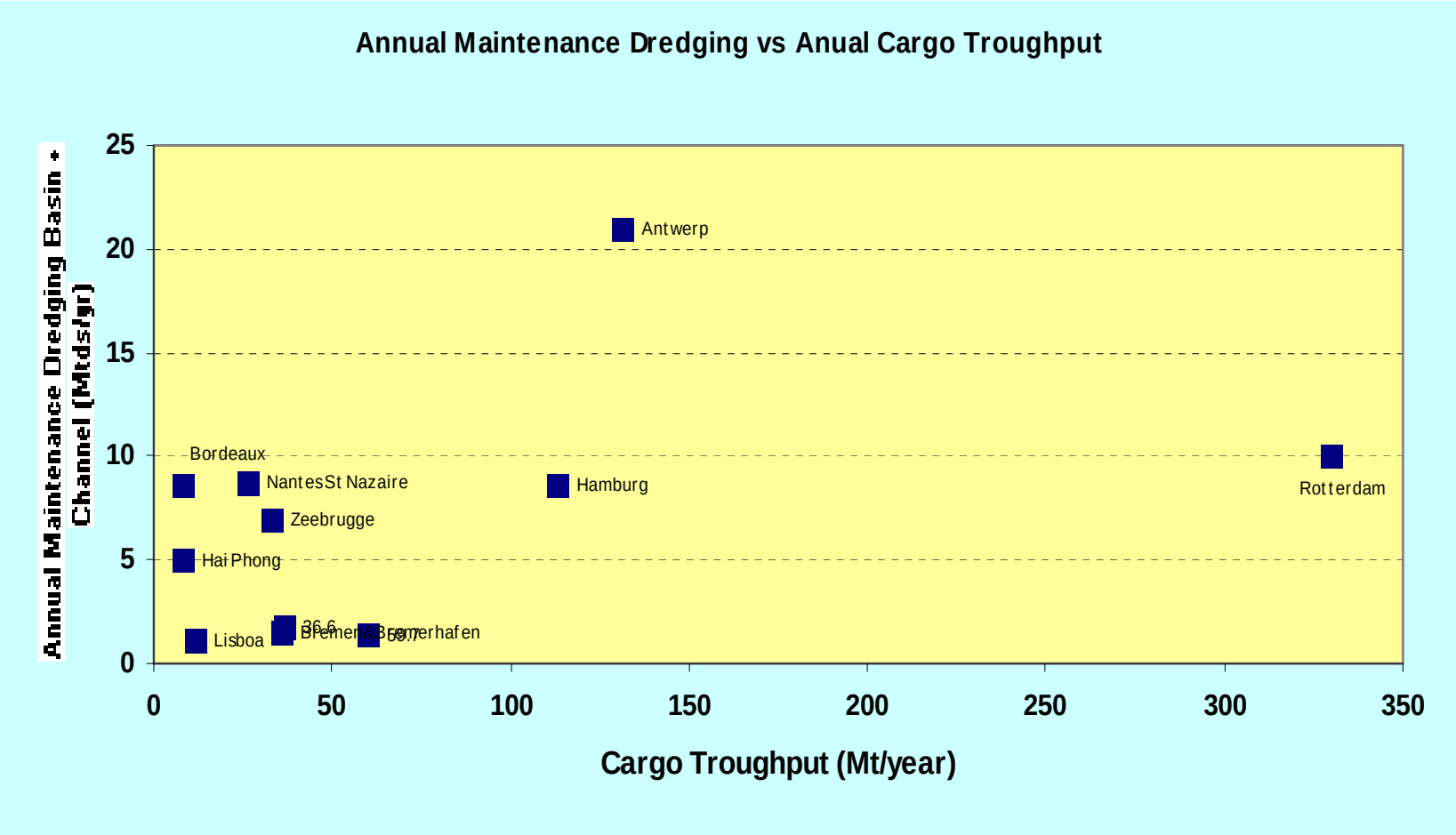
LARGE SHIPS MEANS CHEAPER FREIGHT CHARTER RATES



Estuaries are faced with numerous challenges:

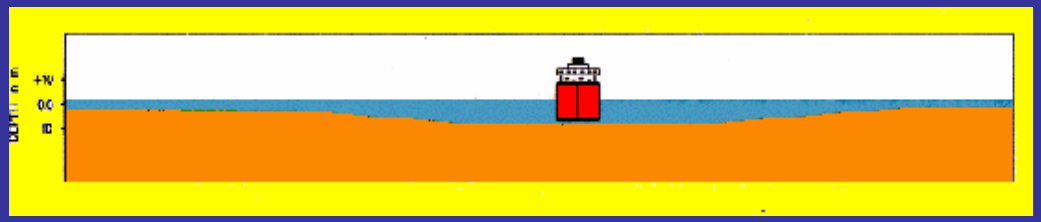
- **They are the system where fine-grained sediments tend to accumulate by resdual sediment-transports > <u>sedimentation of access-channels</u>**
- **There tidal currents, wave-climate and river-discharges meet and interact with loose sediment-deposits > <u>morphodynamics</u>**
- **Many delta's in the world are subsiding > <u>threat of flooding</u>**
- **Typical wetland, intertidal and brackish/salt/fresh ecosystems >> <u>vulnerable ecology</u>**
- **Dense urbanisations linked to trade-routes, industry > <u>anthropogenic stress</u>**

ANNUAL MAINTENANCE DREDGING CAN BE A SIGNIFICANT COST-ITEM IN THE OVERALL PORT'S ECONOMIC BALANCE



SAFETY MARGINS OF A MARITIME ACCESS-CHANNEL ARE SMALL COMPARED TO SEDIMENTATION PROCESSES

Access-channel Type (maritime)	Width		Nautical depth		Dredging tolerance TSHD	
	Width factor	Meters	Keel-clearance kc % of Tst	Keel-Clearance (m)	Vert. (m)	Horiz. (m)
1. Way Traffic Lane	3.B- 6.B	90 - 300	10 to 20	0,8 - 3	0,2 - 0,4	2 - 2,5
2-Way Traffic Lane	6.B-11.B	350 - 900	10 to 20	0,8 - 3	0,2 - 0,4	2 - 2,5



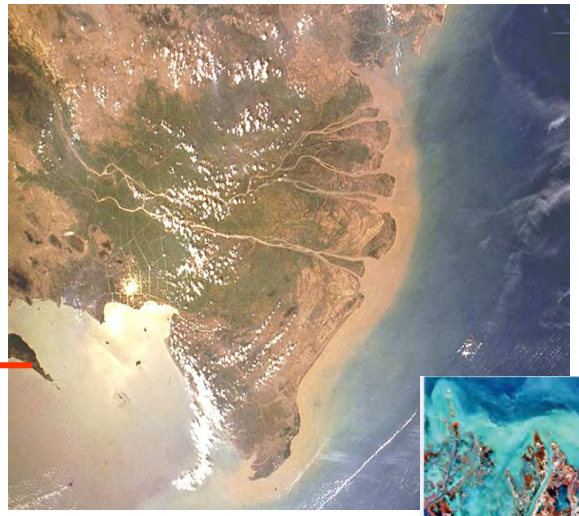
Traditionally maintenance Dredging has be conducted according to 2 different approaches….2 “philosophies”:

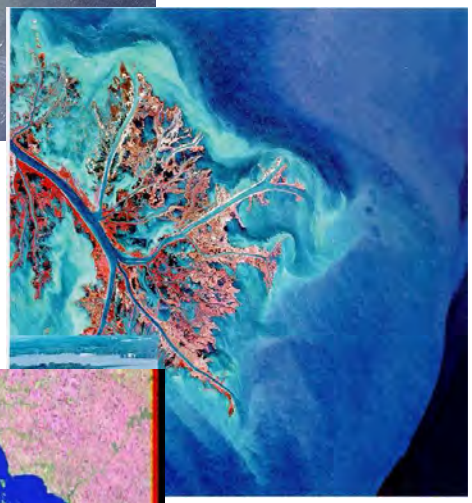
- **“Dynamic Channel” approach: the natural morphology of the sea, estuarine or river bed has been sounded…and the buoyage is adapted and corrective dredging of the shoals is executed (since the most ancient times)**

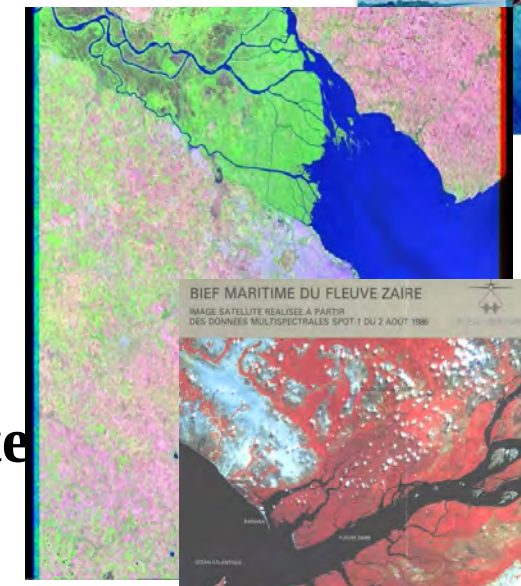
- **“Fixed Channel” approach: the navigational channel is ‘freezed’, the alignment is kept and the observed shoals are dredged (since the XX-th century with the introduction of concrete and heavy construction equipment)**

Examples of “Dynamic Channel” maintenance dredging are:

- **The Mississippi navigation channel (USA)**
- **The Bassac River maritime channel (Viet Nam, Mekong Delta)**
- **The Rio Paranà (Argentina)**
- **The Bief Maritime Région Divagante of the Congo River (RD Congo)**

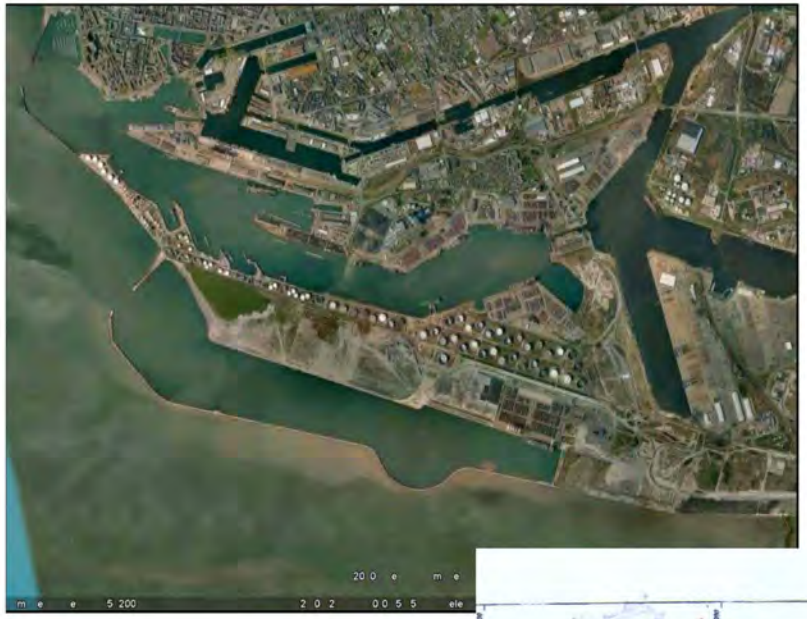


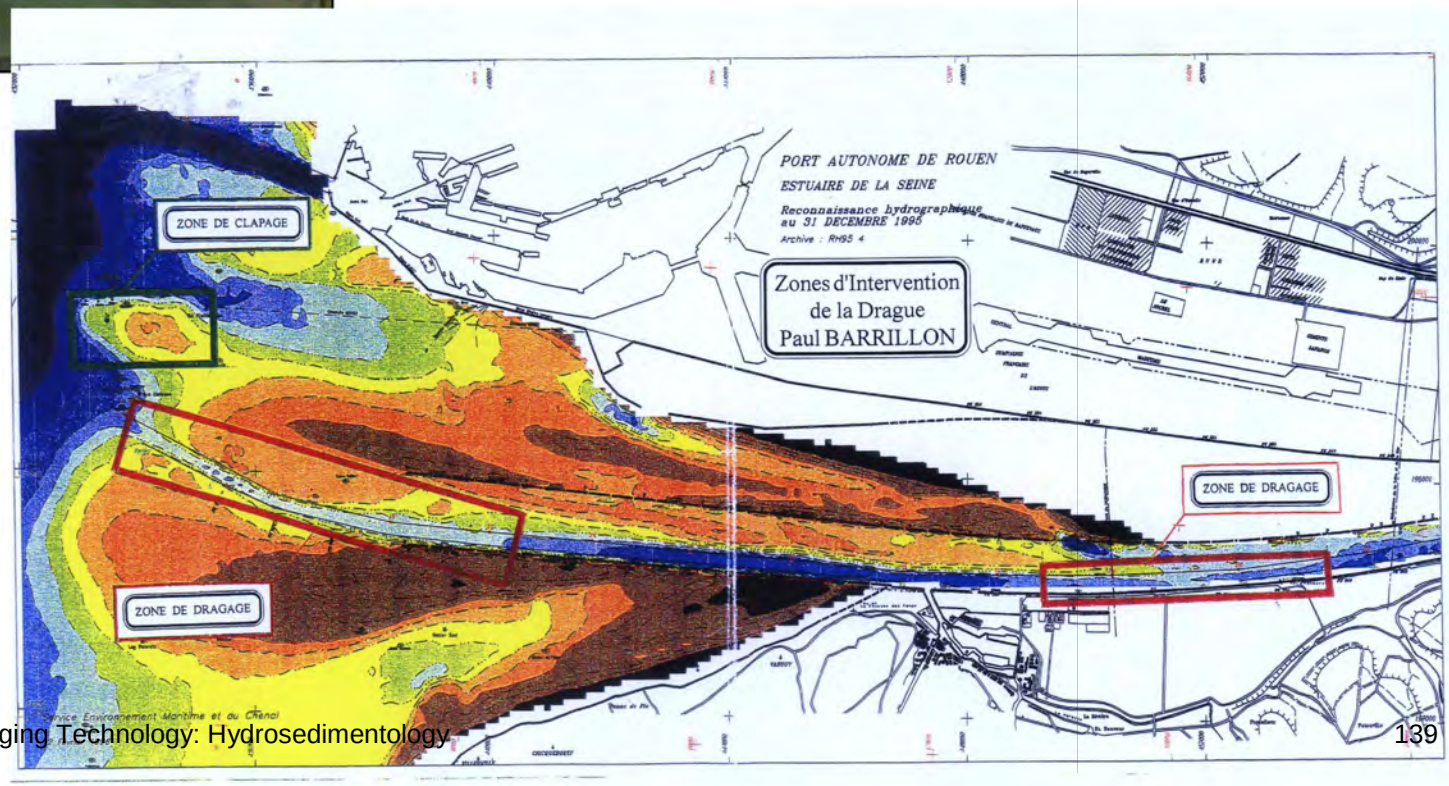




Examples of Fixed Channel Maintenance Dredging are numerous and the most extreme is probably the Rhine-Mose estuary which has been embanked with rigid structures over considerable lengths

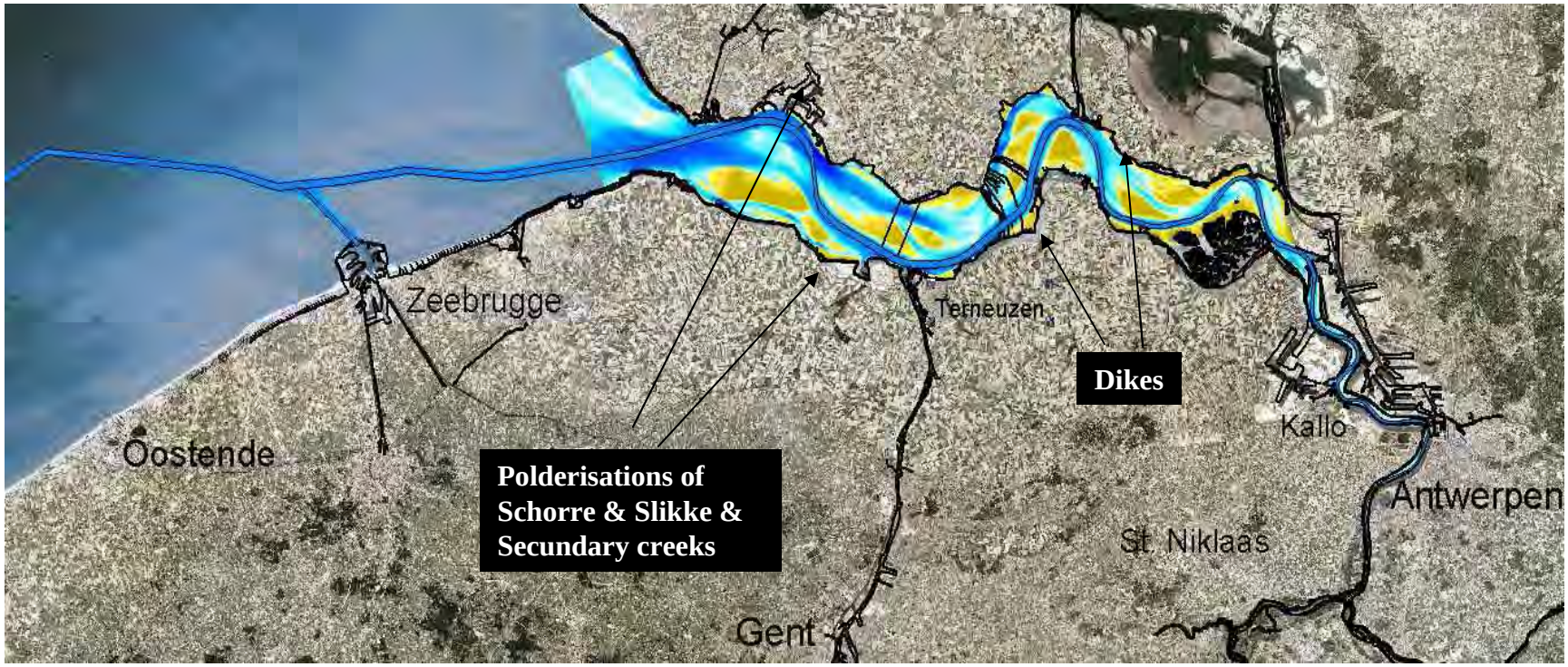
Seine Estuary: fixation of the main ebb-channel by dams





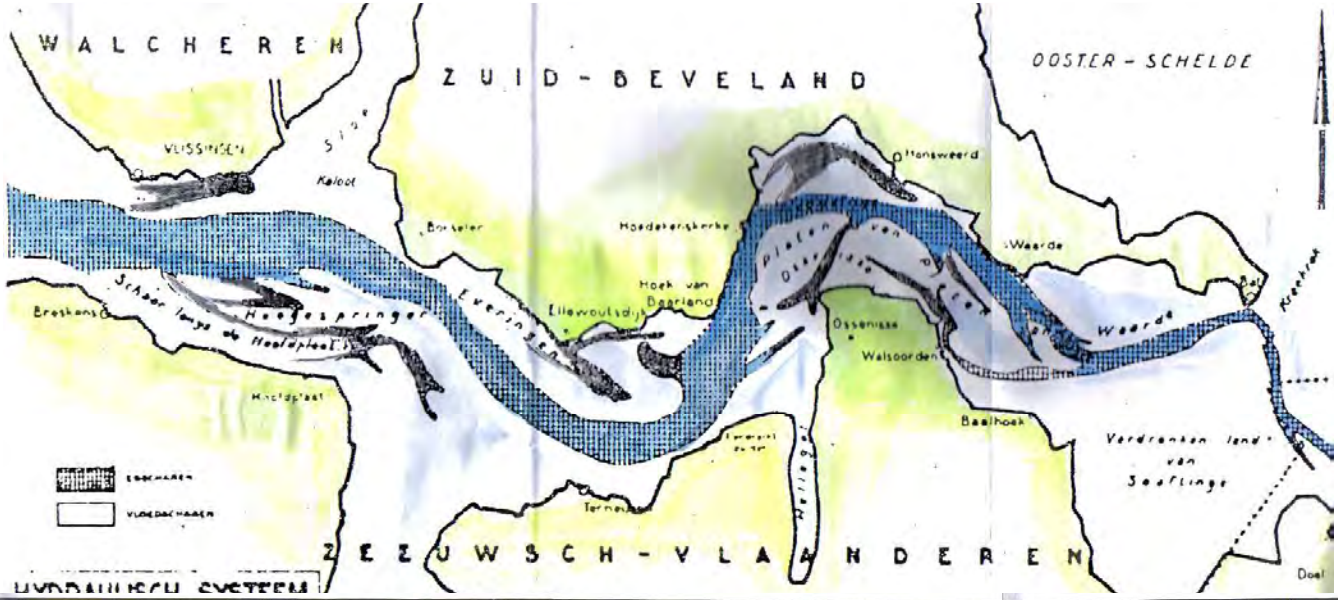
Ref Hauville M, 2002

Western Scheldt Estuary: a creek-system that evolved towards an estuarium with heavy traffic (> 60.000 channel-bound ship movements per year)

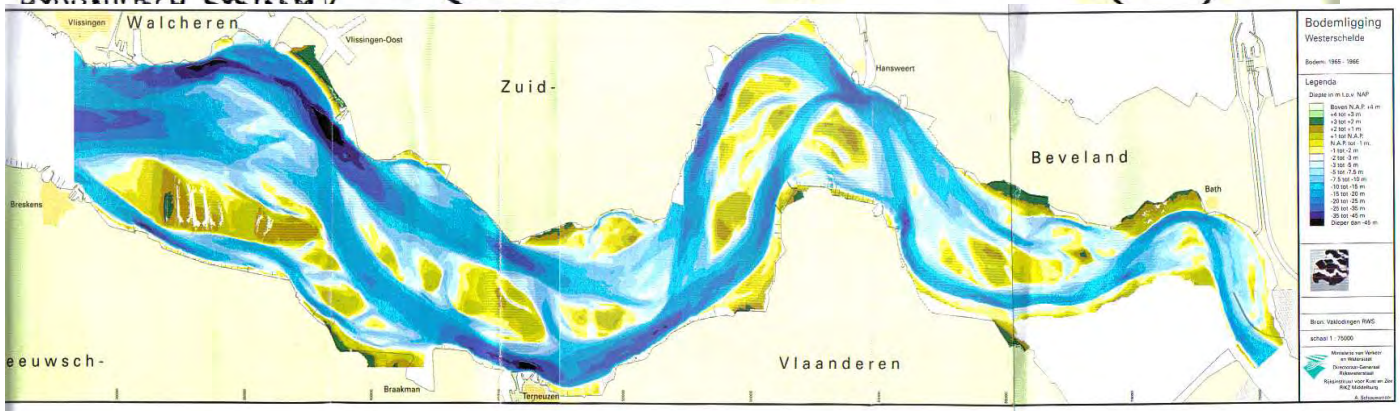


Dredging on shoal-crossing bars

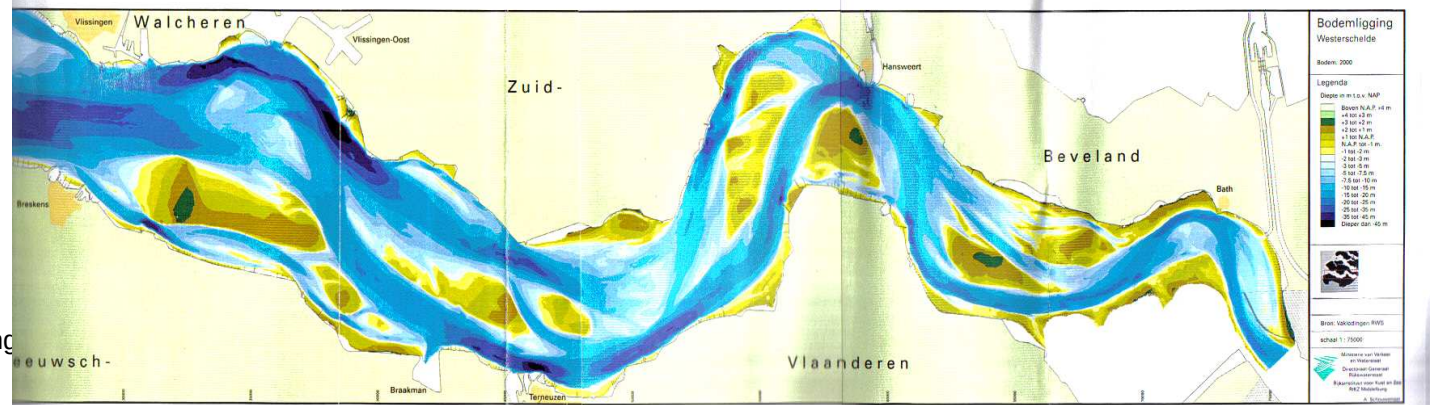
Van Veen, sit. 1800



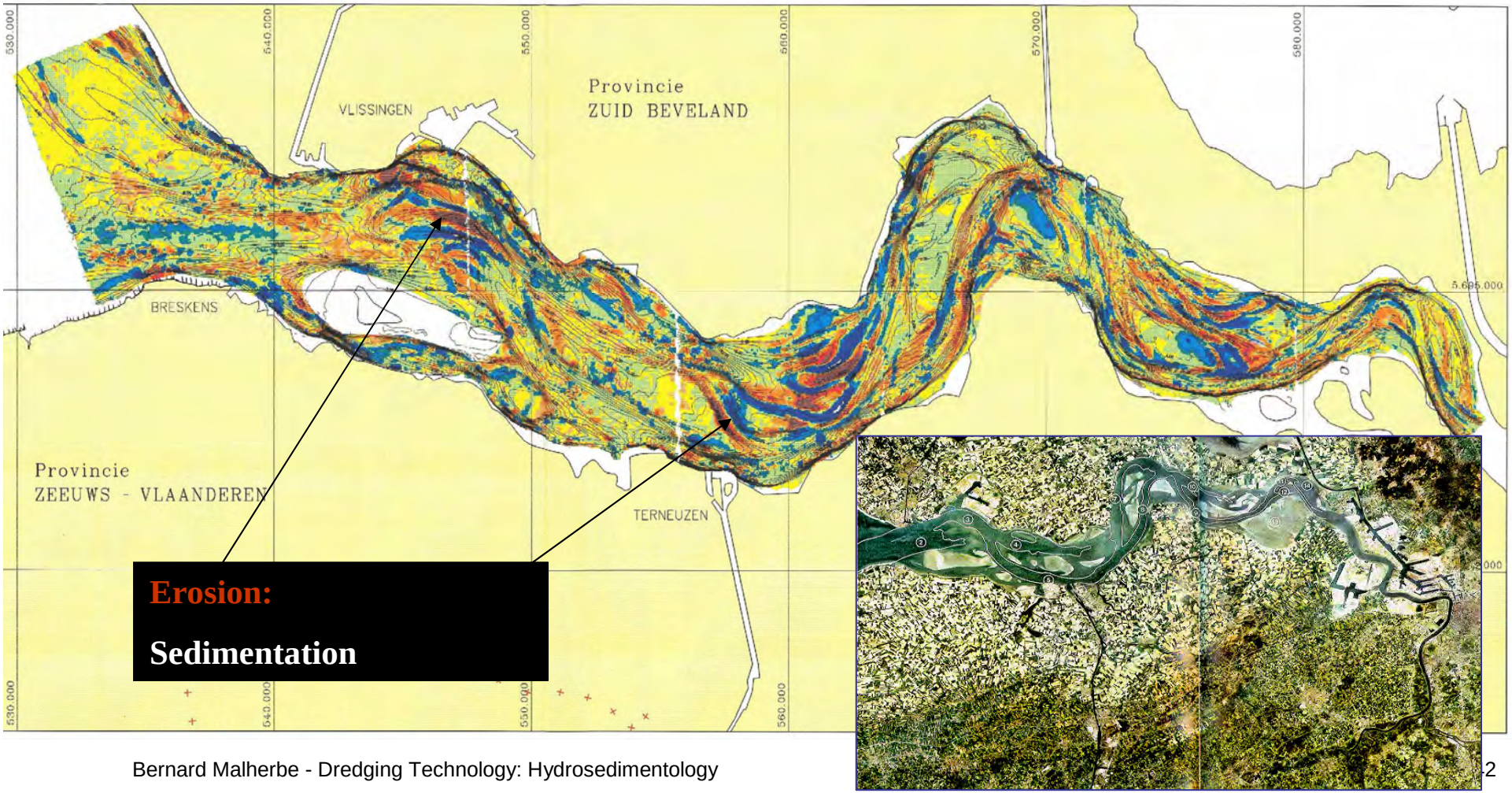
RWS, sit. 1966



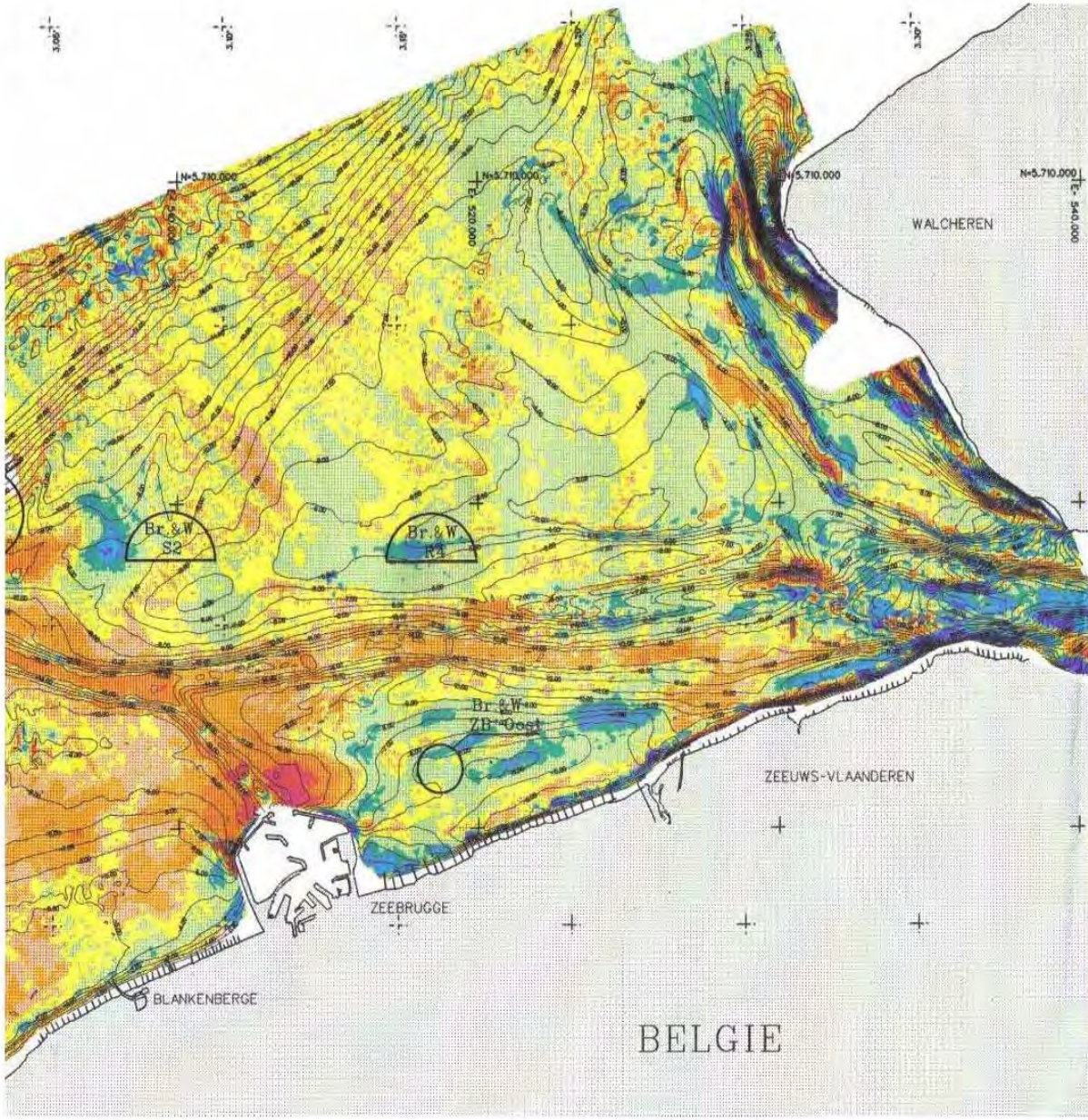
RWS, sit. 2000

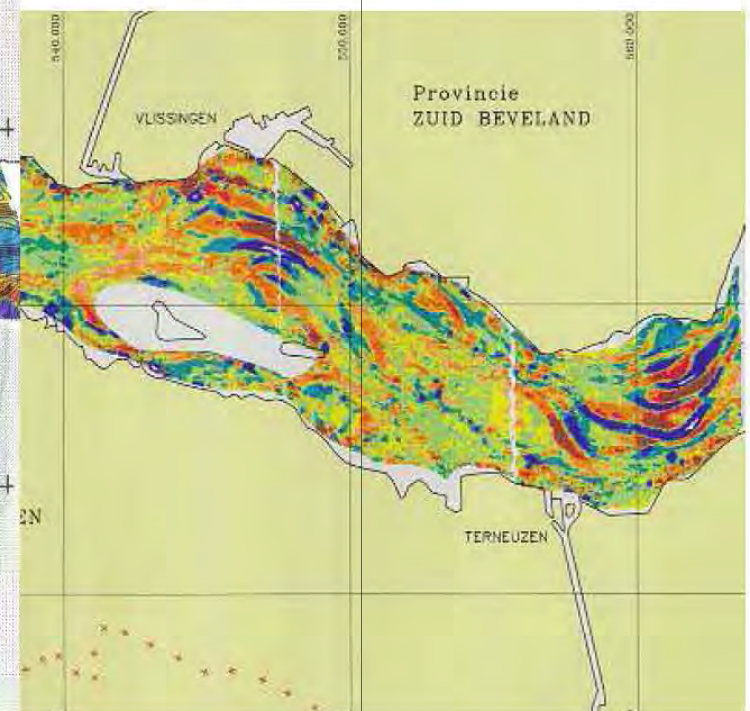


Analysis of morphological changes of the estuary bed (1992-1994)in a period with no deepening dredging works (ref HAECON 1996)



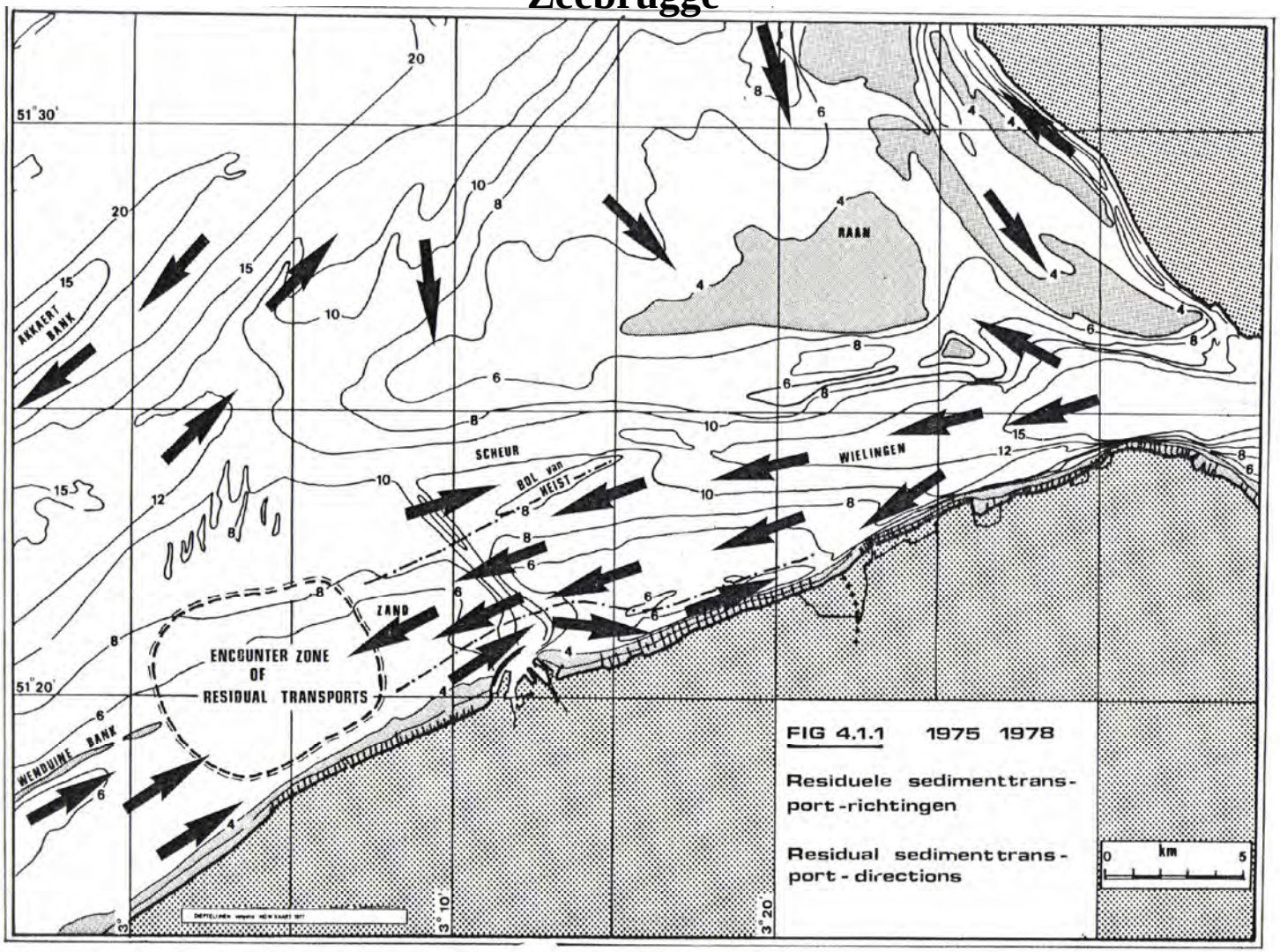
Morphological Analysis and Stability Assessment of the Maritime Access-Channel





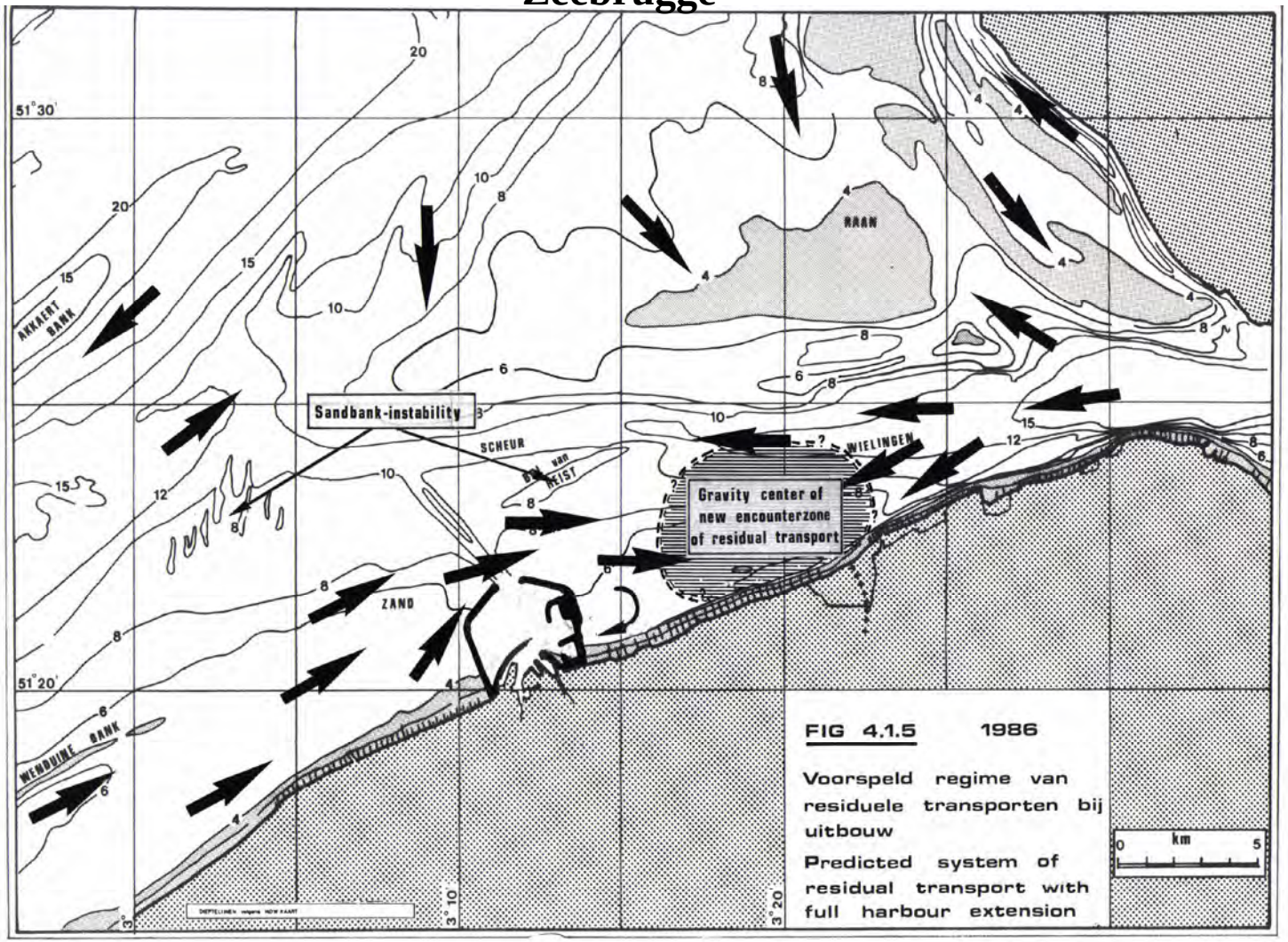
Digital Terrain Model and Differential Mapping (1992-1994) of the Western Scheldt Estuary Bed (HAECON, 1997)

Residual sediment-transport patterns and morphology before the new extension of the Port of Zeebrugge

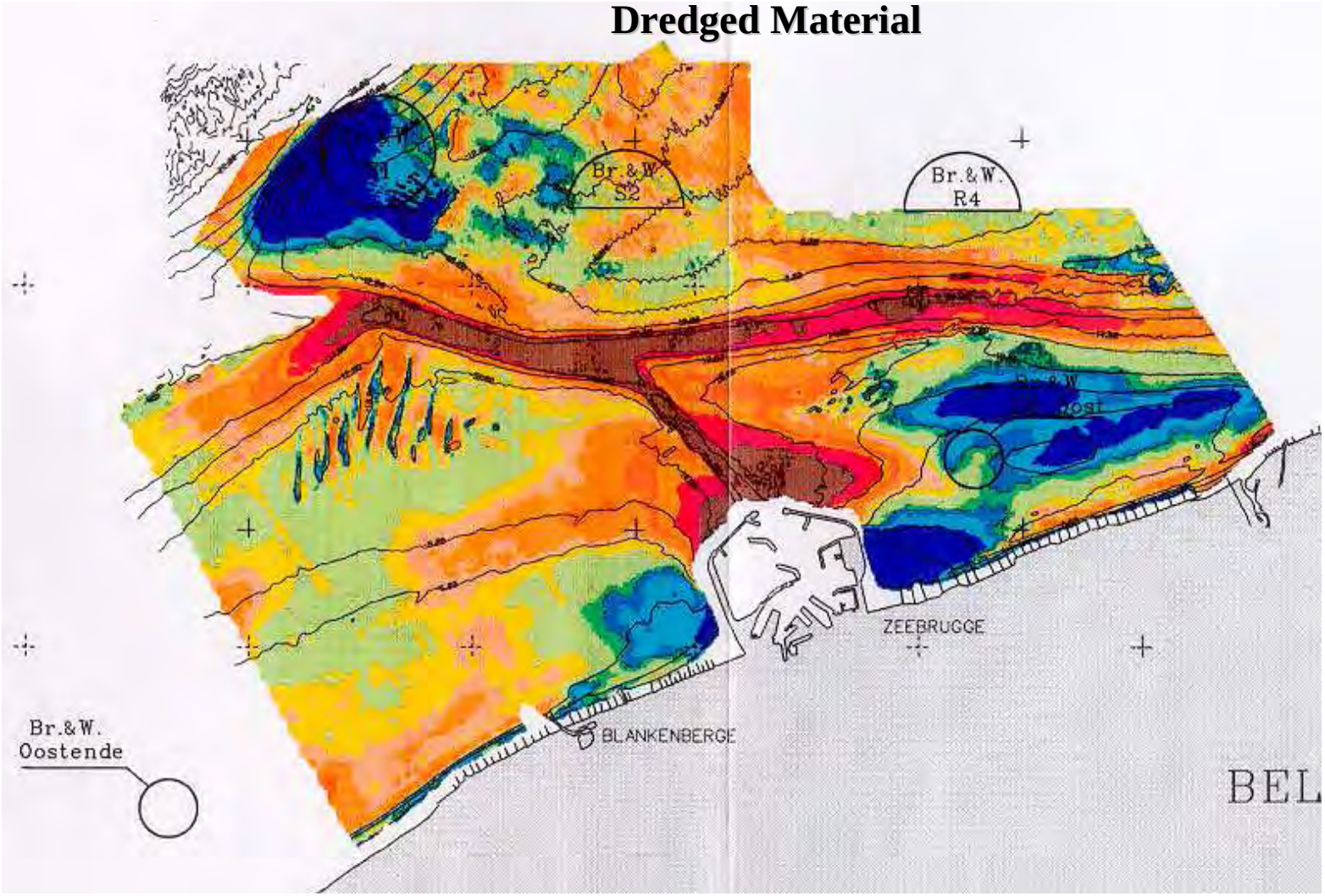


Satellite Image illustrating the existence of the Marine Turbidity Maximum Area (ref Belfotop, 1982)

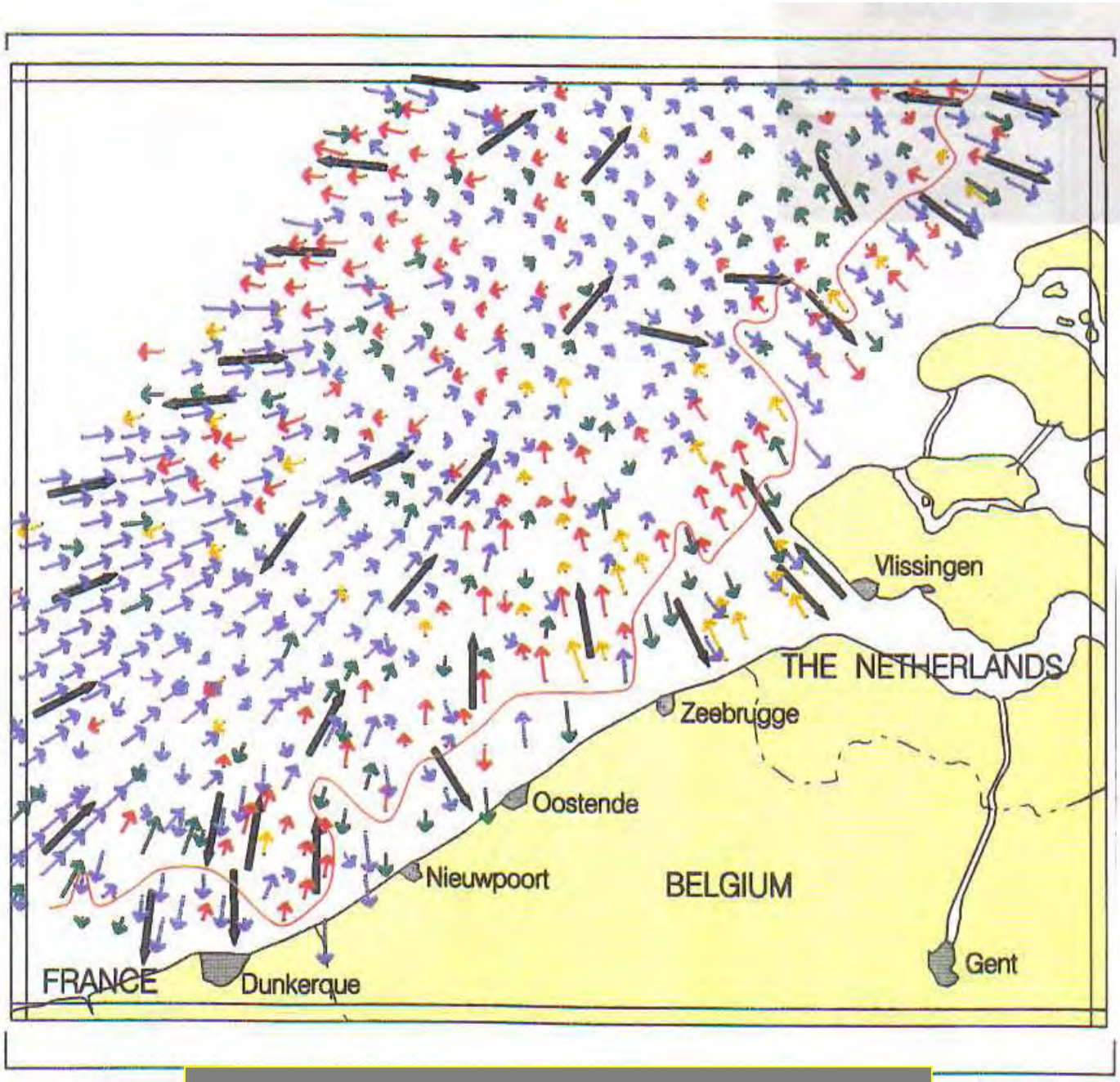
Predicted residual sediment-transport pattern and morphology after the extension of the new Port of Zeebrugge



Morphological Analysis and Stability Assessment of the Maritime Access-Channel and the Dumping Sites of Dredged Material



Digital Terrain Model and Differential Mapping (1976-1994) of the Seabed including port development, dredging and dumping (HAECON, 1996)



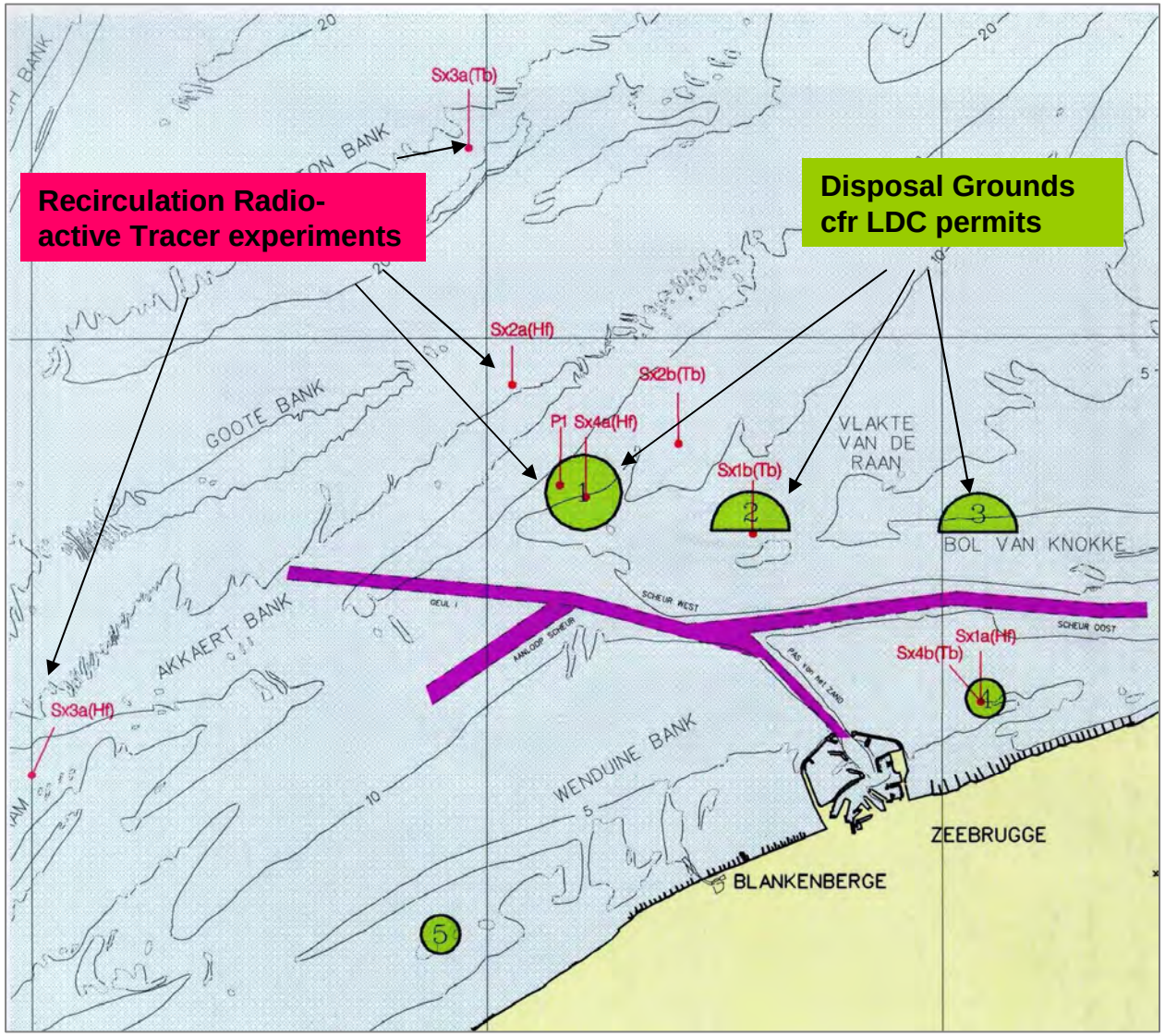
Compilation of results of :

- **grain-size distributions of seabed sediments**
- **radioactive tracer-experiments**
- **fixed station profilings**

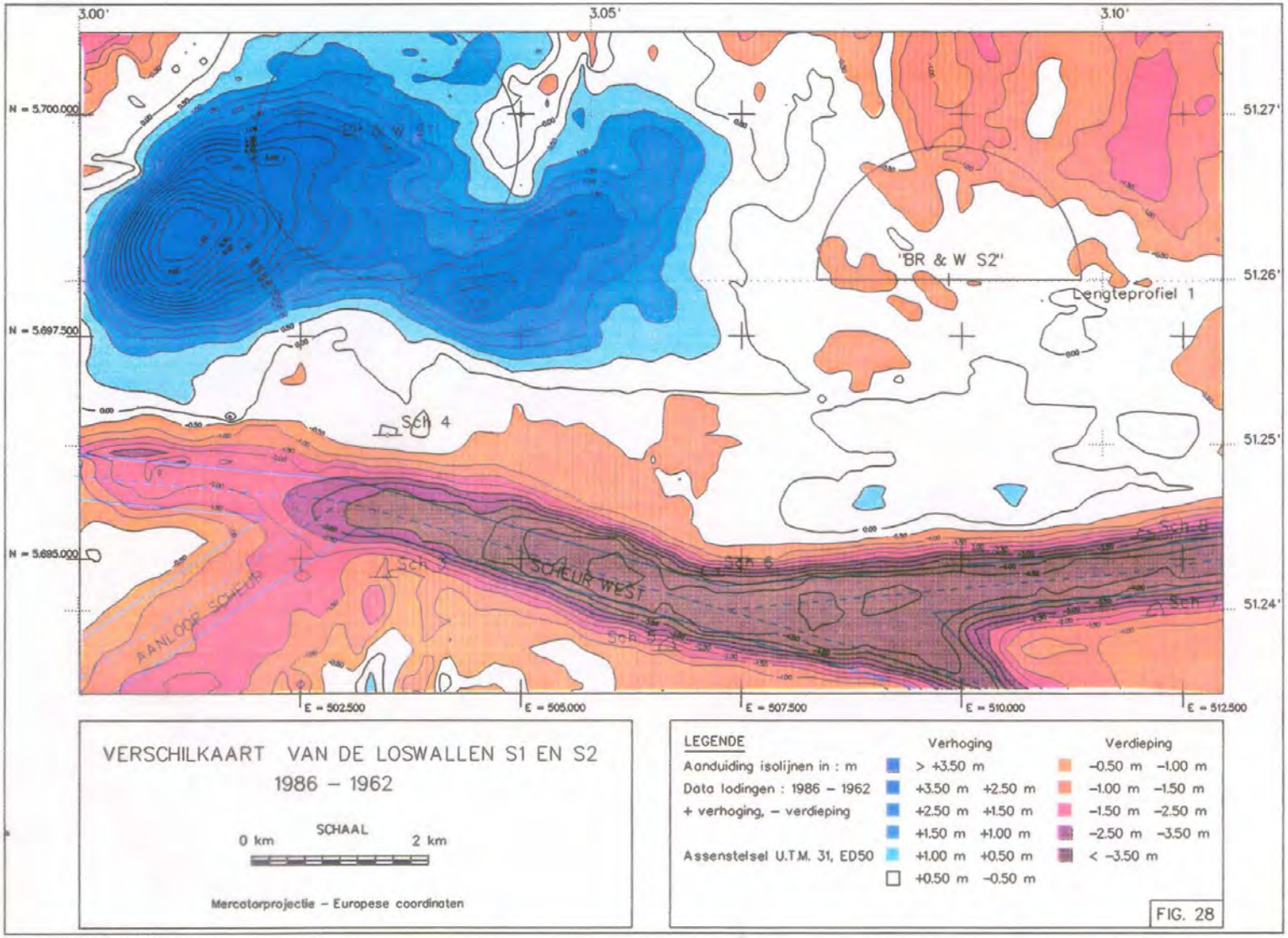
Residual sediment-transport pattern in the Southern Bight of the North Sea

Ref HAECON, 1998

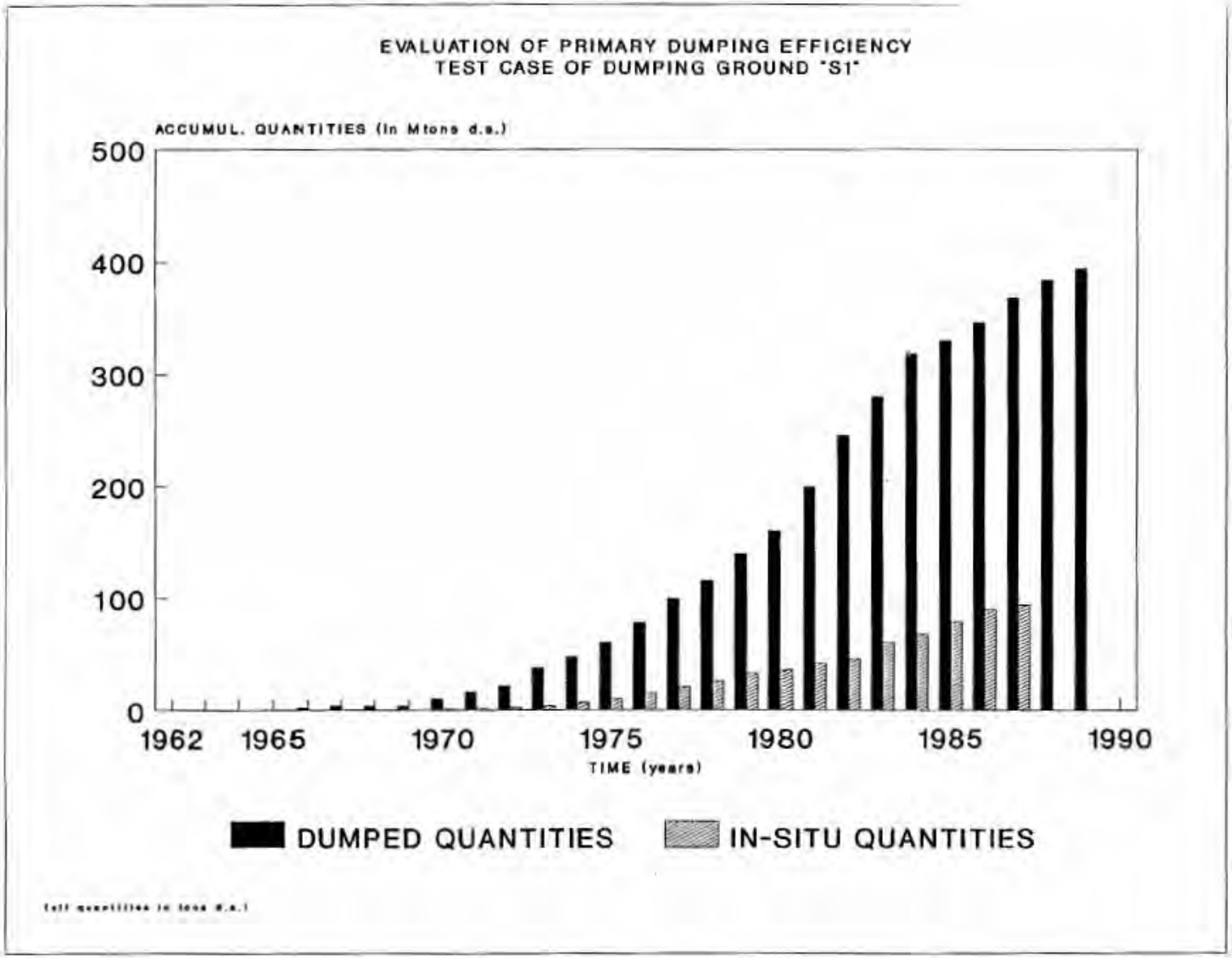
Morpho-Sedimentological Management of Aquatic Disposal Sites of Dredged material: Case Belgian North Sea



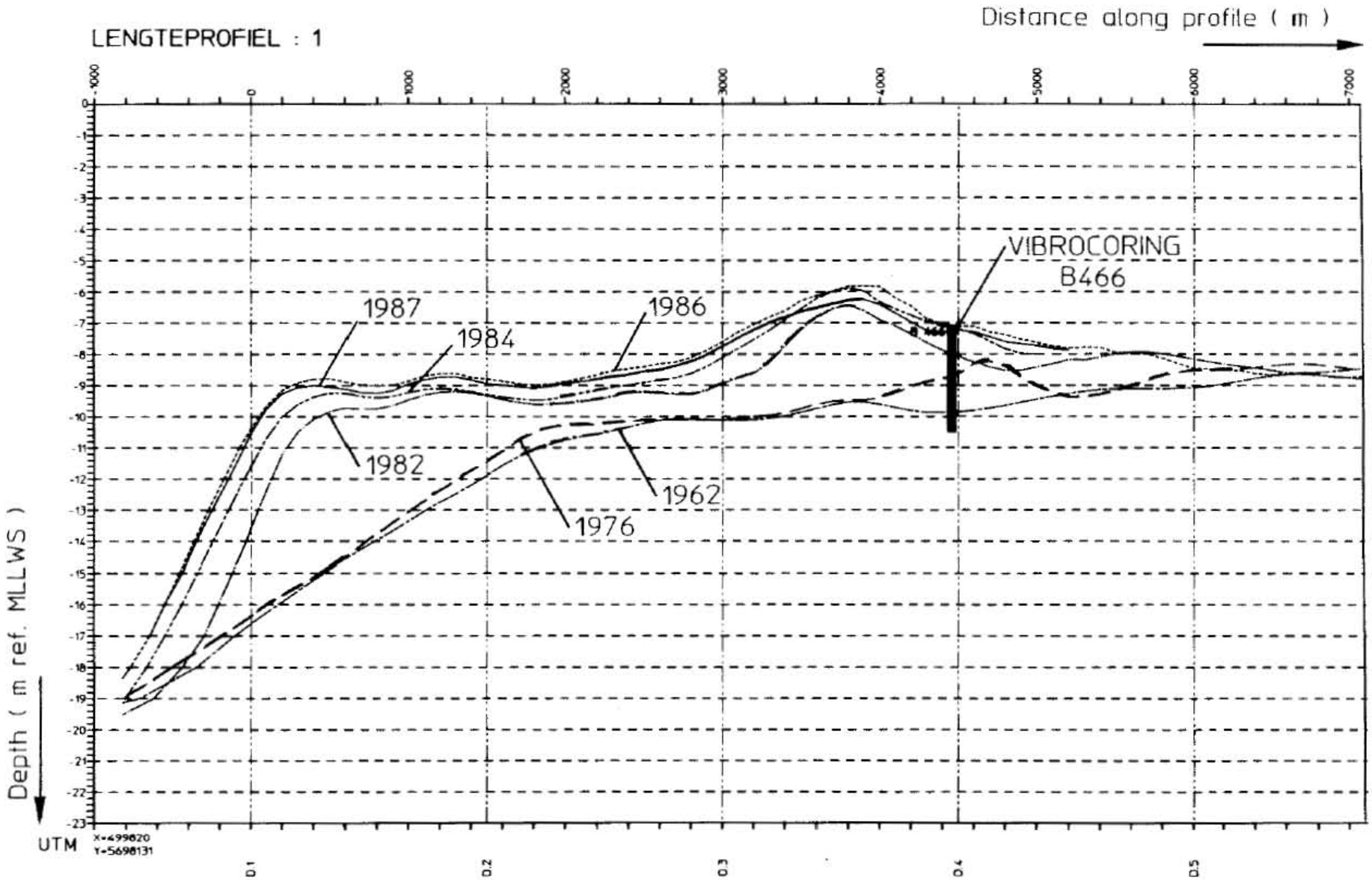
Detailed Differential Mapping of Disposal Ground to assess Morpholo-dynamics of dumping



Evaluation of Primary Dumping efficiency



Morphological and Geotechnical investigations on Dumping Grounds

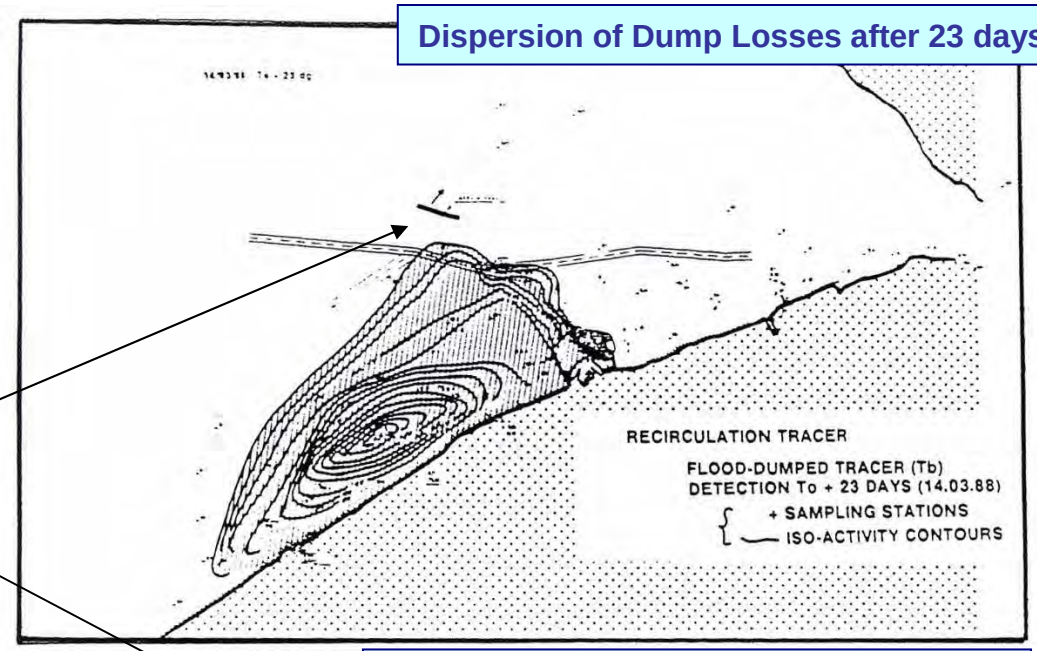


Recirculation Tracer Test results of dumping on S1 dumping ground

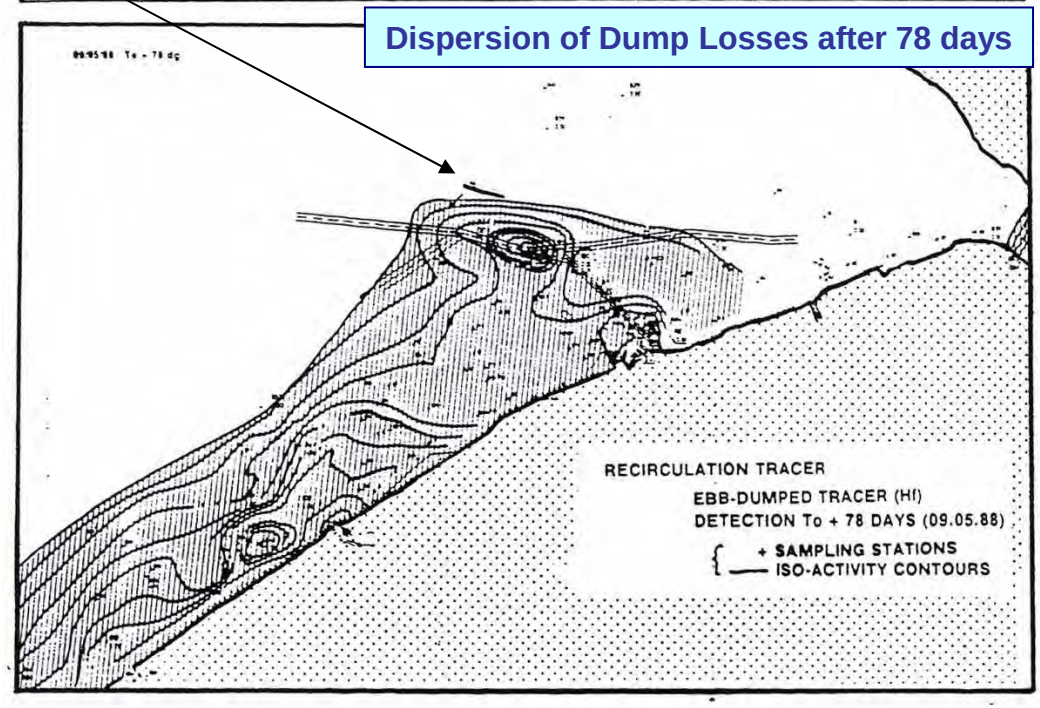
Dumping Ground S1:

Injection of tracer at T0

Dispersion of Dump Losses after 23 days

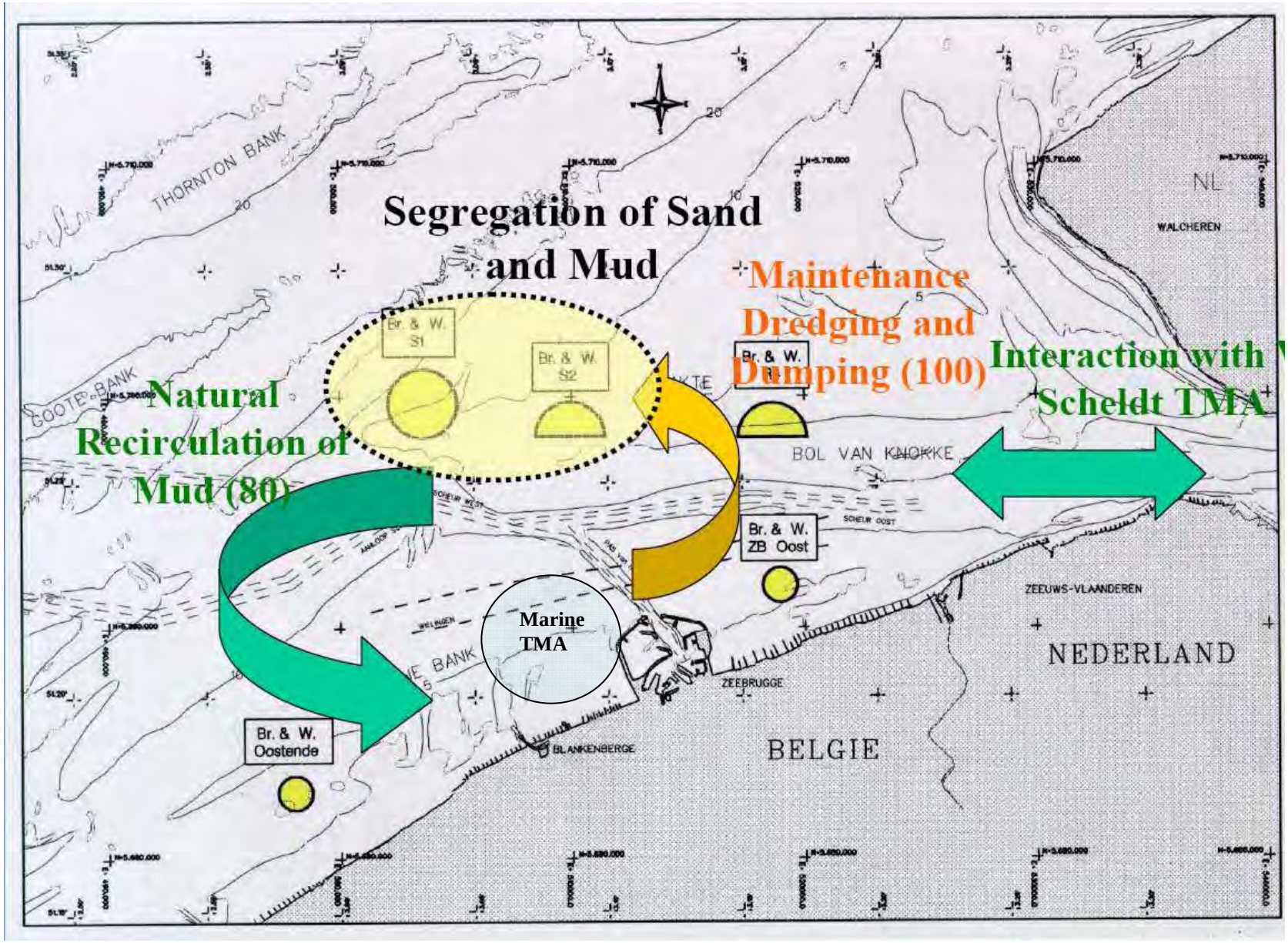


Dispersion of Dump Losses after 78 days

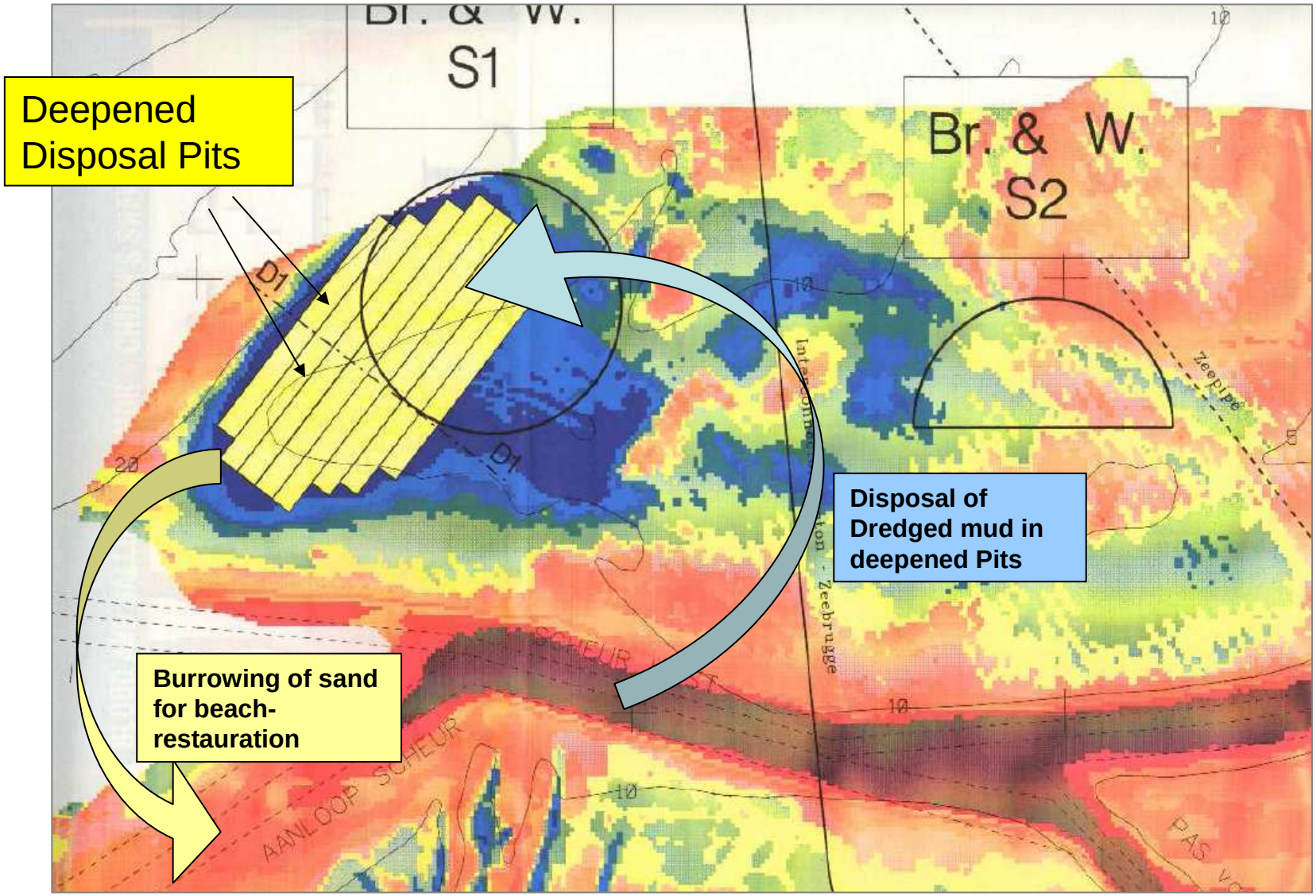


Tracer Technique developed by CEA, Saclay and HAECON

General Sediment-Dynamics deduced from Tracer-experiments & Sediment transport measurements



Proposed Management Plan of Disposal Ground

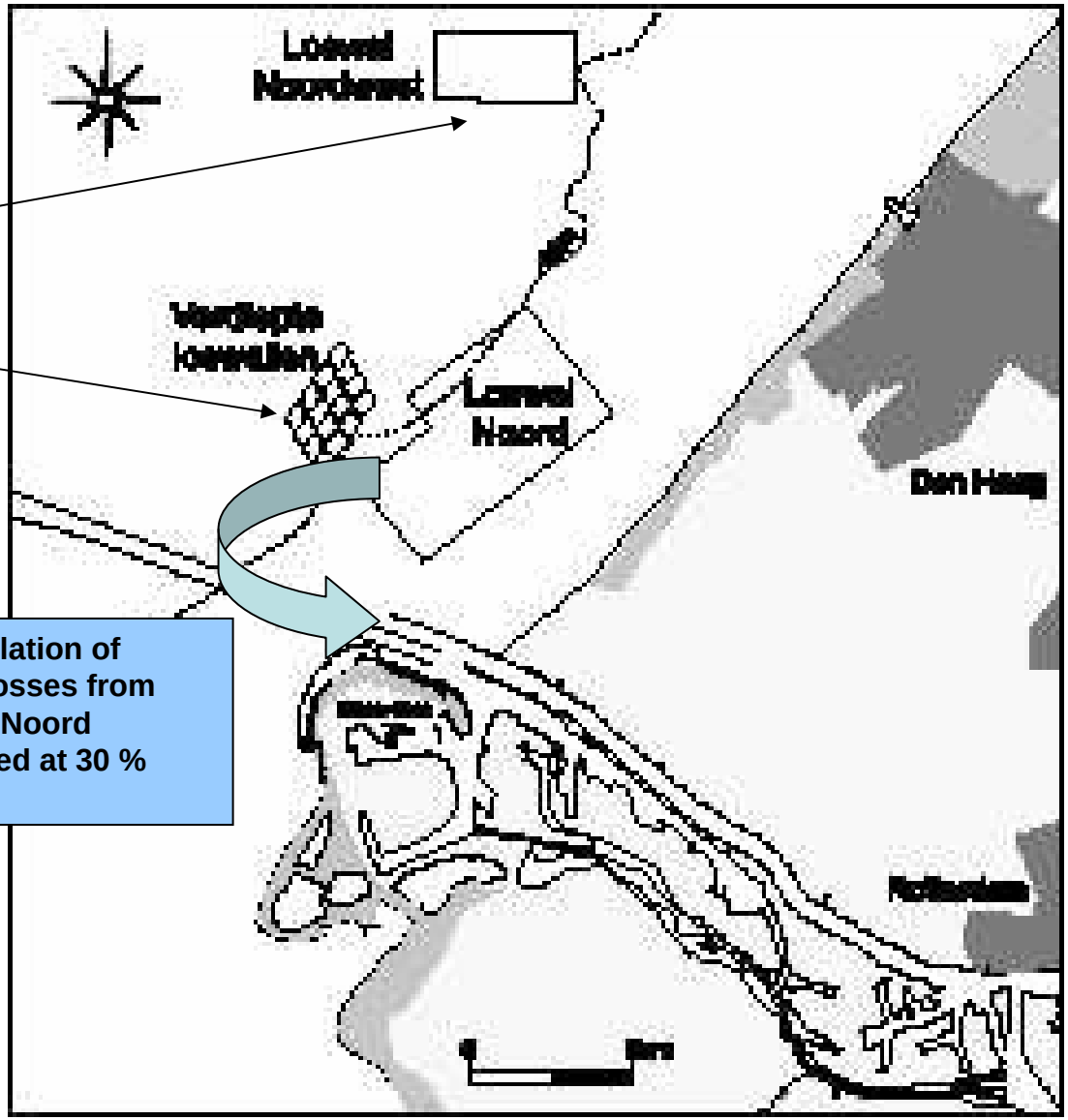


Sediment –Management of Dumped Dredged Material for Port of Rotterdam

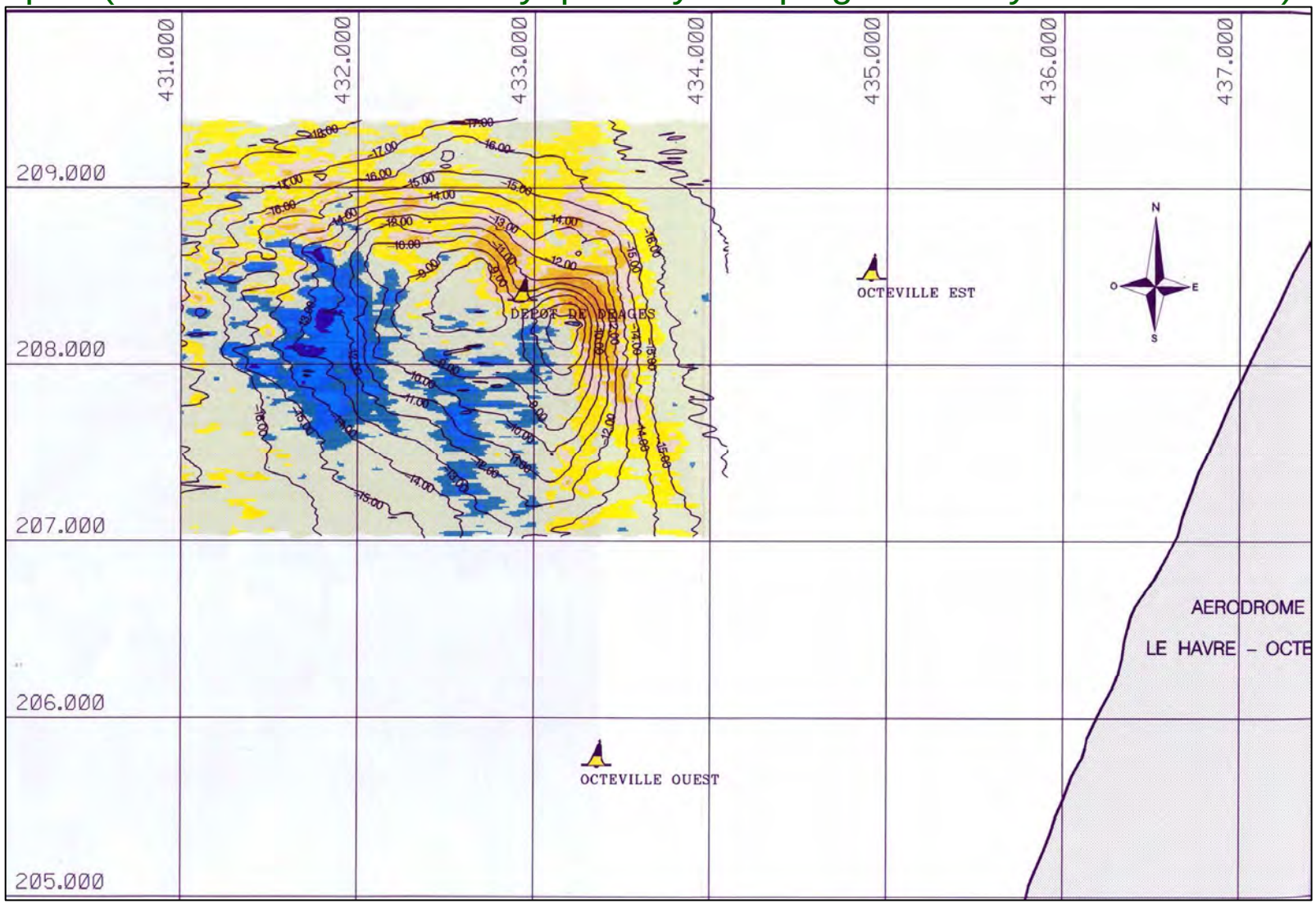
Distant Disposal Ground: Loswal Noord-West

Deepened Disposal Pits

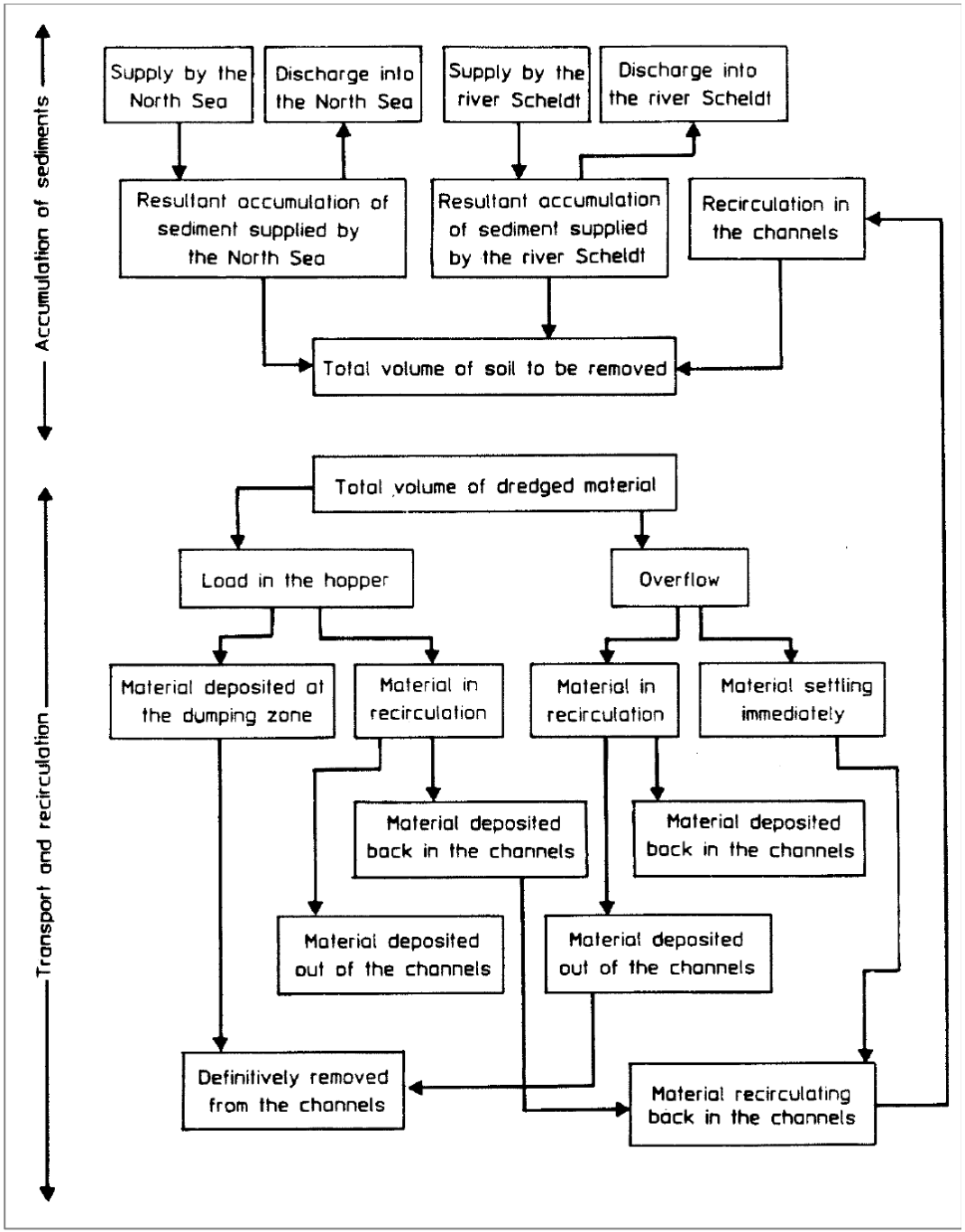
Recirculation of dump-losses from Loswal Noord estimated at 30 % (RWS)



Differential Map of Octeville Disposal Ground, for Port Autonome du Havre. Accretion of about 1,7 Mio m3 (between 1990 and 1995) for about 5 Mio m3 dumped (referred to same density: primary dumping efficiency of about 60 %)



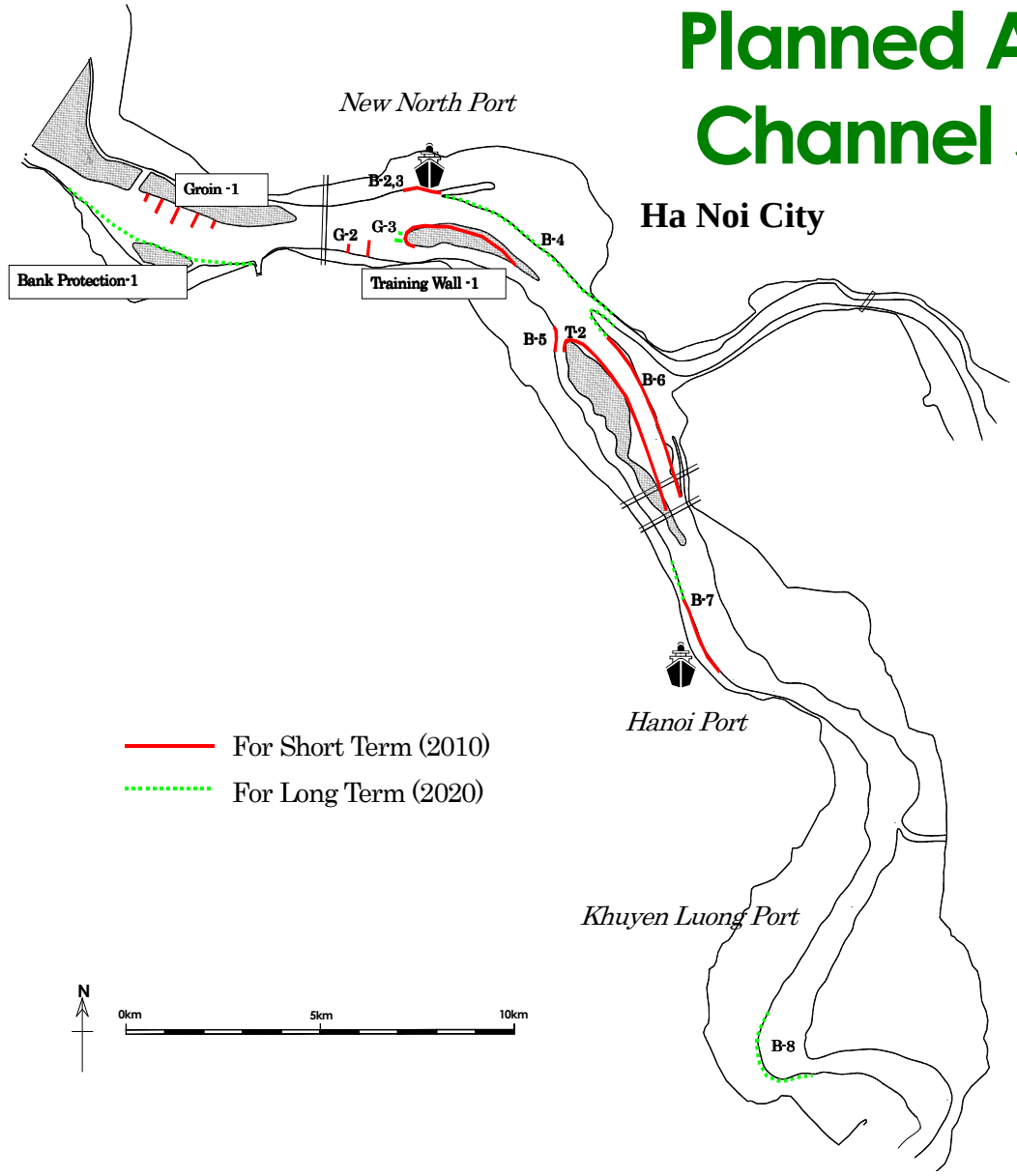
Basis for Sediment Management in areas where dredging and dumping operations are made: Conceptual scheme cfr dredging and aquatic disposal in the Southern Bight of the North Sea



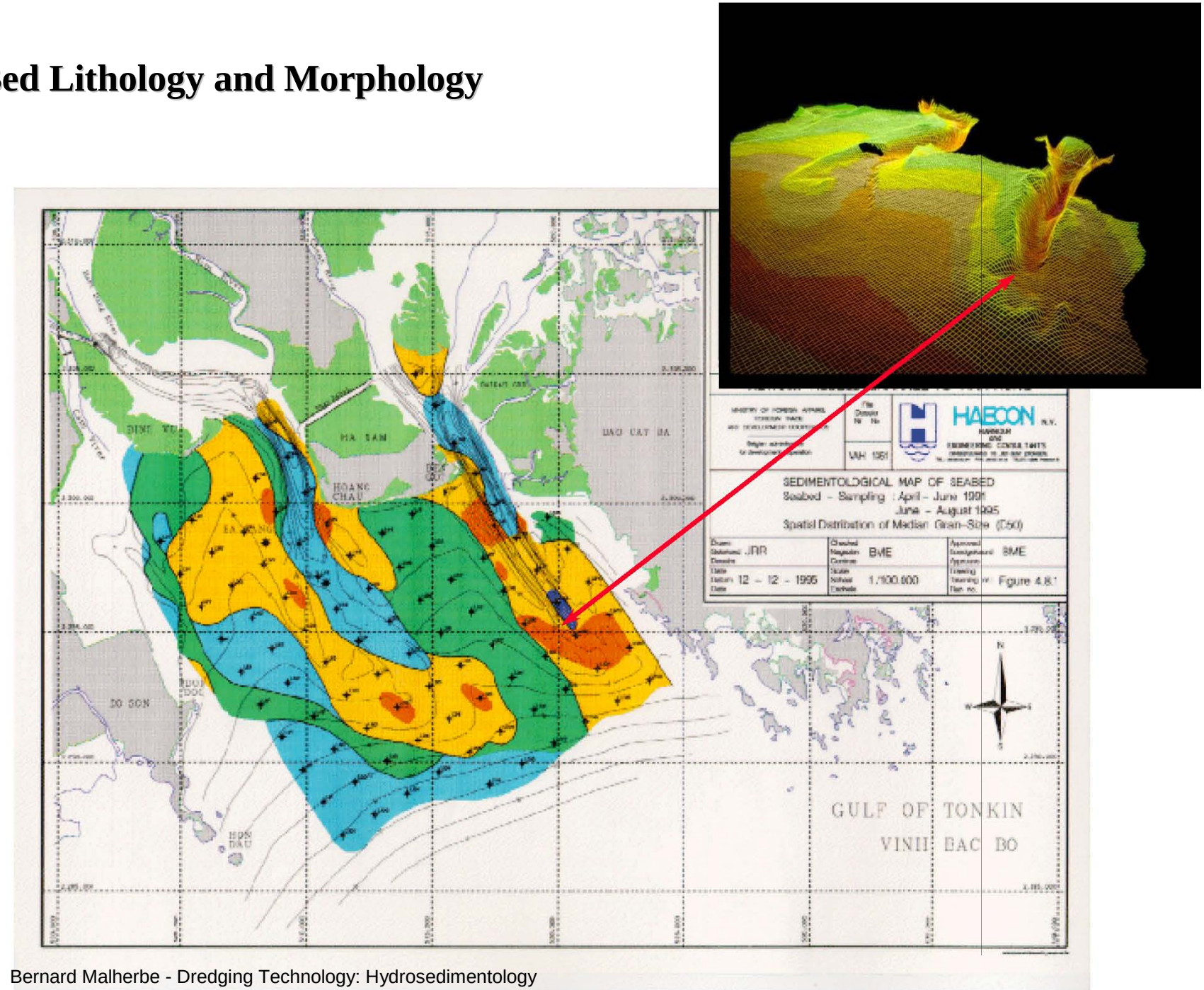
The Red River Delta and Estuary: discharges of up to 30.000 m3/sec and sediment supply of up to 150 Mtds/year

Proposed Channel Stabilization of the Red River in the Ha Noi Section: ref JPC & HAECON, 2003

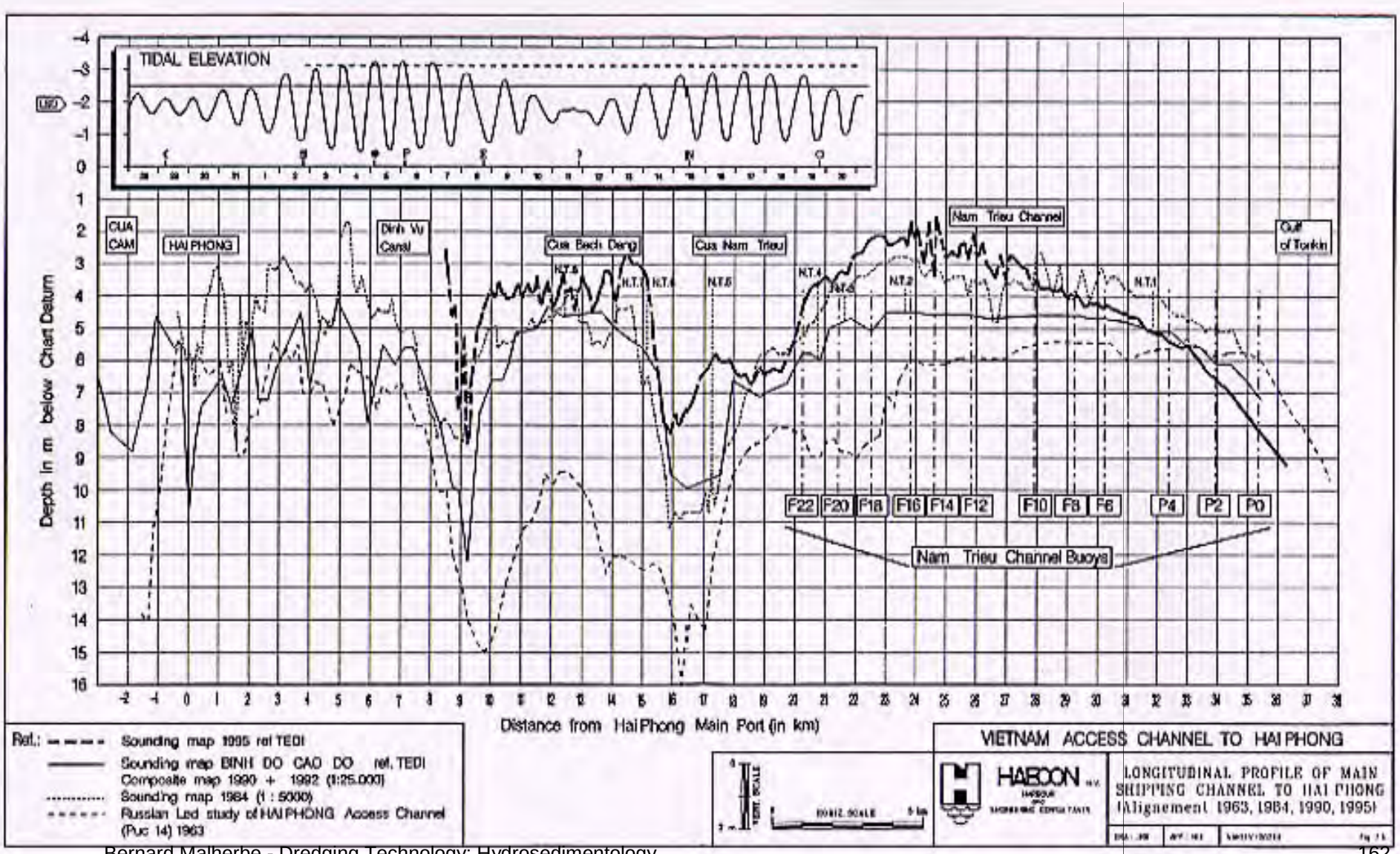
Planned Alignment of Channel Stabilization Measures

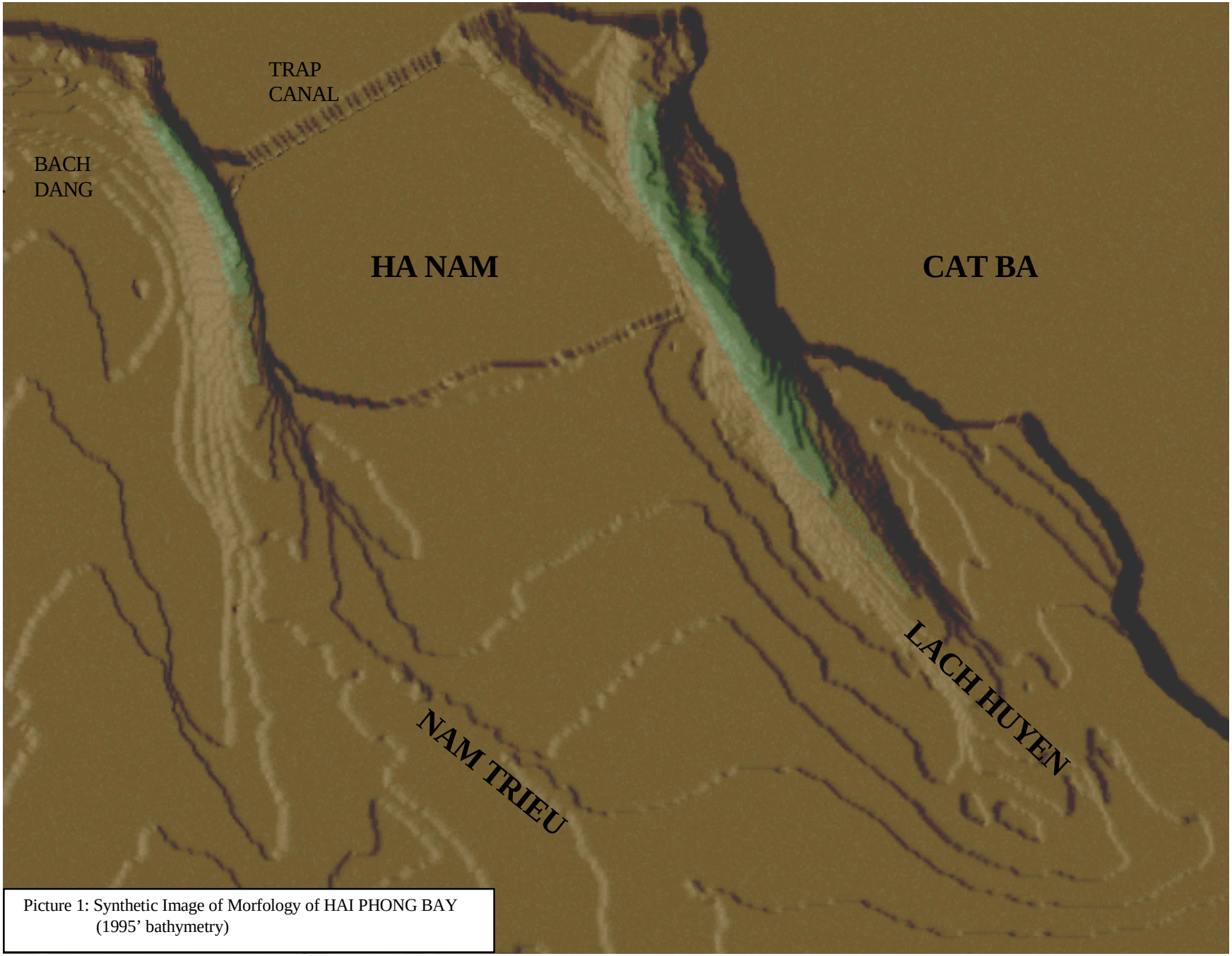


Sea-Bed Lithology and Morphology



Red River Delta, Cam River & Nam Trieu Access-Channel
Longitudinal section along the existing channel



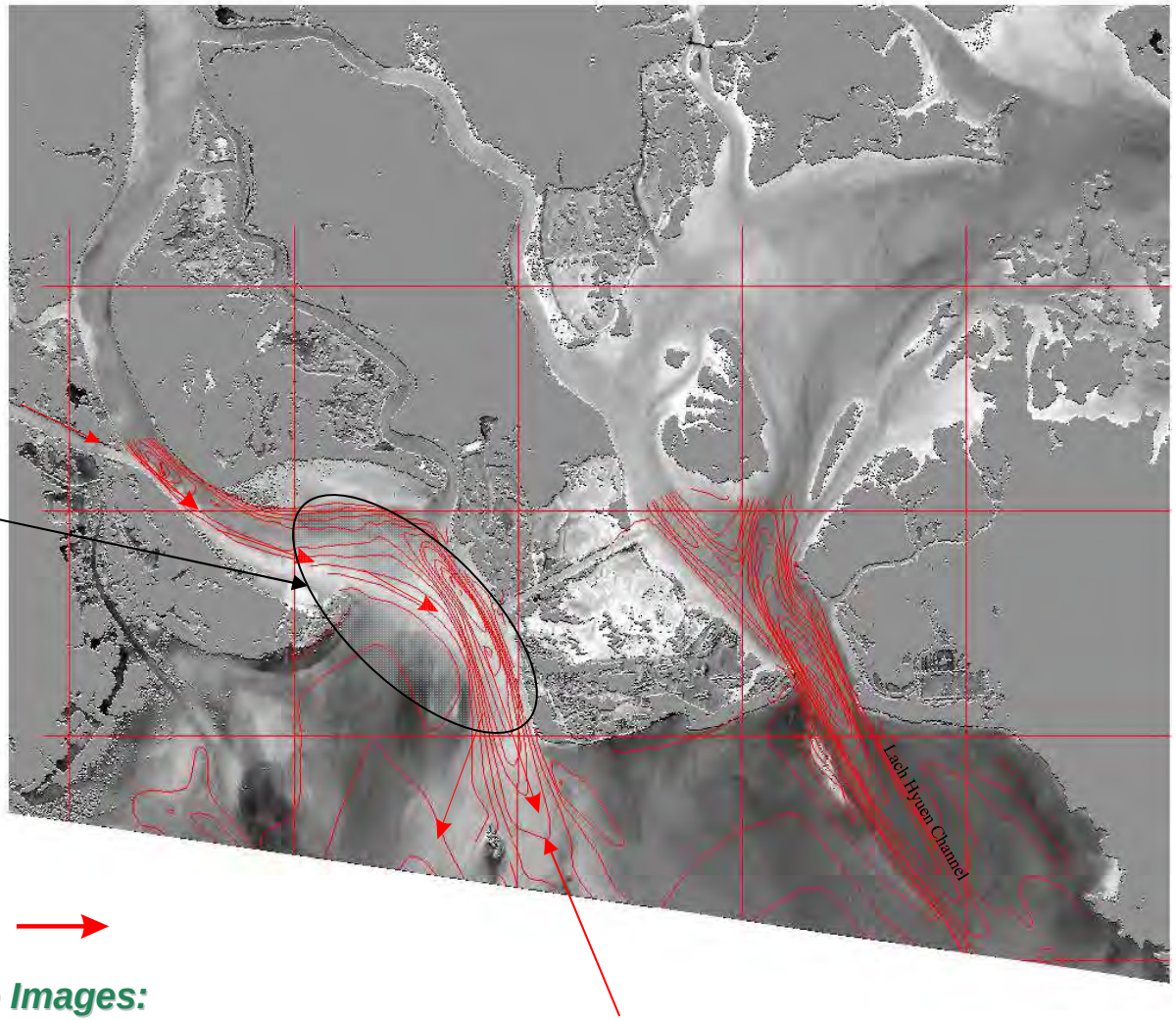


Picture 1: Synthetic Image of Morfology of HAI PHONG BAY
(1995' bathymetry)

3D numerical Model of Bathymetry in Hai Phong Bay

Hydrosedimentological survey of sediment transport: fixed station profiling

Turbidity Maximum Areas in estuaries: here the Cam River (Red River Delta Northern Viet Nam)



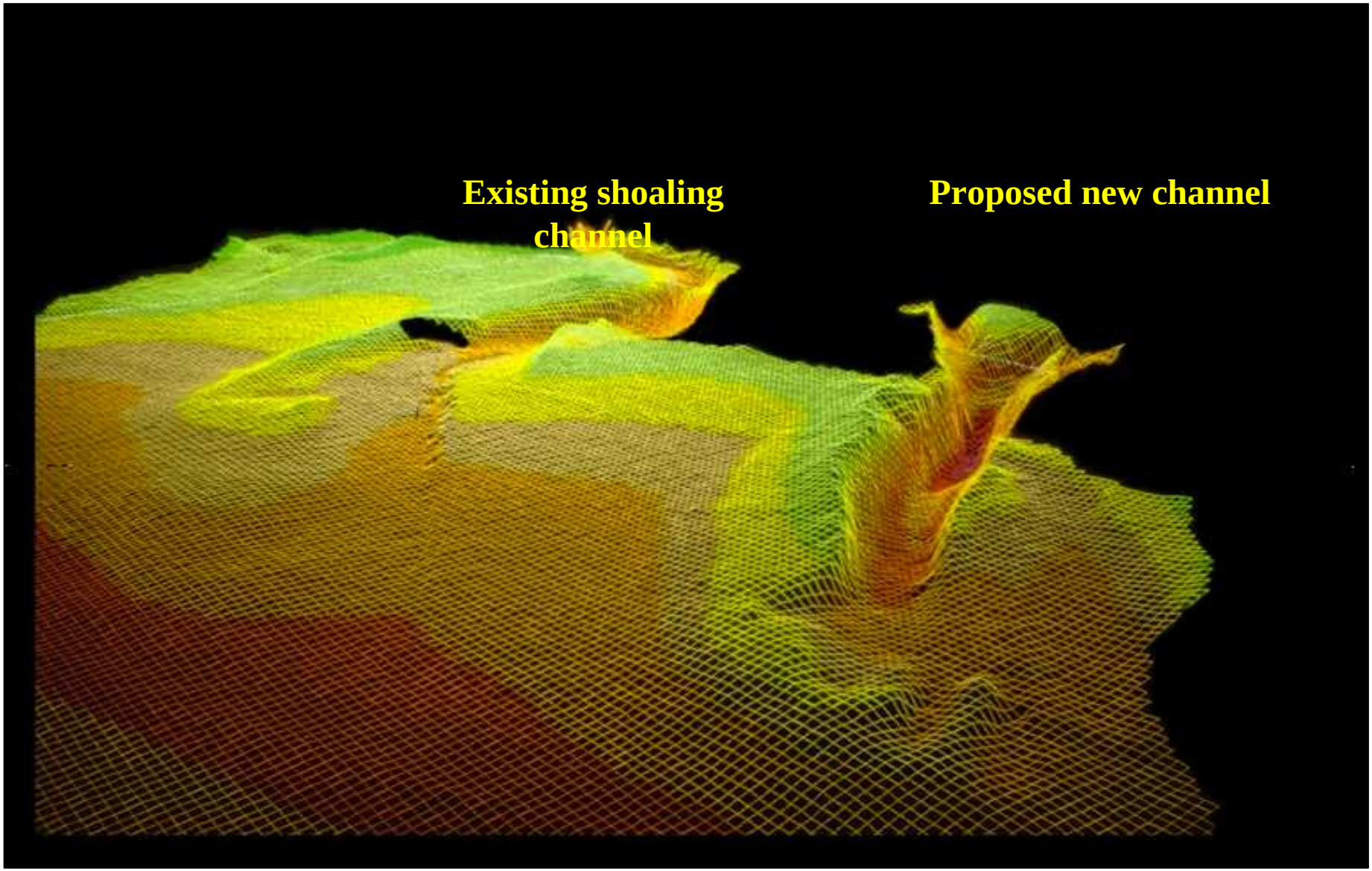
Turbidity Maximum Area

Residual sediment-transport

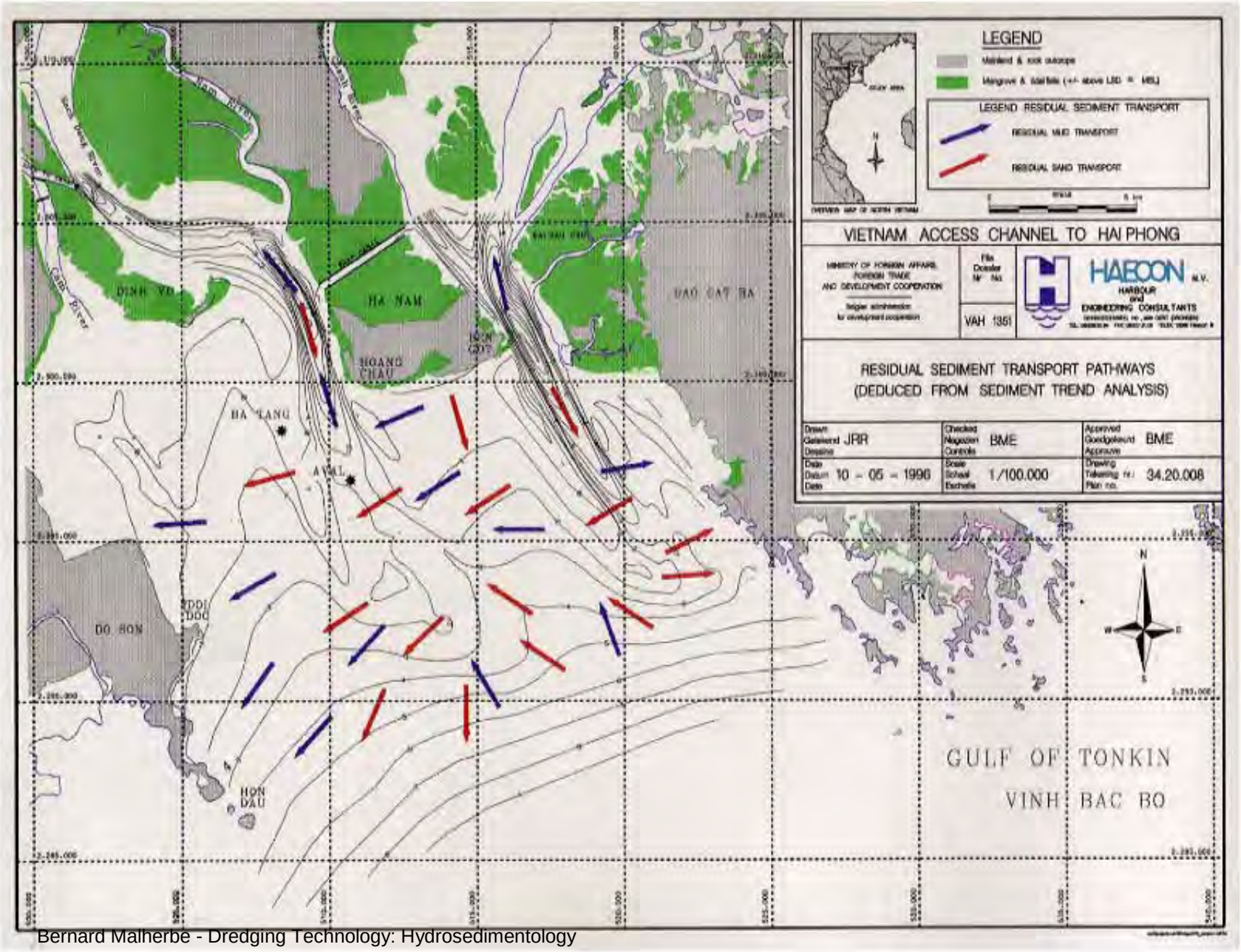
Differential Spot Satelite Images:
Numerical Differences
between Rainy and Dry Season : identification of TMA

Consolidated and Fluid Mud

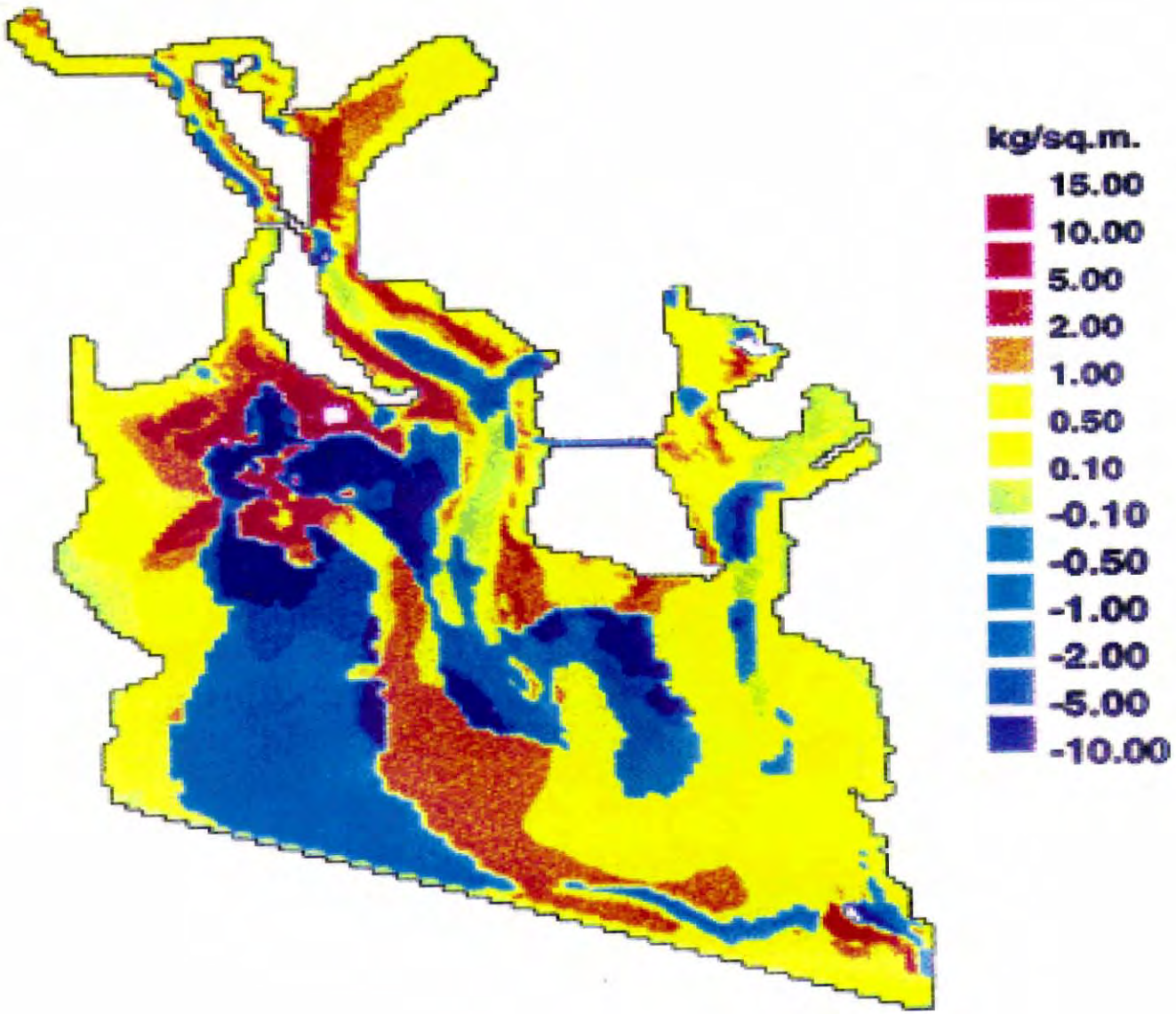
NATURAL MORPHOLOGY CAN BENEFICIALLY BE EXPLOITED FOR NAVIGATION AND MARITIME ACCESS-CHANNEL DESIGN



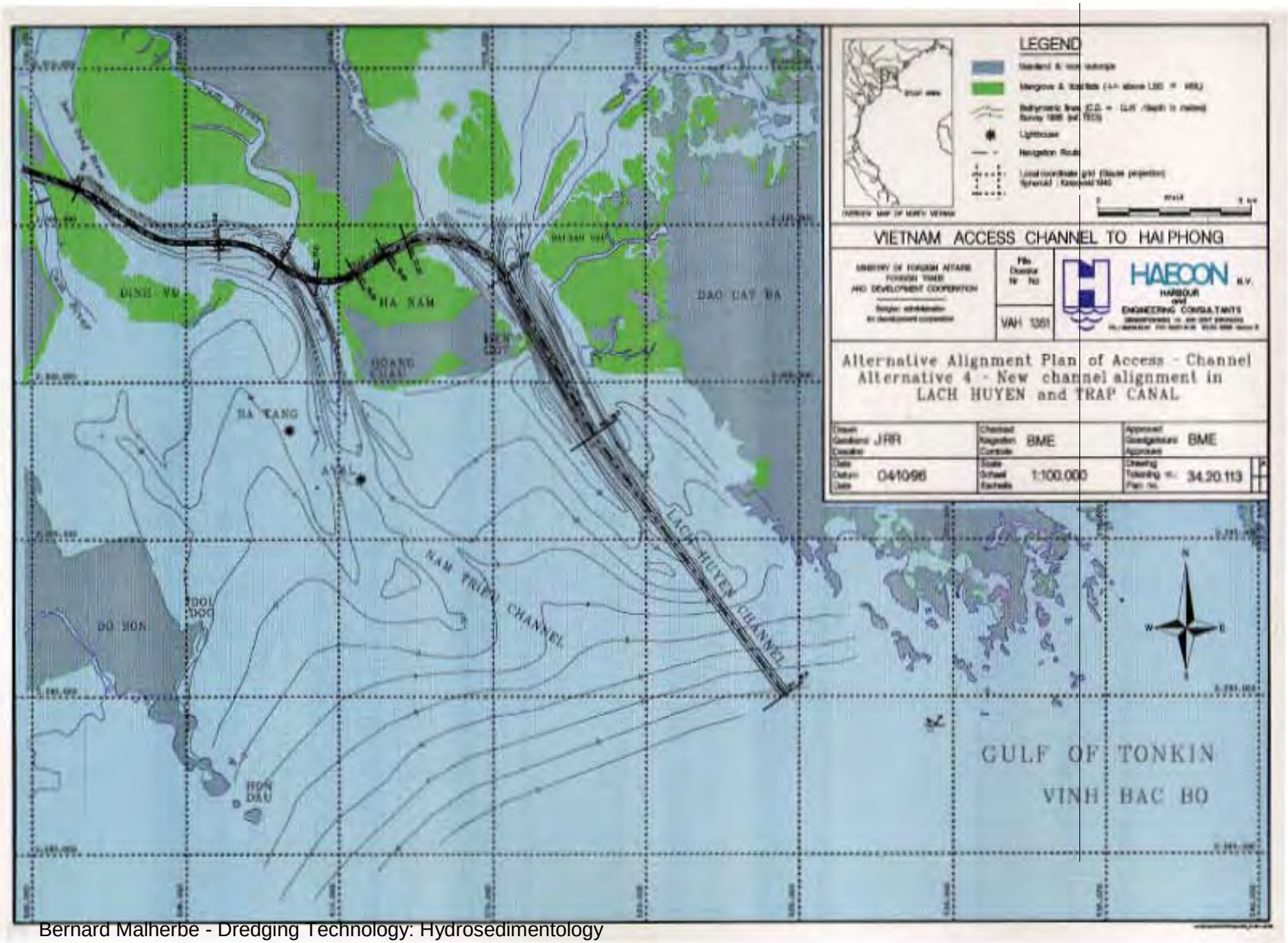
Residual Sediment Transport Paths deduced from Sedimentological Trends



Residual Sedimentation- Erosion Pattern of Seabed (1 year)



Proposed new Maritime Access-Channel trough Lach Huyen



BAHIA DE FONSECA, El Salvador

CAPITAL & MAINTENANCE DREDGING IN A TROPICAL ESTUARY

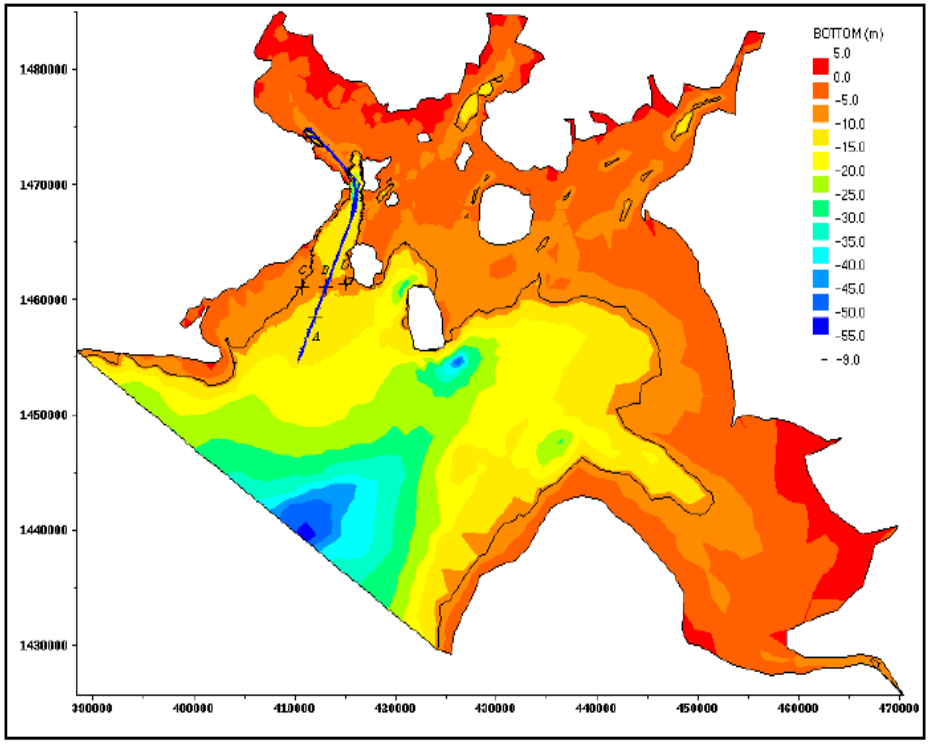


Figure 4 TELURAY model bathymetry showing location of proposed channel and nearshore wave climate prediction points

Wave refraction on dredged channels

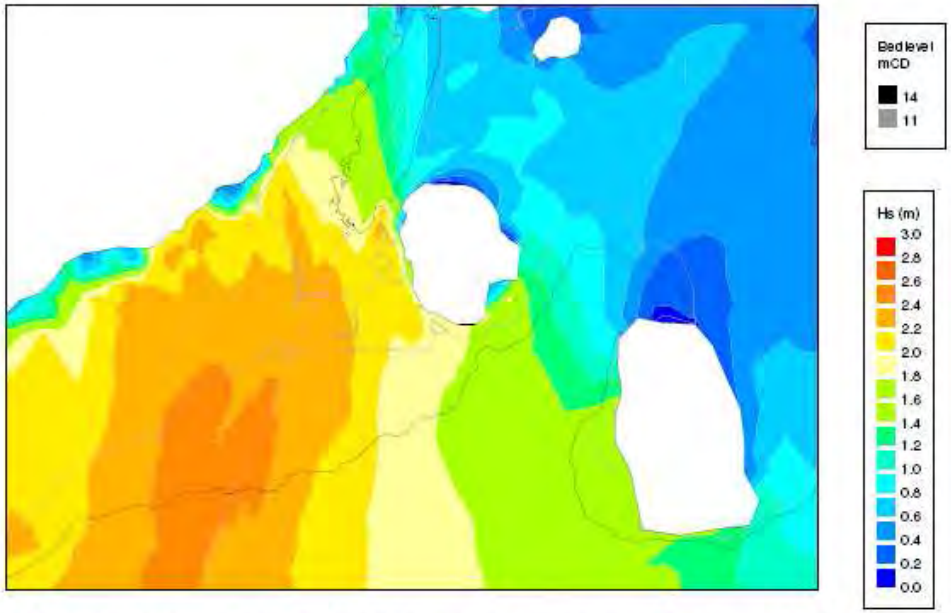


Figure A5 Distribution of wave height in area of interest resulting from a 2.45m wave from 180°N, T_m= 10 seconds, pre-dredge scenario

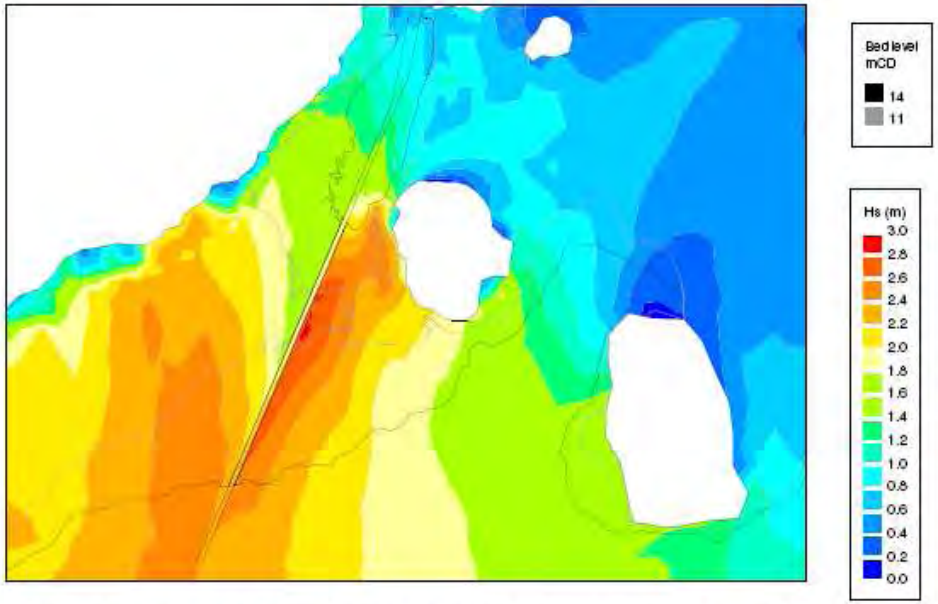


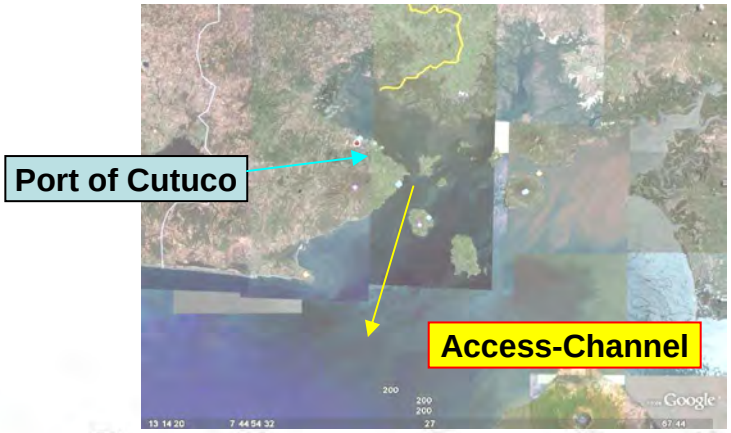
Figure A6 Distribution of wave height in area of interest resulting from a 2.45m wave from 180°N, T_m= 10 seconds, side slopes dredged to 1:5

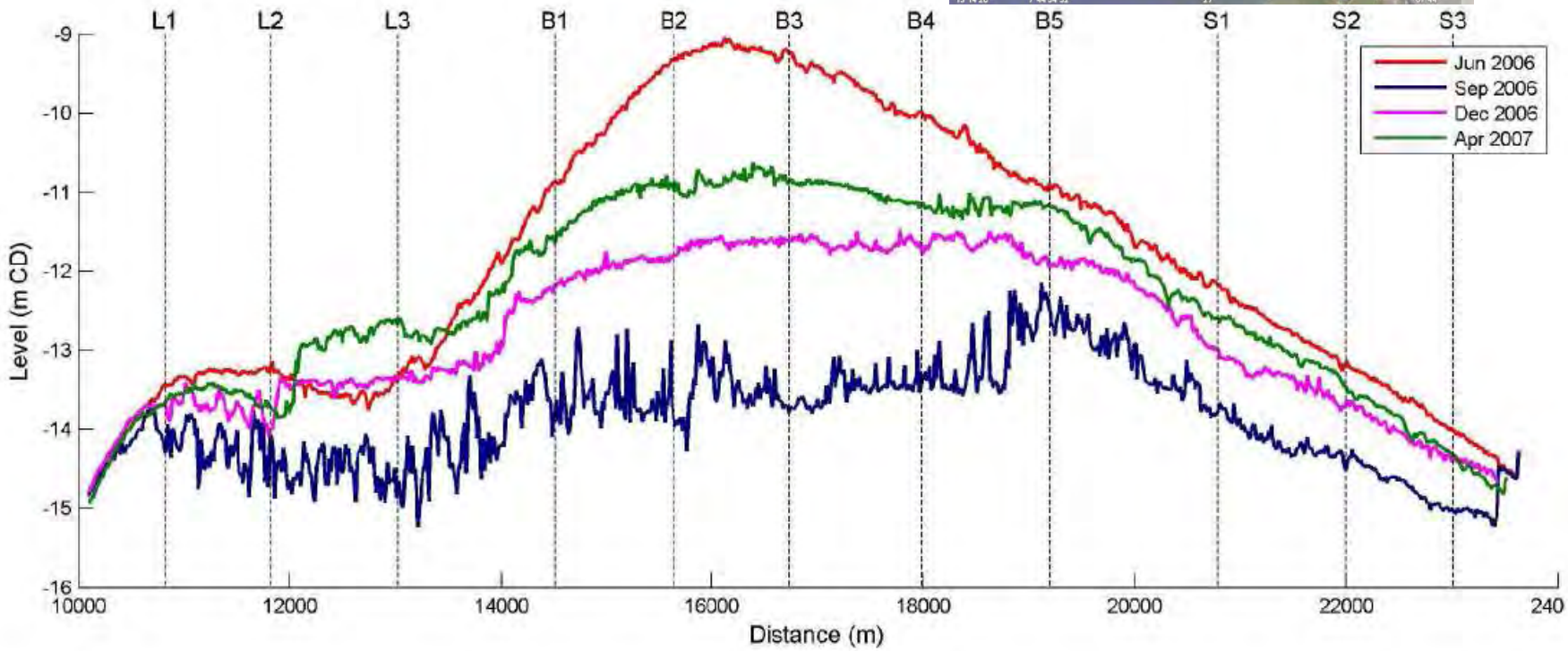
Wave Propagation Simulations with TOMAWAC model (HR Wallingford)

July 2007

Wave sector 180 °N

Bay of Fonseca, Outer Access-Channel to the Port of Cutuco (San Salvador): observed accretion in the OC centerline (longitudinal profile)





Outer Channel: Comparative cross-profiles

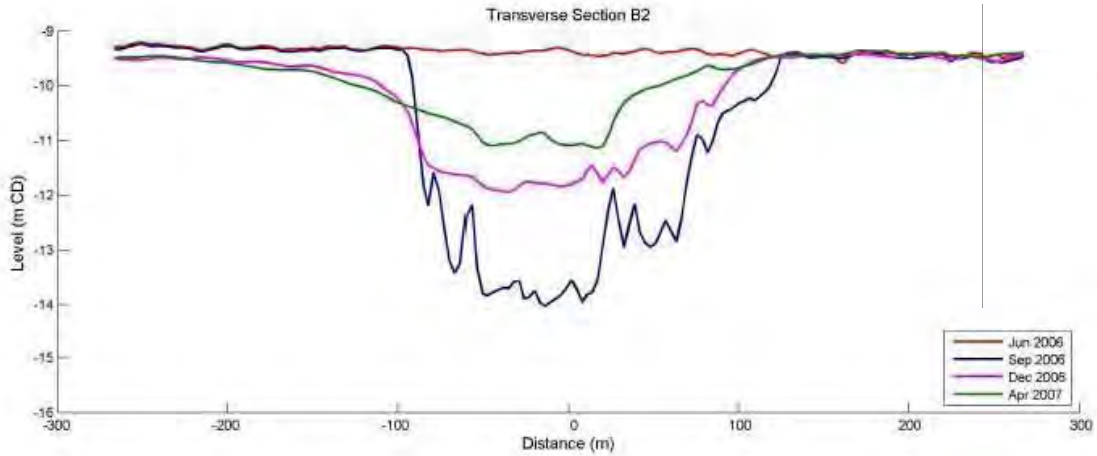


Figure 19 Transverse cross-section bathymetry for B2

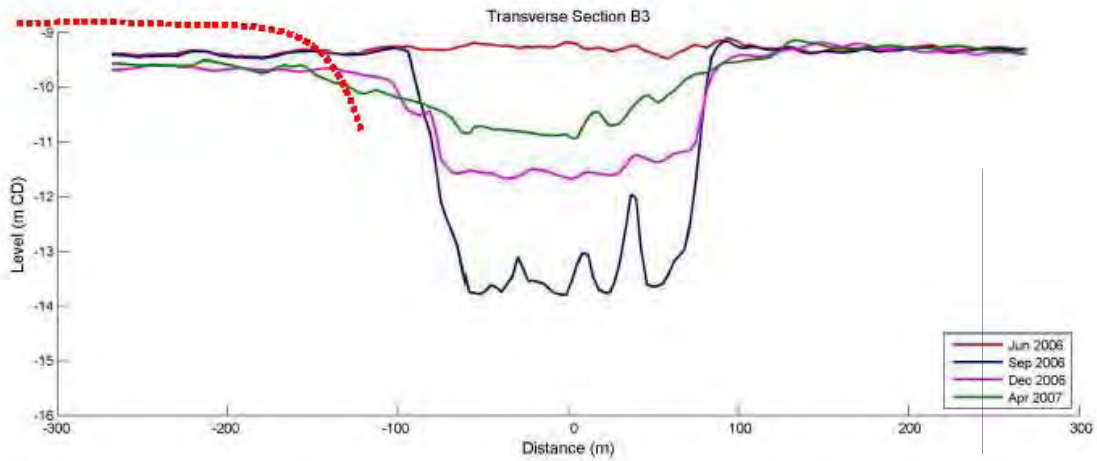
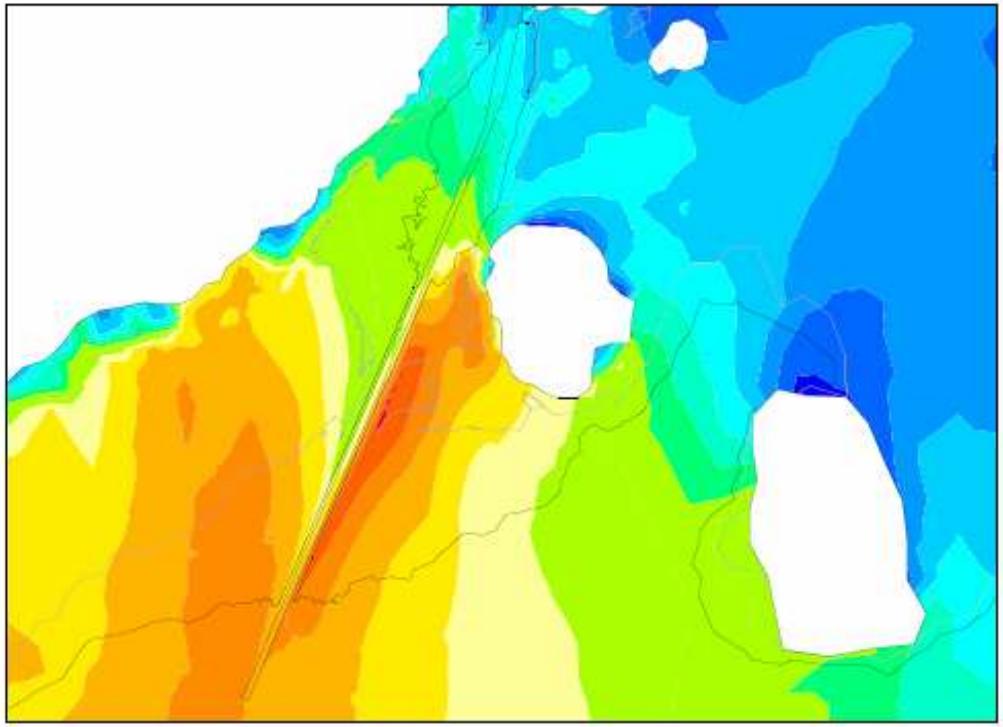
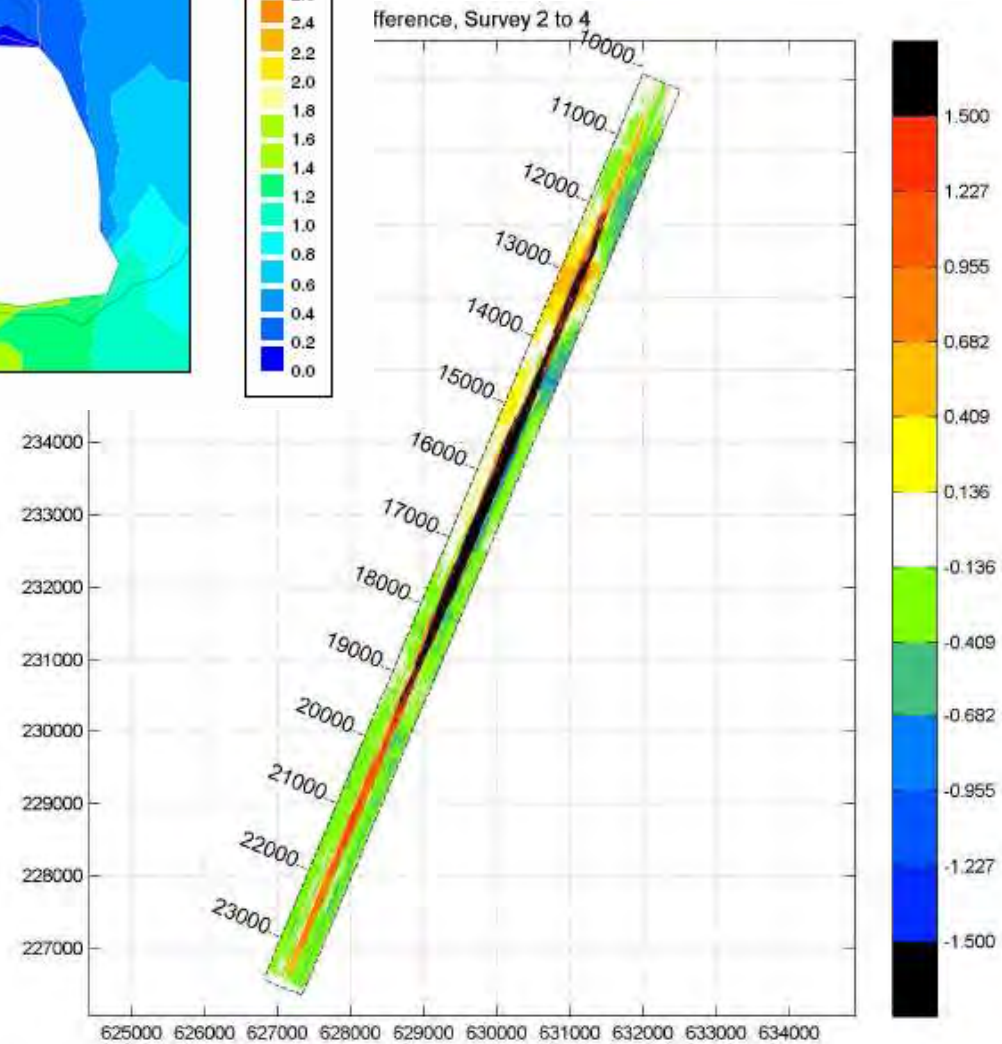


Figure 20 Transverse cross-section bathymetry for B3



Predicted sedimentation/erosion pattern (m/year)



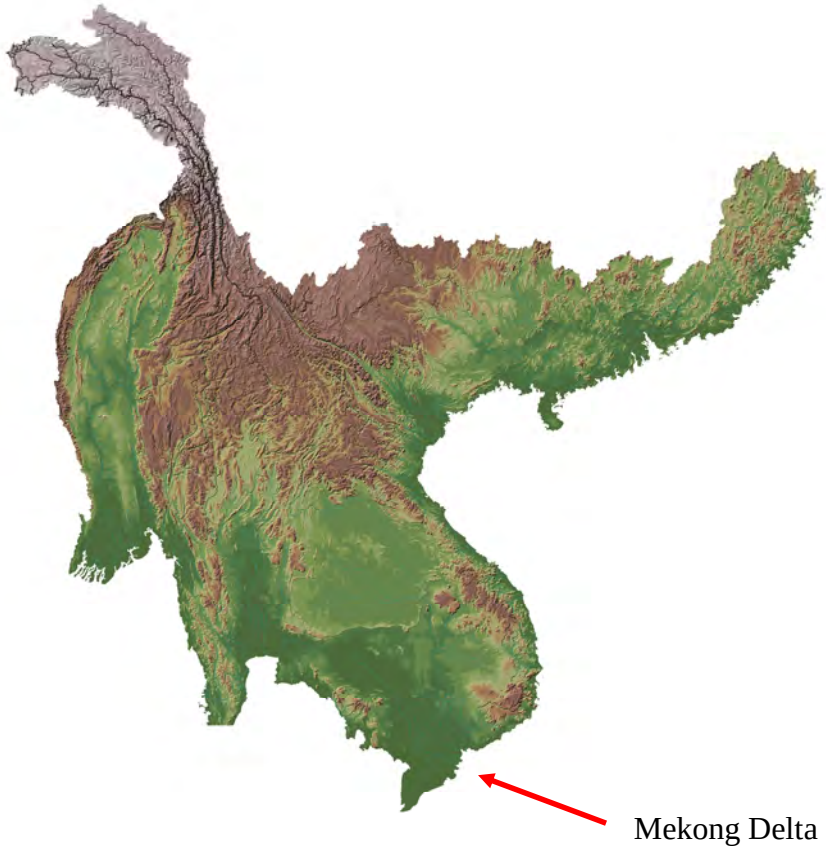
Bay of Fonseca and access-channel to Cutuco Port (El Salvador):

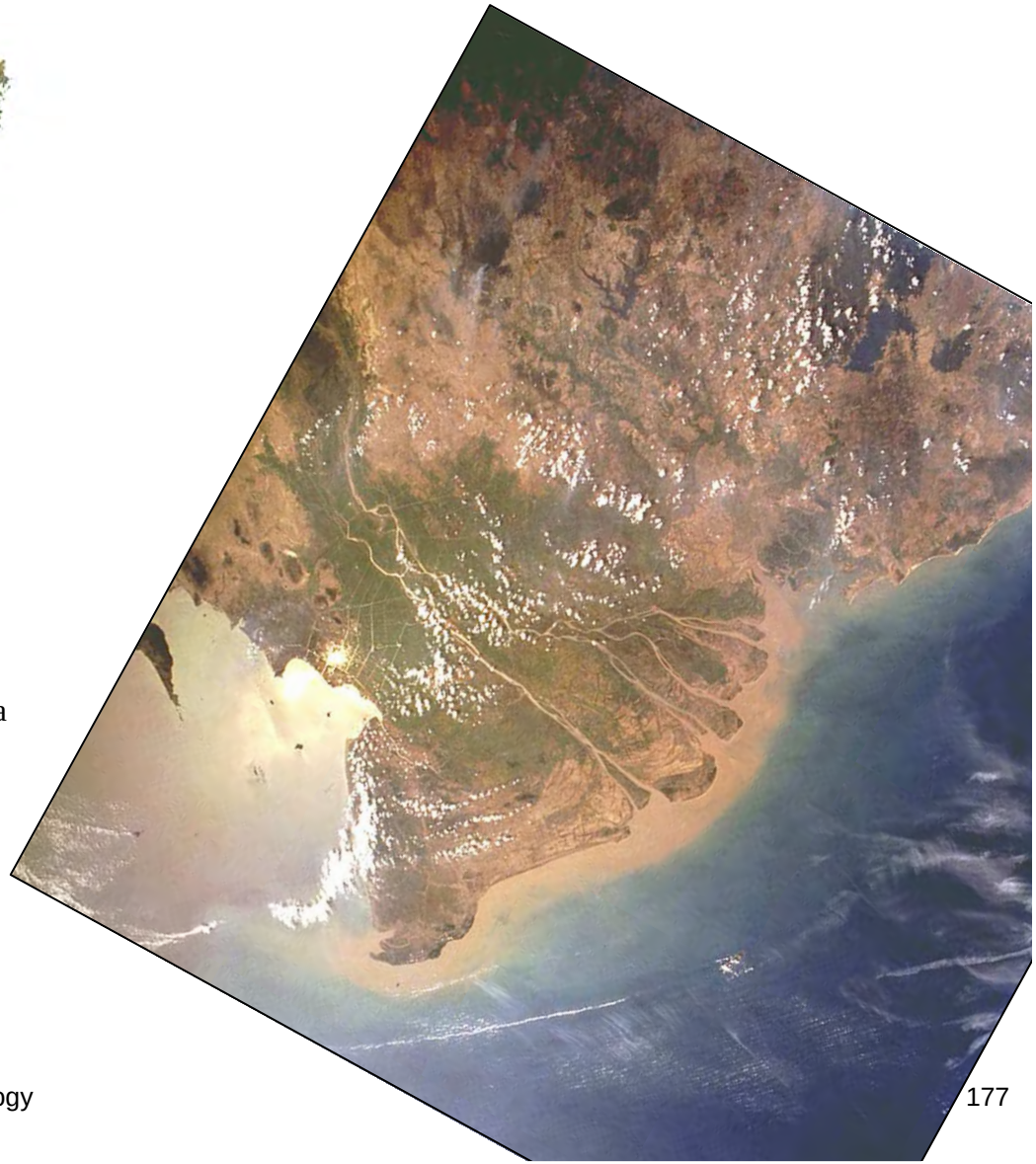
Differential wave propagation and eroding action explaining differential morphological evolution

THE PHYSICAL MANIFESTATION OF RESIDUAL SEDIMENT-TRANSPORT IS REFLECTED BY THE BED-MORPHOLOGY

Sea (or River) bed morphology is the ultimate finger-print of residual transport of sediments in an open-flow system.

Mekong River Basin

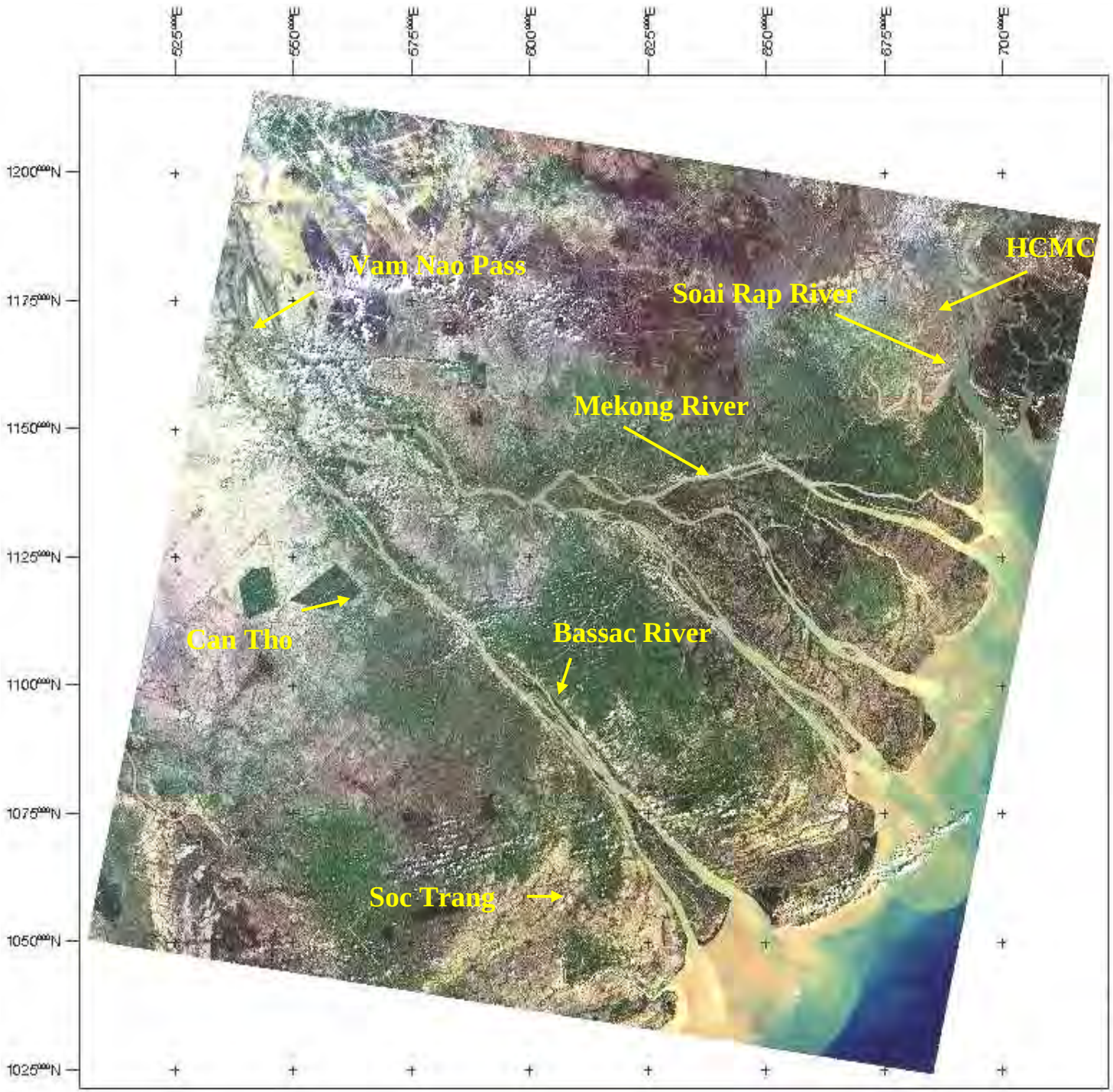




The Mekong:

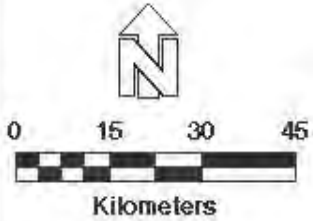
Q = 4.000 – 60.000 m3/sec

Sed= 150 – 250 Mtds/year



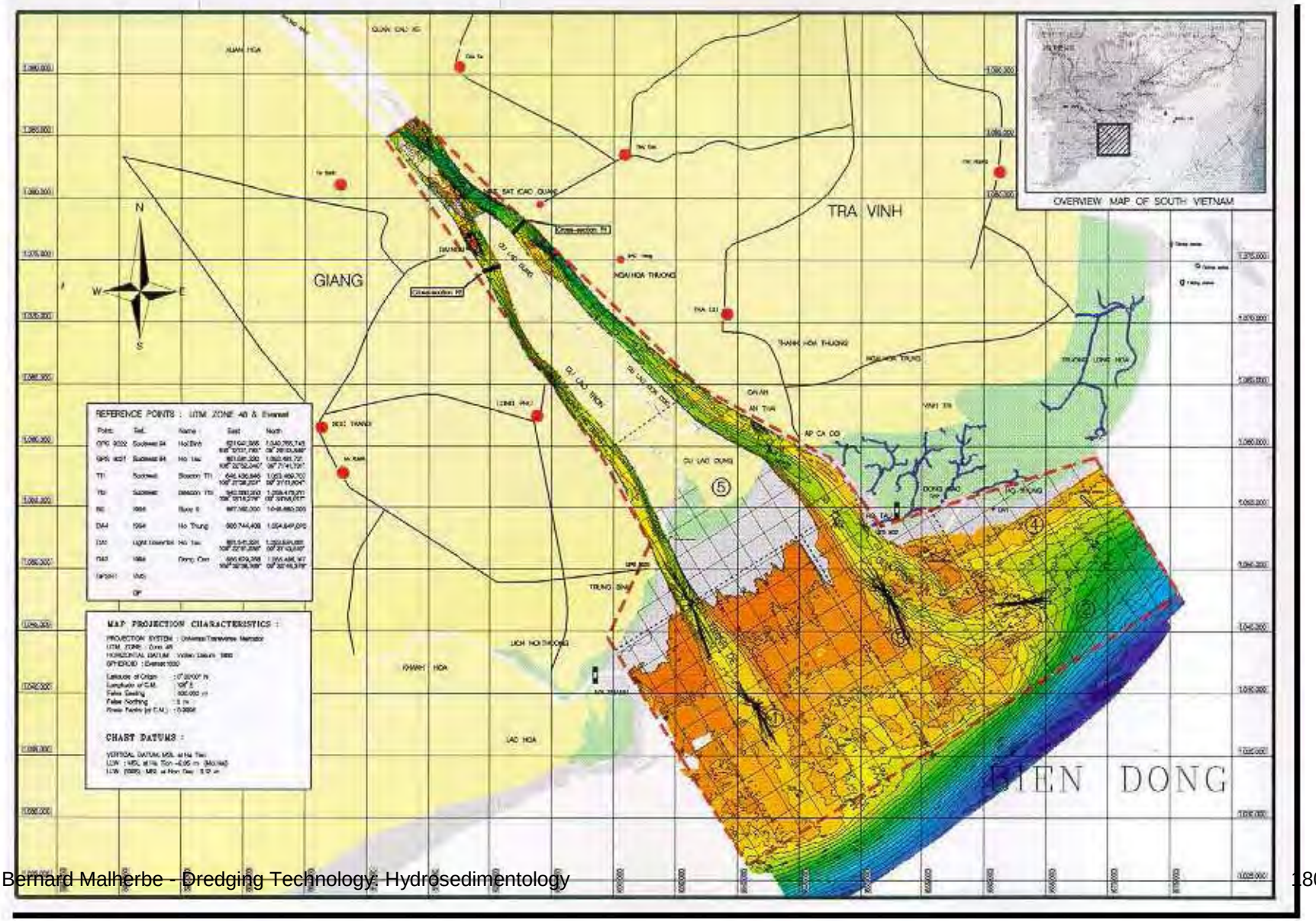
Landsat TM image
Jan. 6 1997
Col/Row: 125/053
Colour composite 321

The Mekong Delta: the 9 headed dragon river

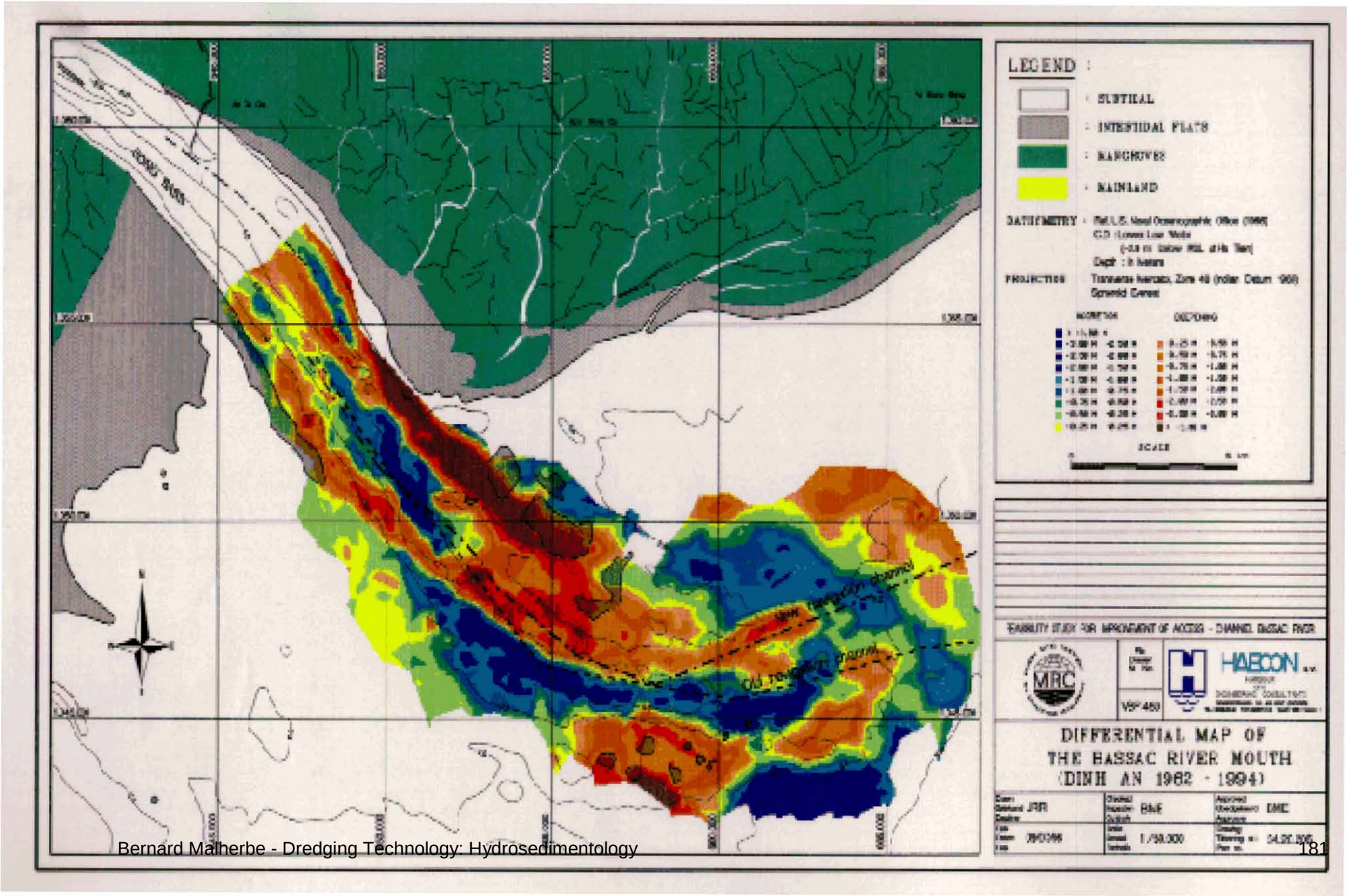


High Resolution Satellite Image of Cua Dinh An, Cua Tran De, Bassac River

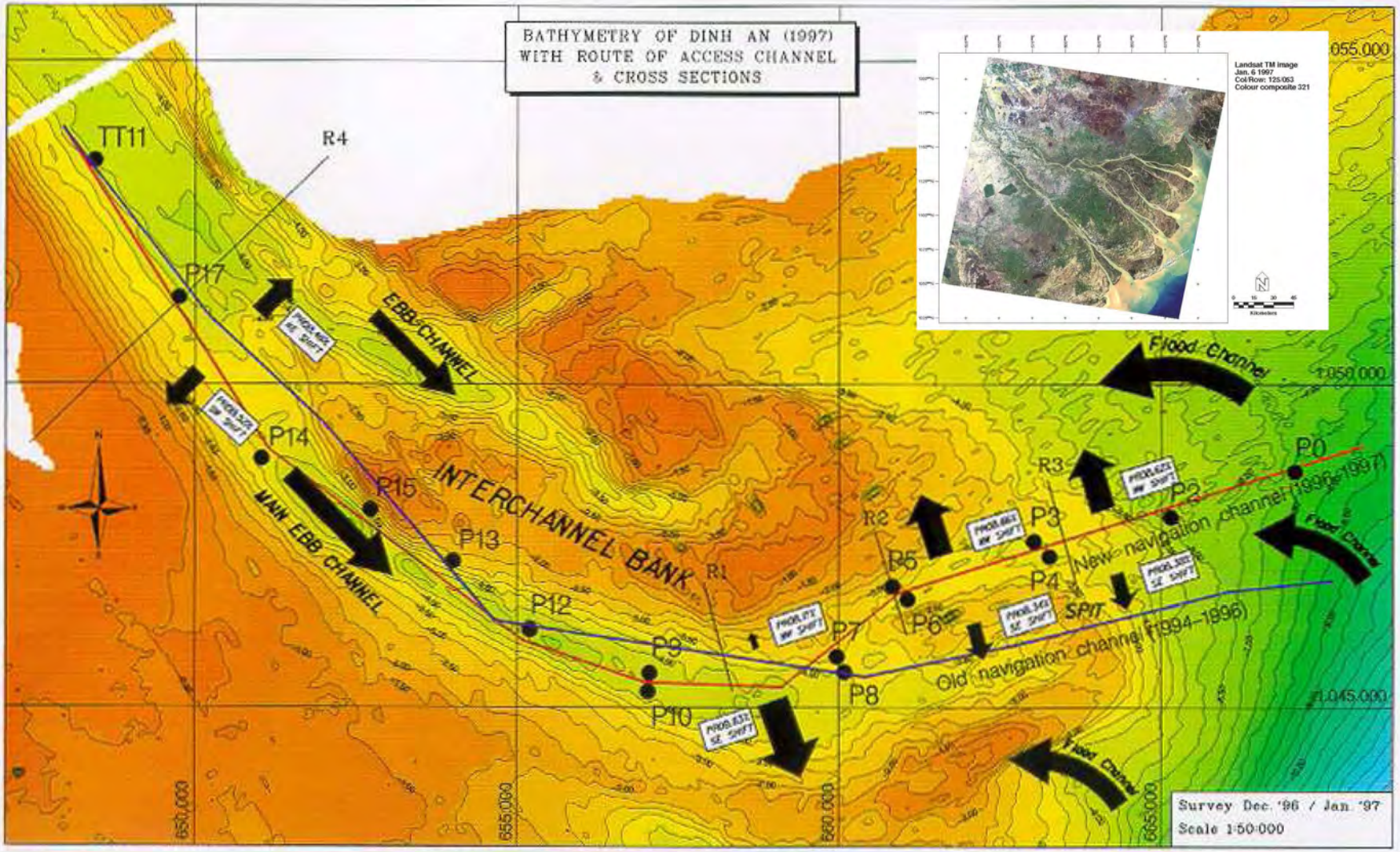
Detailed Bathymetric survey and Fixed Station Sediment transport survey (bedload and suspension-load)



Morphological Analysis of Seabed in Dinh An Estuary

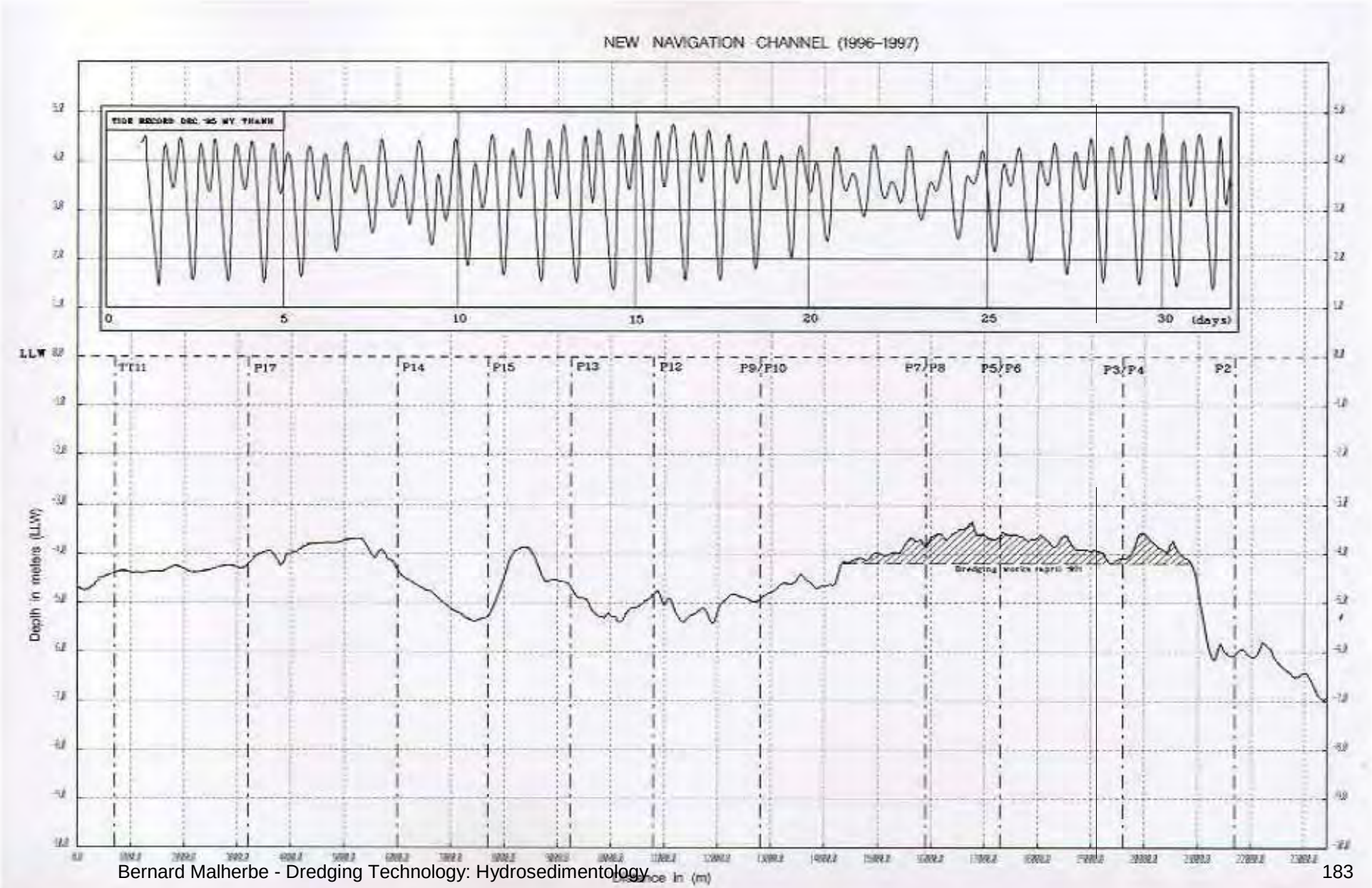


Morphological Analysis and Stability Assessment of the Maritime Access-Channel and the Dumping Sites of Dredged Material

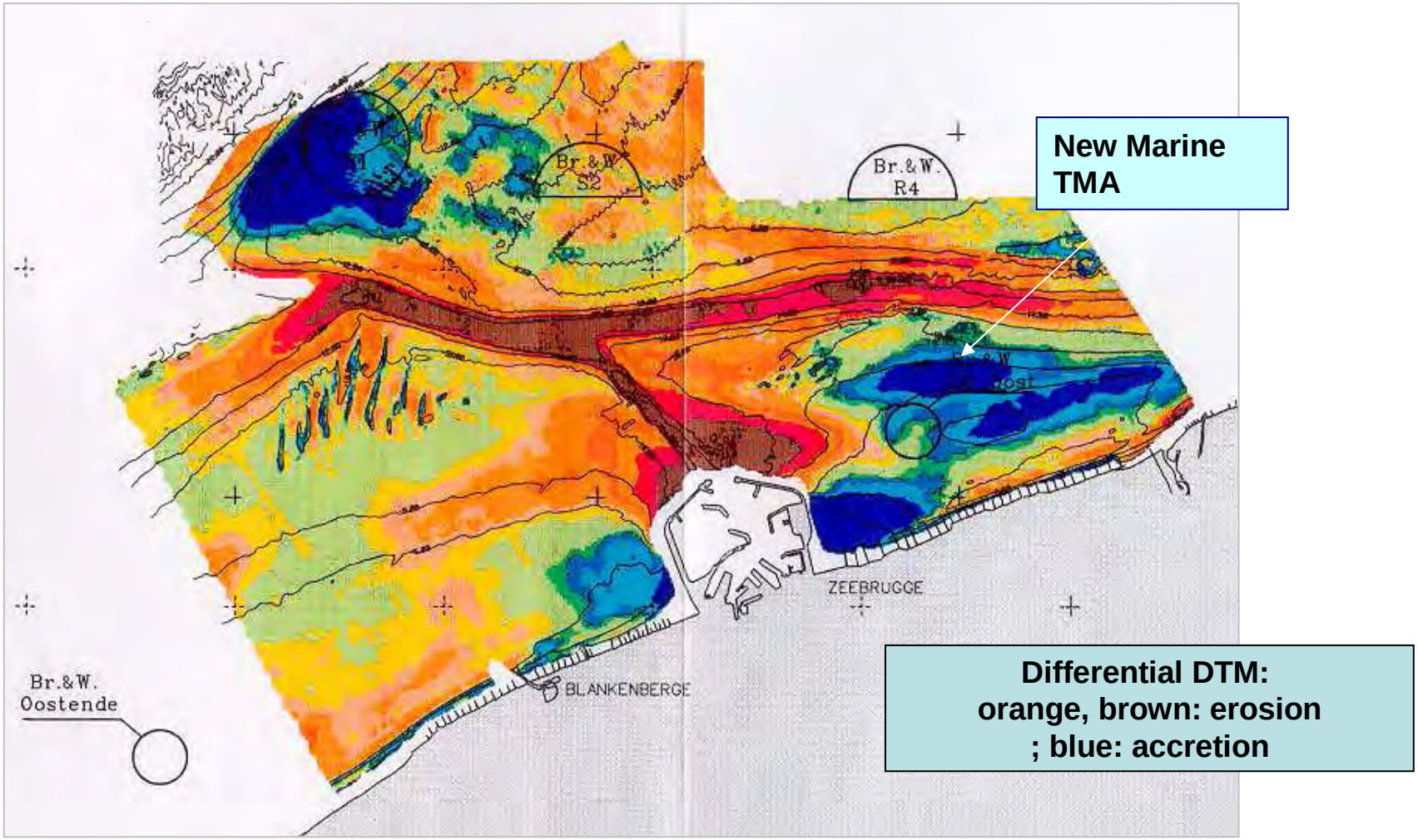


Navigational channel to Mekong Delta, South Viet Nam

Bassac River Entrance: Nautical accessibility study and proposed dynamic dredging (ref: HAECON, 1998)

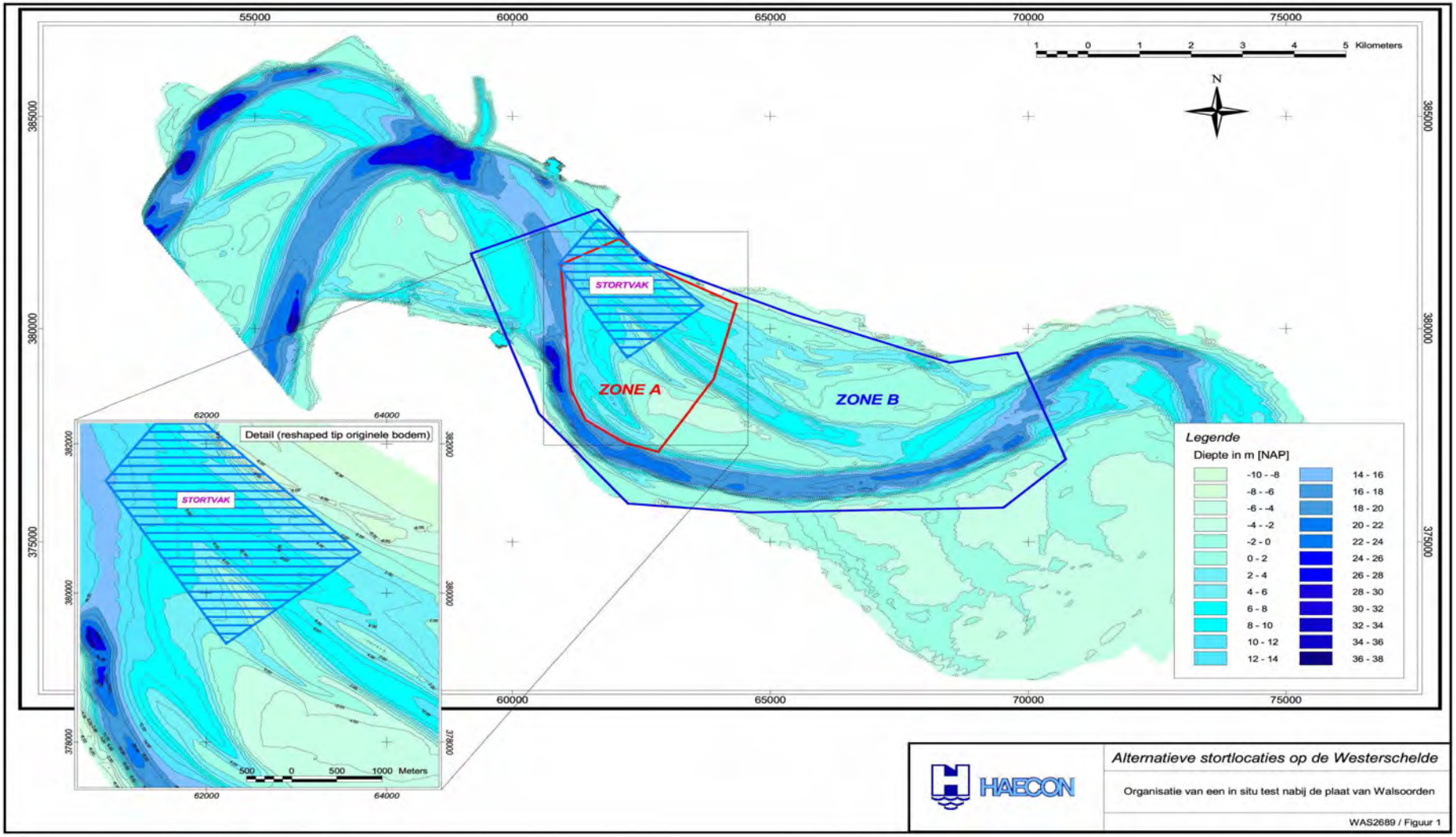


Morphological Analysis and Stability Assessment of the Maritime Access-Channel and the Dumping Sites of Dredged Material

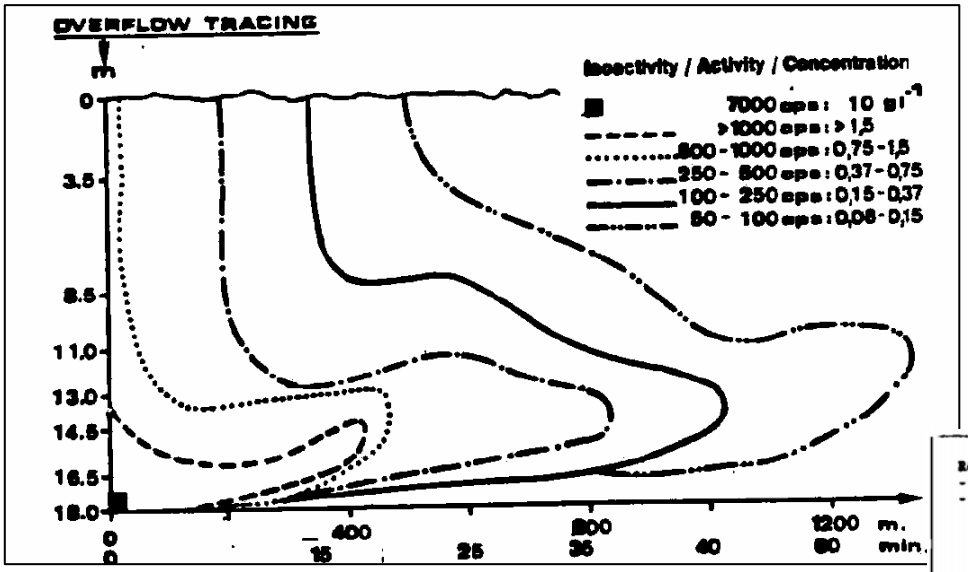


Digital Terrain Model and Differential Mapping (1976-1994) of the Seabed including port development, dredging and dumping

Use of morpho-dynamics to plan dredging works and manage disposal of dredged materials

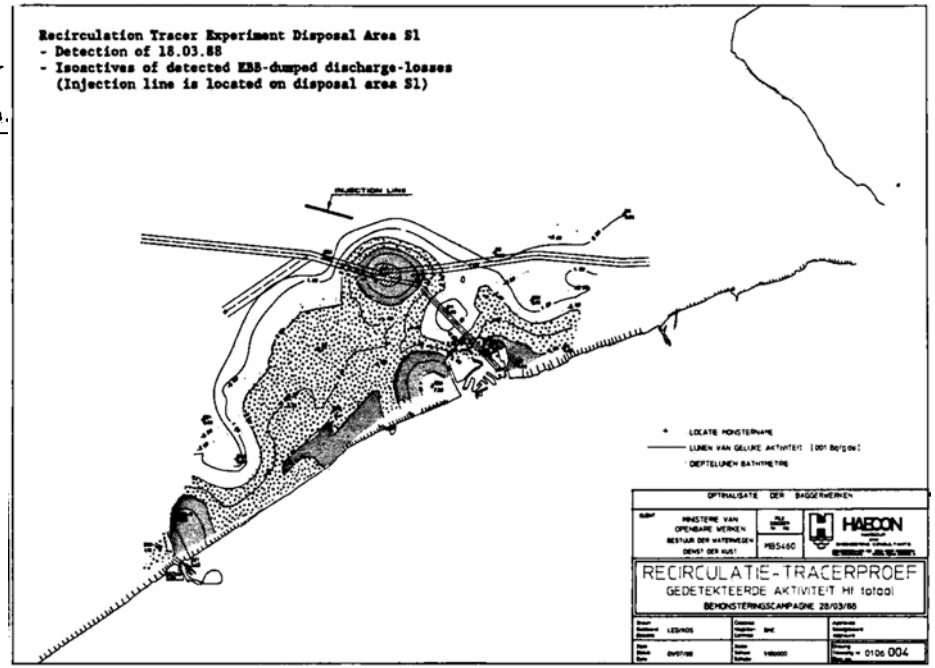


Analysis of sediment-transport in relation to dredging & dumping: radio-active tracer techniques



Tracing of overflow-mixture: short-living tracers

Tracing of dumped material:long-living recirculation tracers



Sediment dynamics in tidal shallow seas

(B. Malherbe PhD thesis)

Vmean: average water-velocity

d: waterdepth

Ts mean: average sediment-concentration

u* : shear-stress velocity

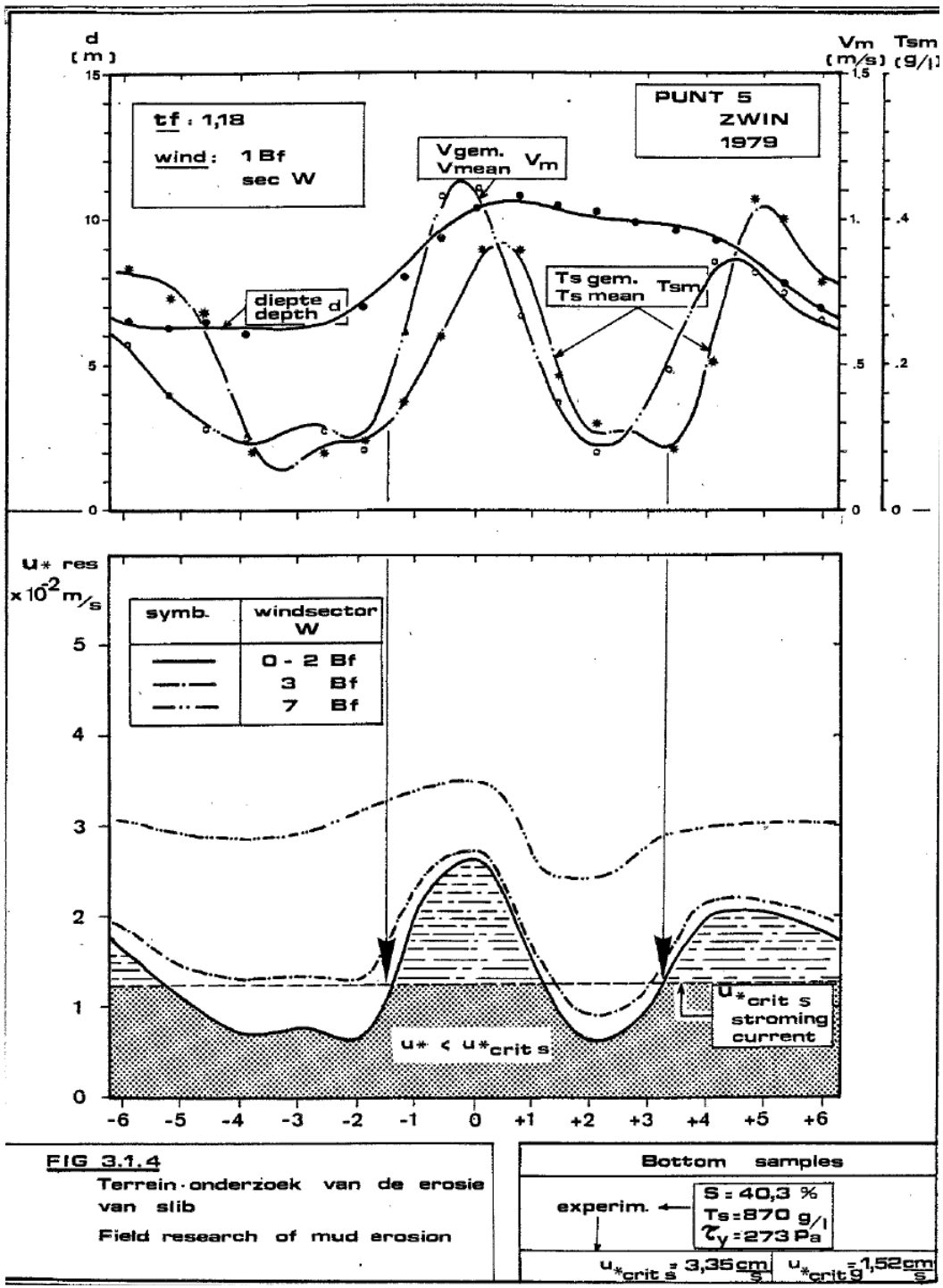


FIG 3.1.4
Terrein-onderzoek van de erosie van slib
Field research of mud erosion

Velocity and suspension-solids concentrations in tidal shallow seas

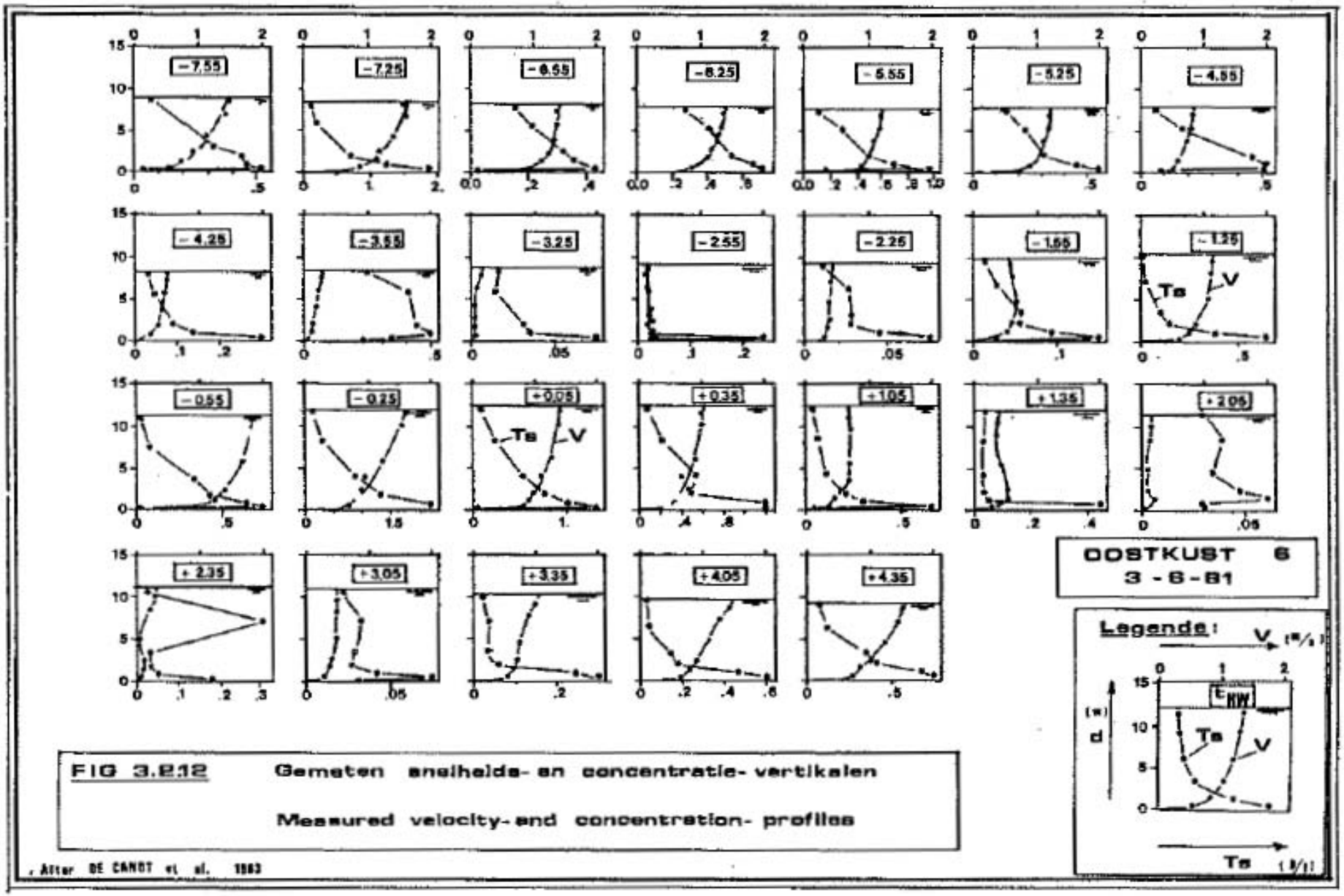
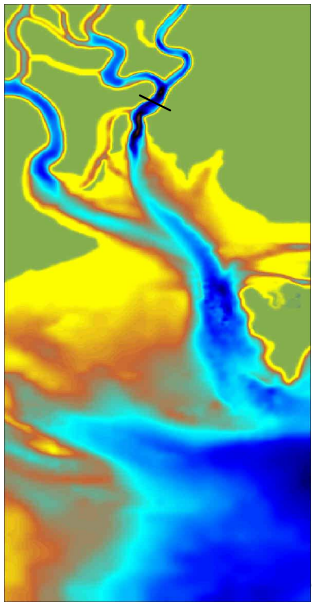
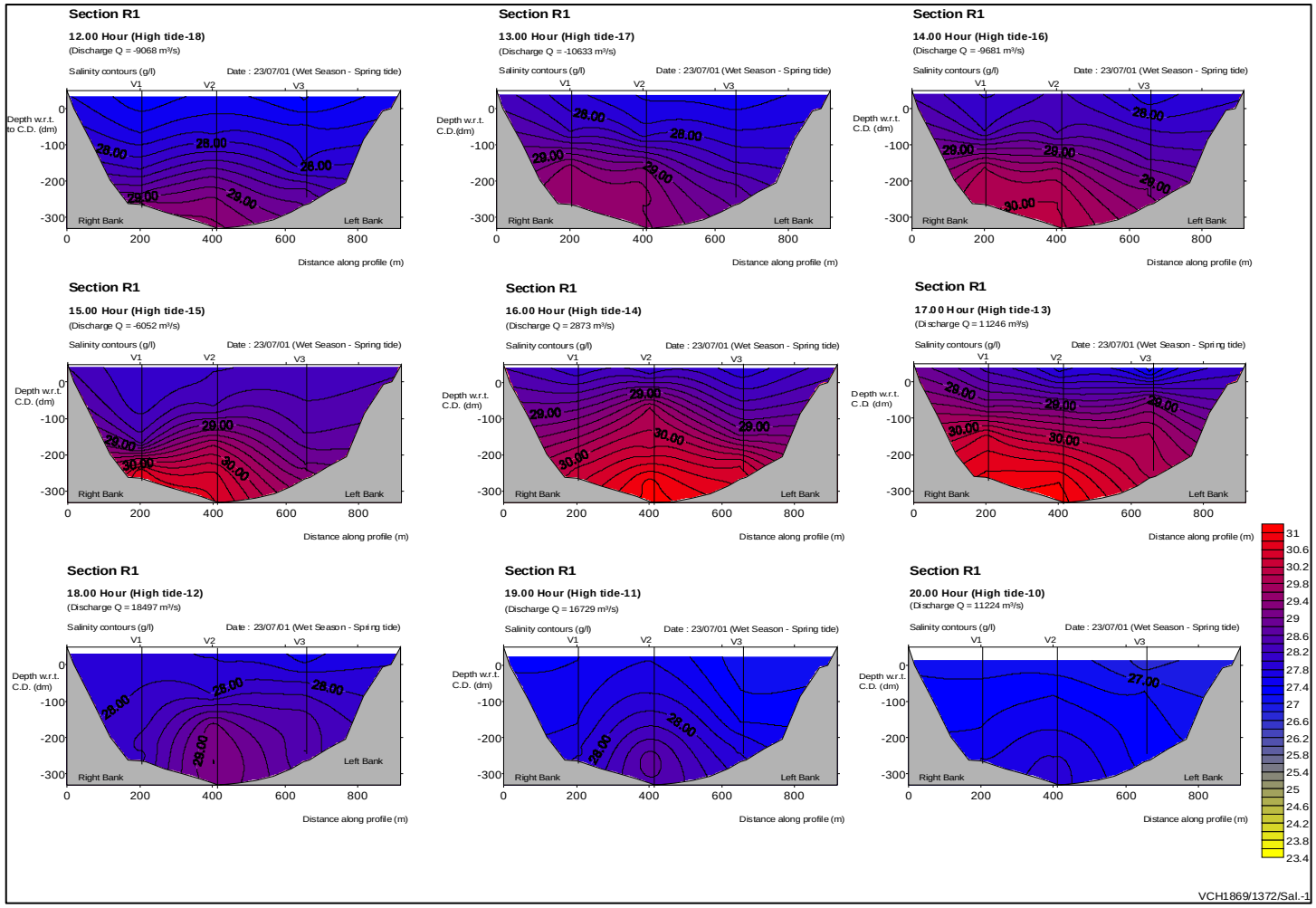


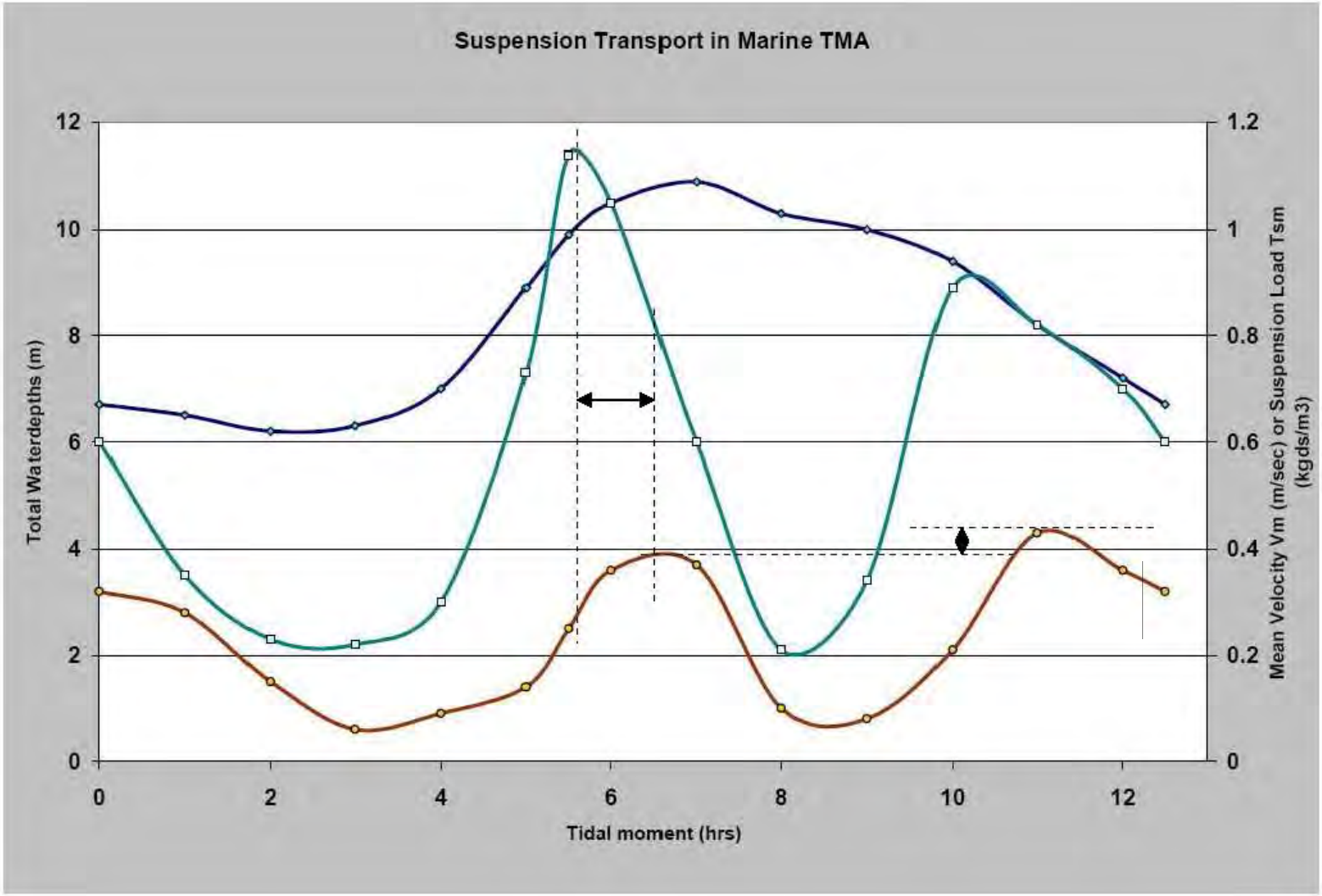
Illustration of salt-wedge density flow in tidal creek system , Cai Mep S Viet Nam : Wet season - spring tide - transsection R1

salinity contours (hour/discharge/section/depth)

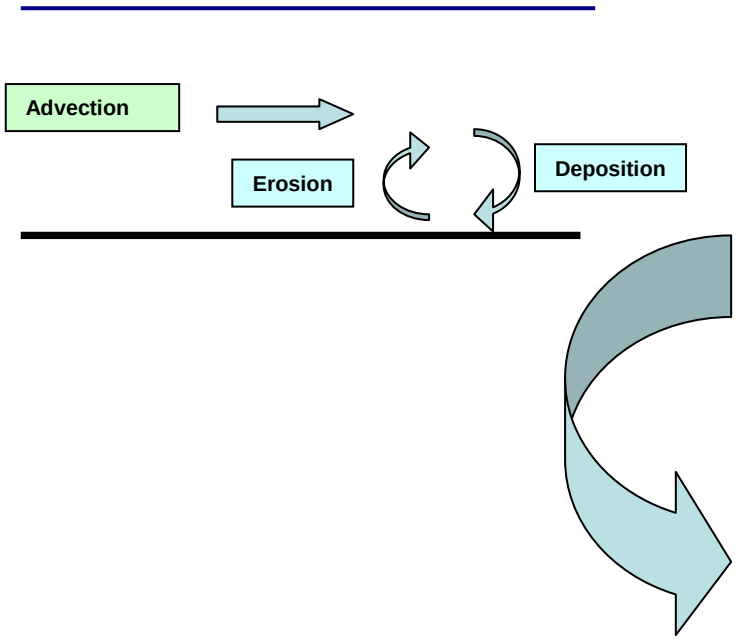


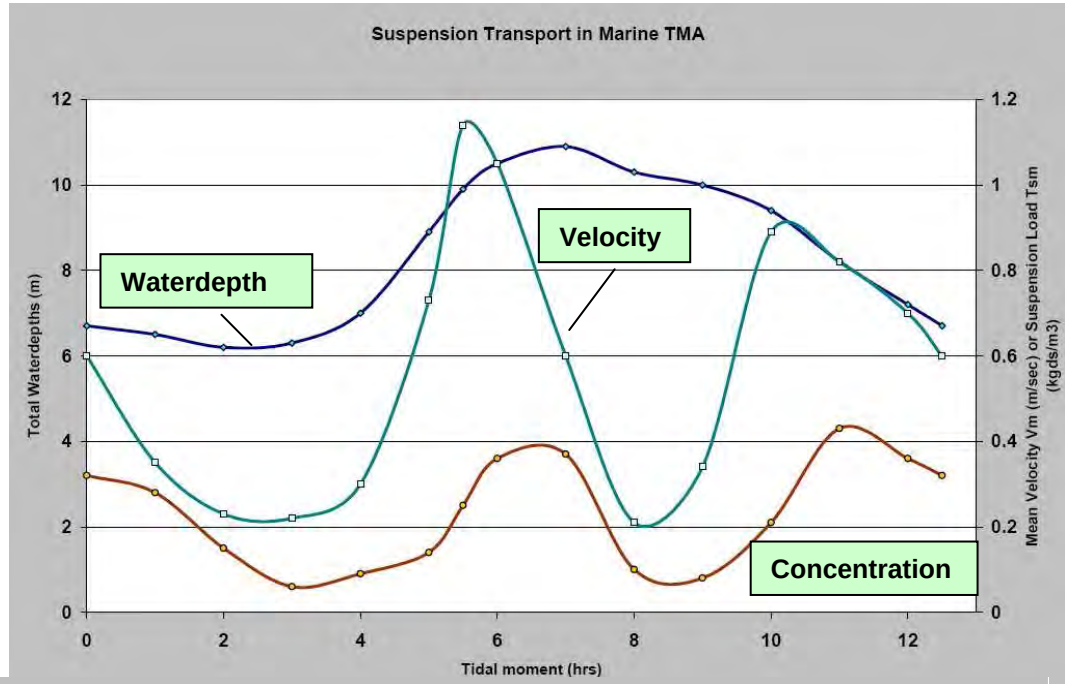


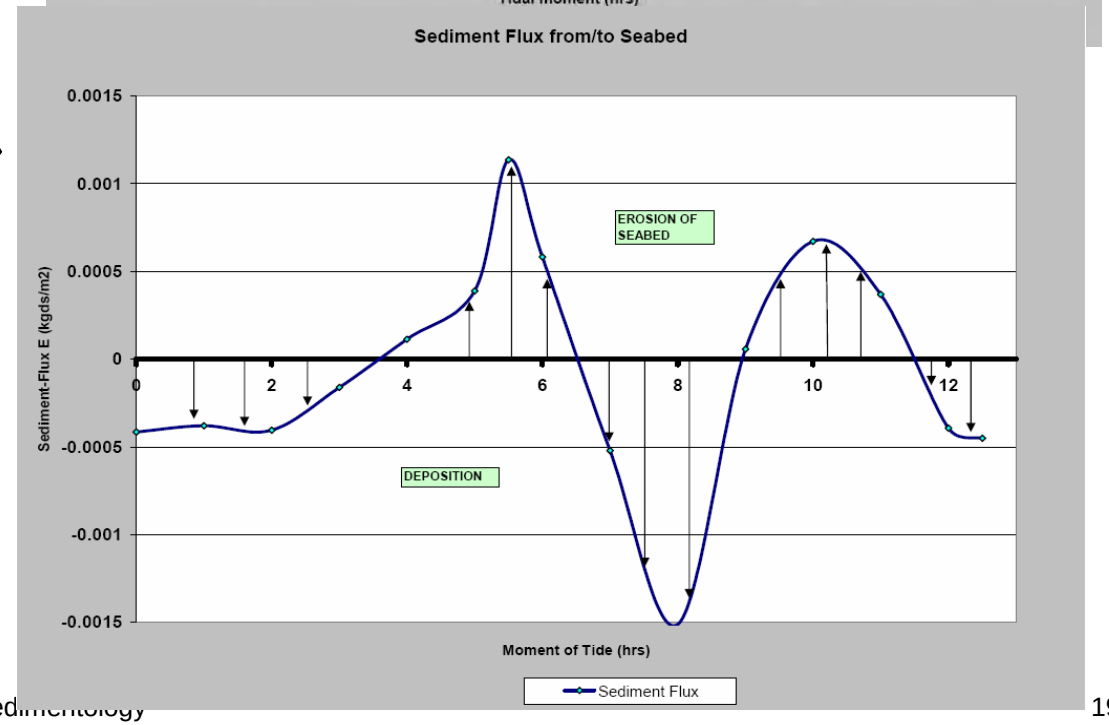
Suspension Transport of Mud and Fine Sand in Tidal Seas



Continuity of Sediment Flux







HIDROVIA S.A.

A Unique Project: the concession for capital dredging, maintenance dredging, buoyage and toll of more than 700 km of waterways

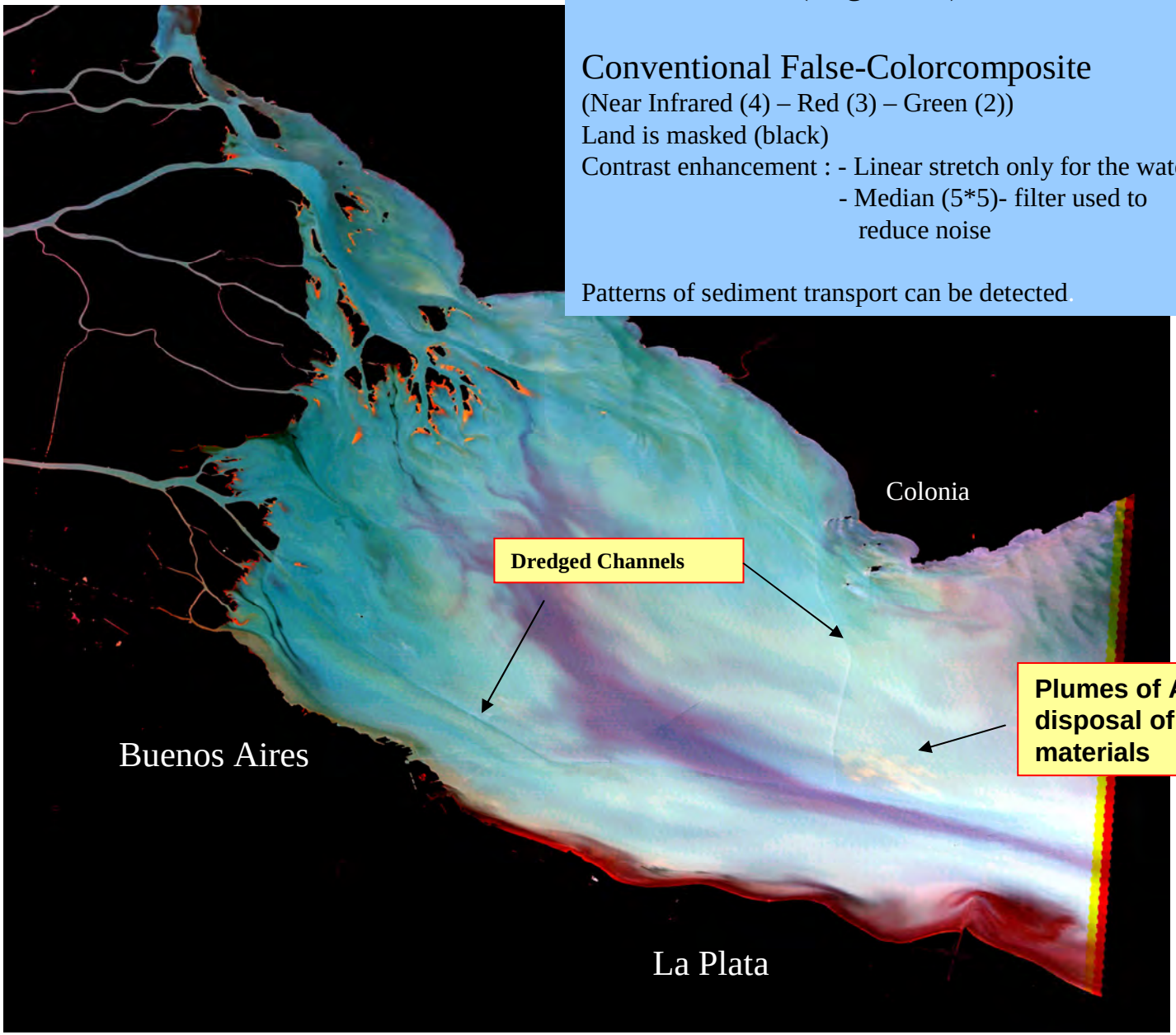
Welcome to Argentina and the mother of all estuaries: the Rio de la Plata

Satellite Imagery for Observation

LANDSAT 7 ETM+ DATA – 19/01/2000
Rio de la Plata (Argentina)

Conventional False-Colorcomposite
(Near Infrared (4) – Red (3) – Green (2))
Land is masked (black)
Contrast enhancement : - Linear stretch only for the water
- Median (5*5)- filter used to reduce noise

Patterns of sediment transport can be detected.



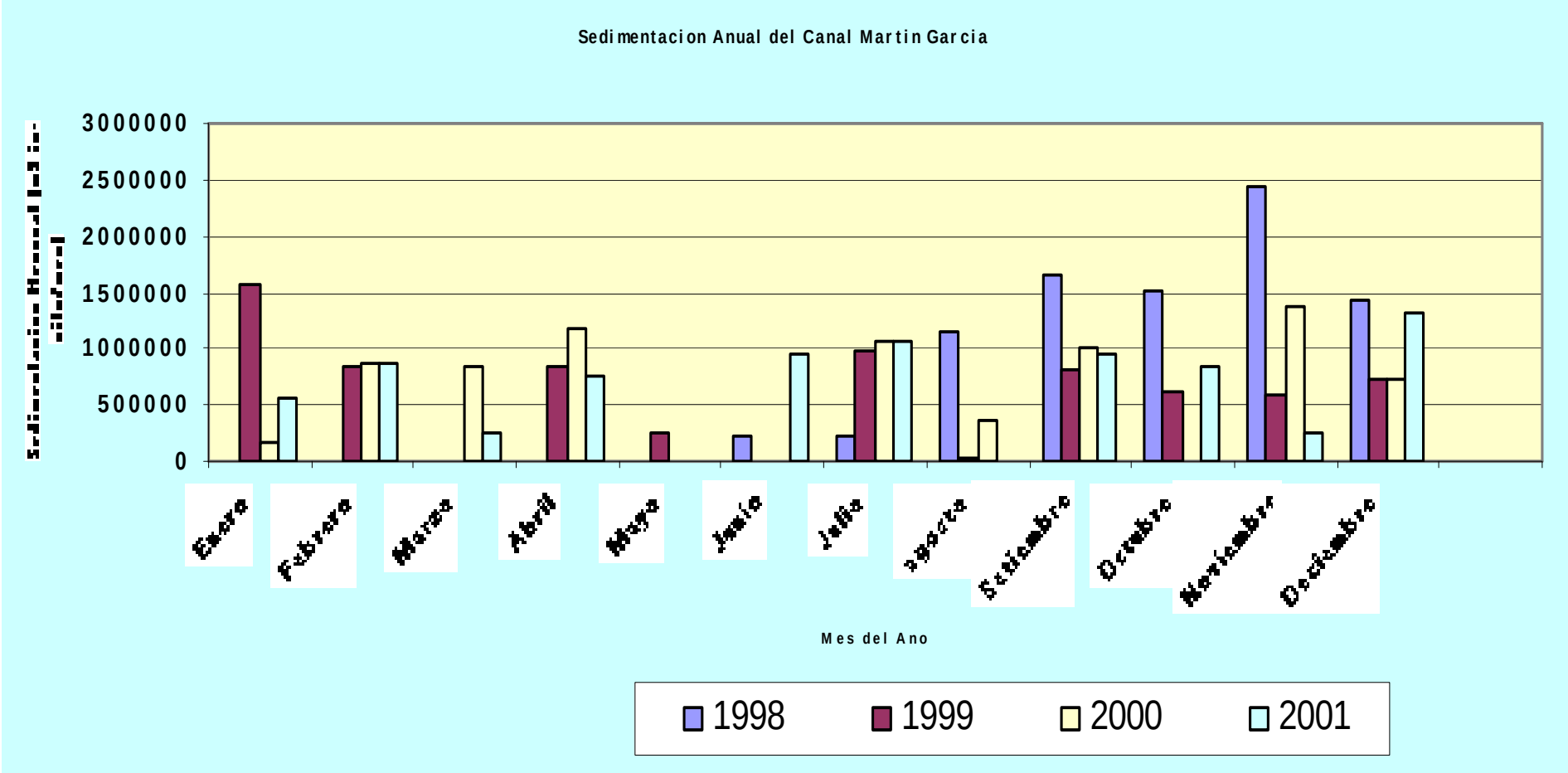
Dredging the Rio Paranà

TSHD Amerigo Vespucci maintenance dredging

CSD Marco Polo widening the Paranà River

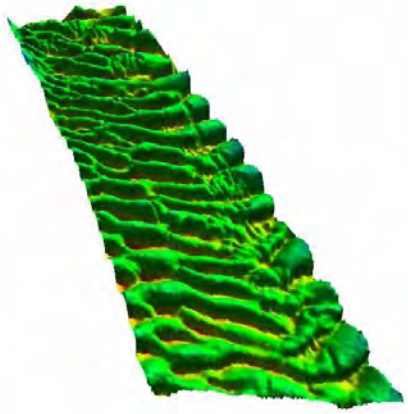
SEASONALITY IN SEDIMENTATION IS NOT ALWAYS SIMPLE: EFFECTS OF LONG TERM CLIMATIC CYCLI MAY AFFECT THIS SCHEME

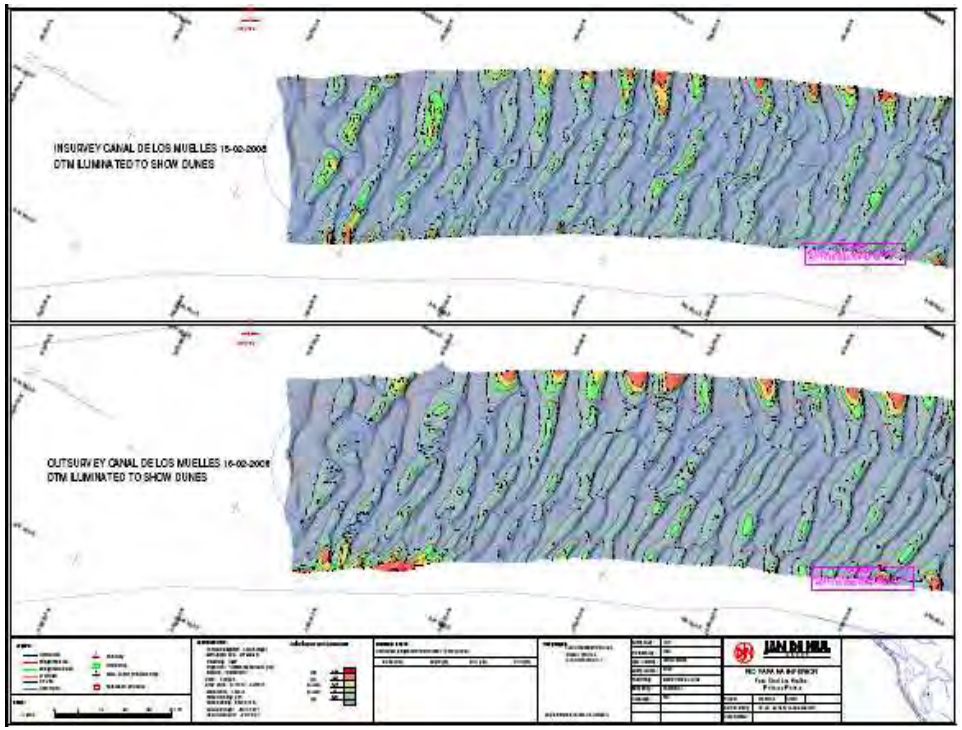
HERE EFFECT OF EL NINO ON SEDIMENTATION IN THE MARITIME ACCESS-CHANNELS IN THE RIO DE LA PLATA

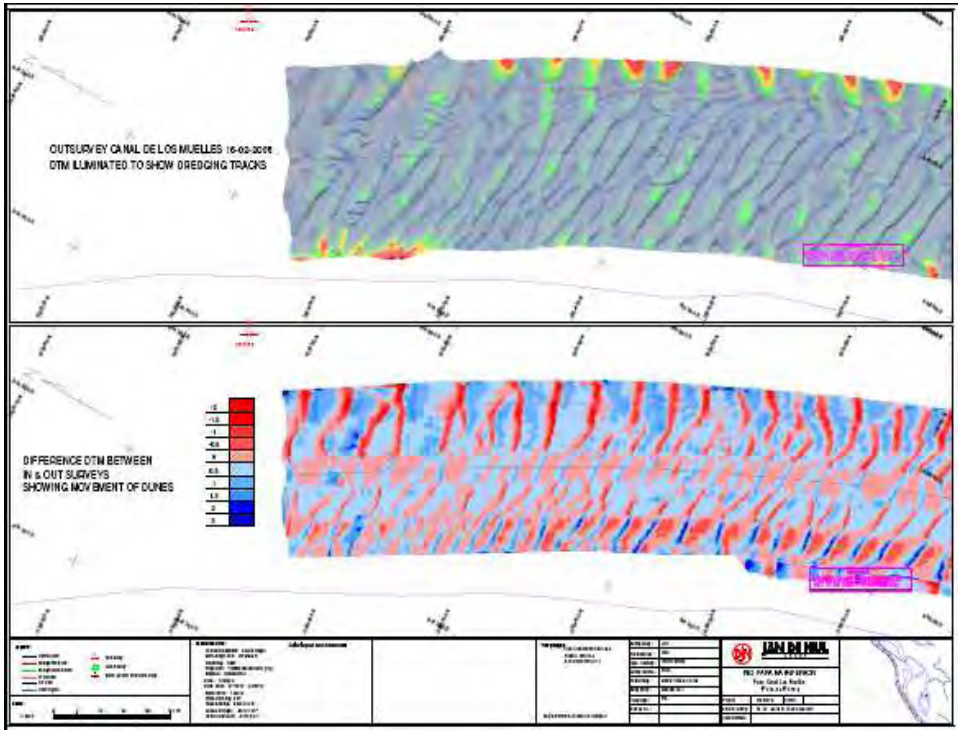


Maintenance dredging in Rio Parana (Canal de Los Muelles)

Sand-dunes moving downstream

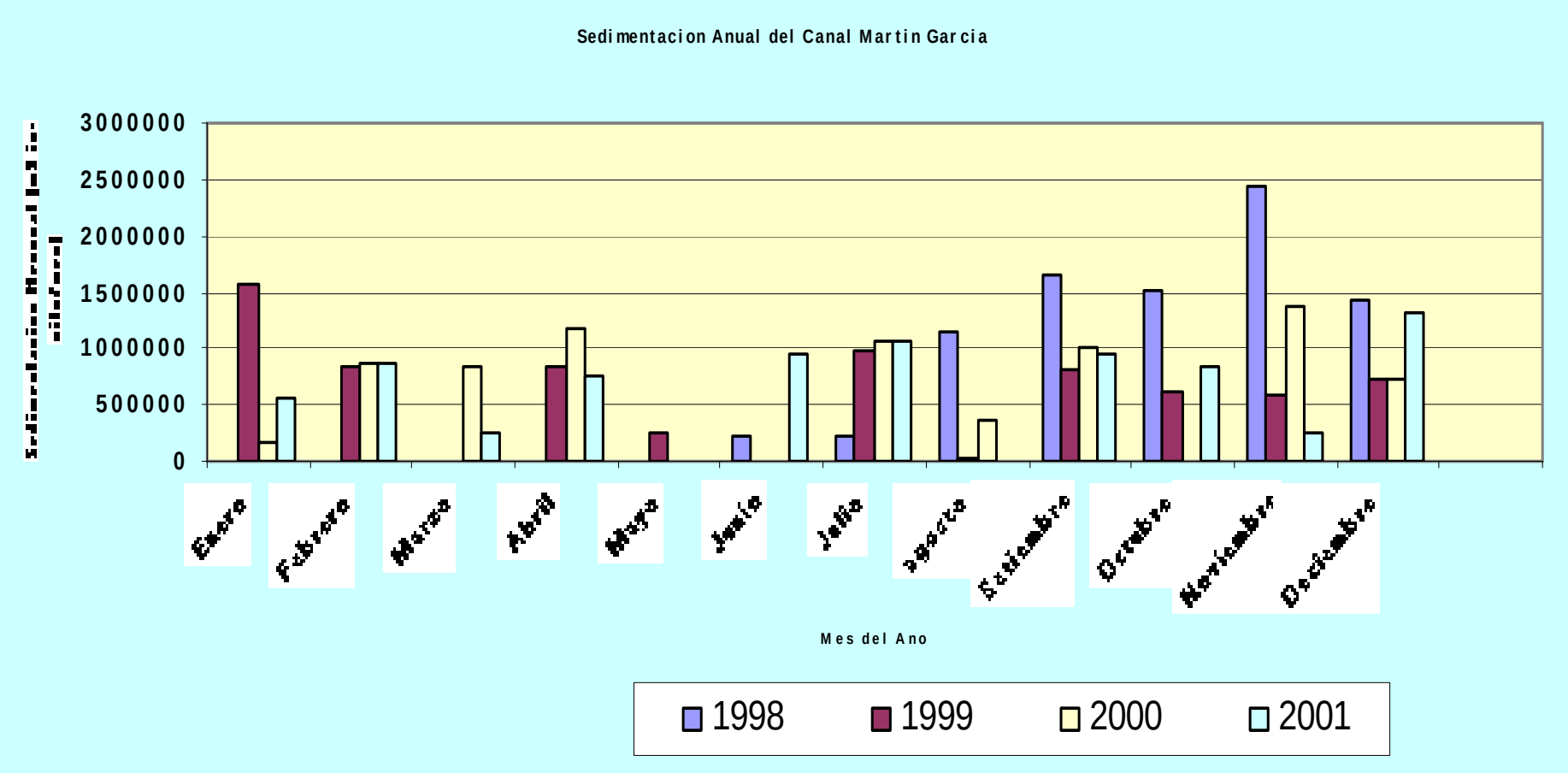






SEASONALITY IN SEDIMENTATION IS NOT ALWAYS SIMPLE: EFFECTS OF LONG TERM CLIMATIC CYCLI MAY AFFECT THIS SCHEME

HERE EFFECT OF EL NINO 1998 ON SEDIMENTATION IN THE MARITIME ACCESS-CHANNELS IN THE RIO DE LA PLATA



Cement exporting Port Hon Chong &Cement Plant, South Viet Nam

Location Map

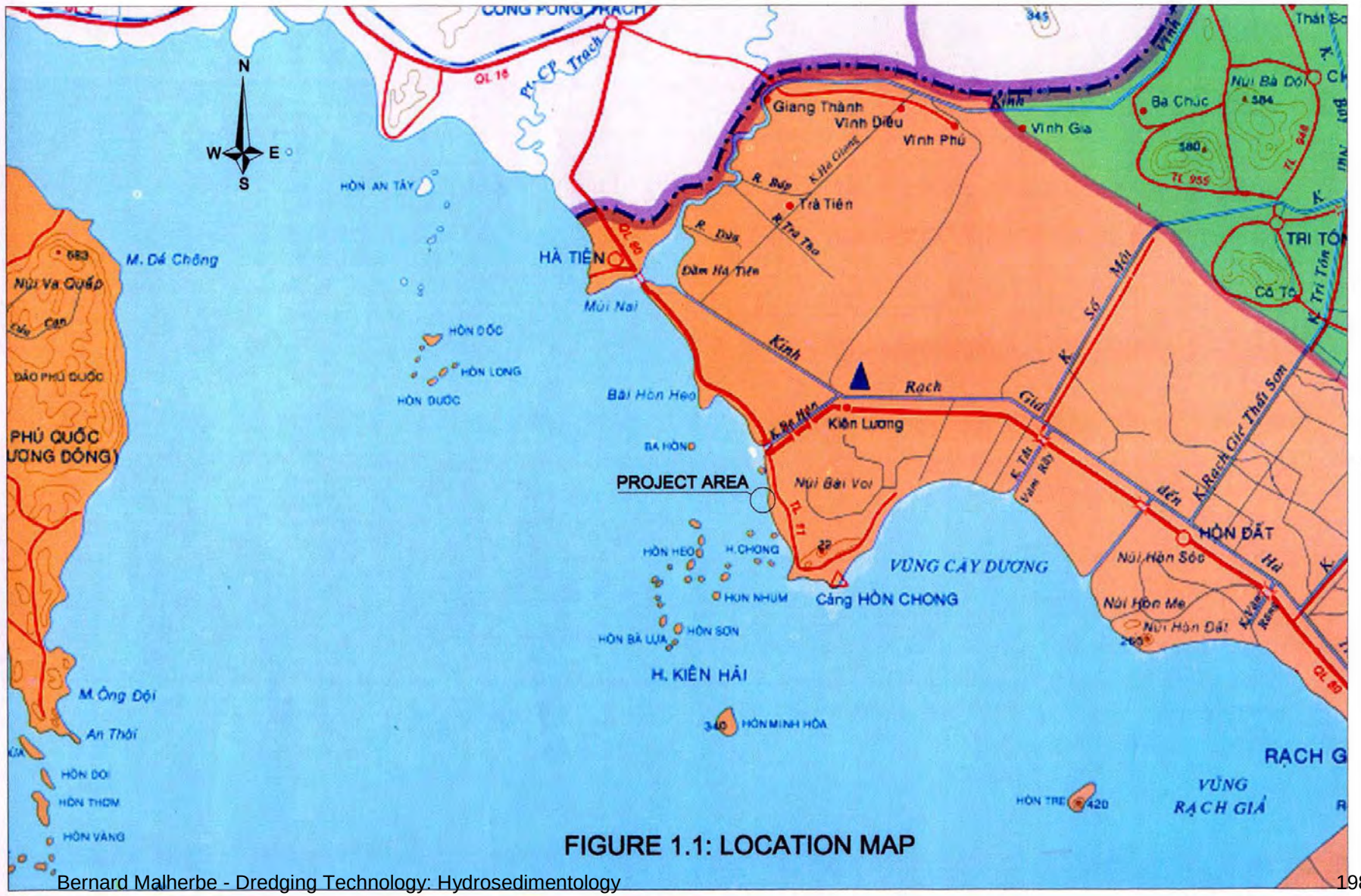
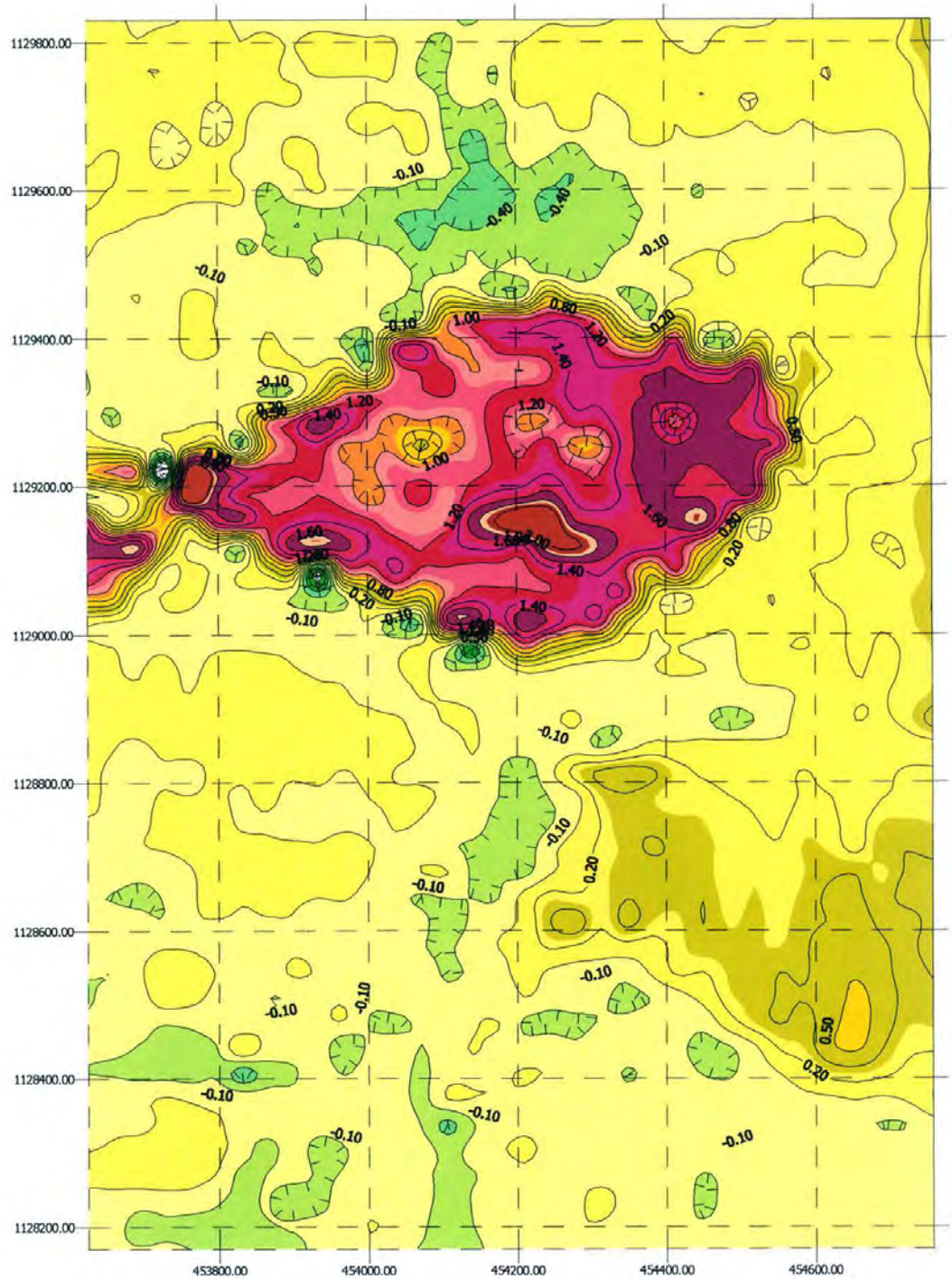


FIGURE 1.1: LOCATION MAP

Cement exporting Port Hon Chong &Cement Plant, South Viet Nam

Differential Map of Binh Tri Port

(June-October 2000; 33 kHz)

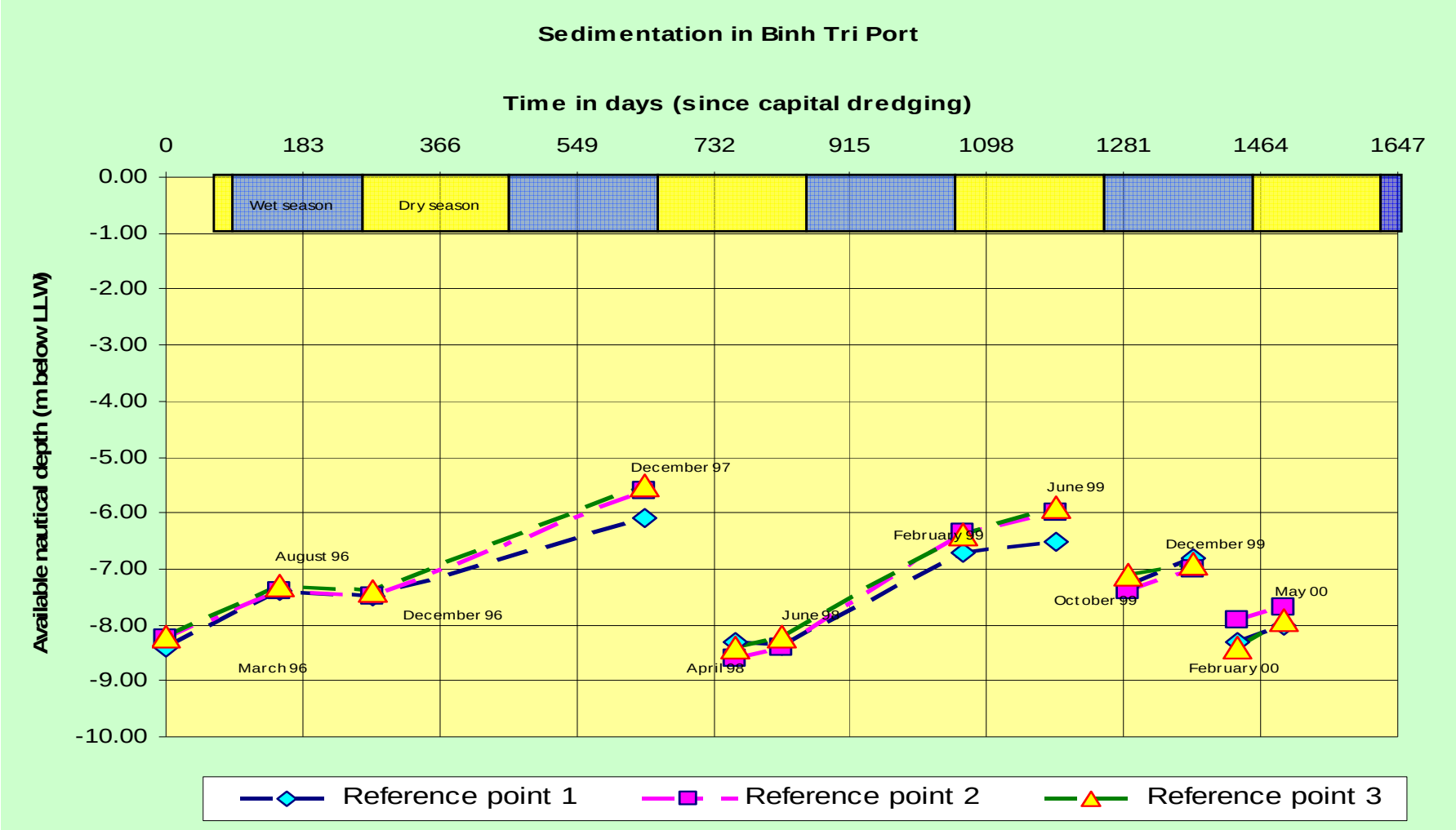


Erosion

Sedimentation

Status Quo

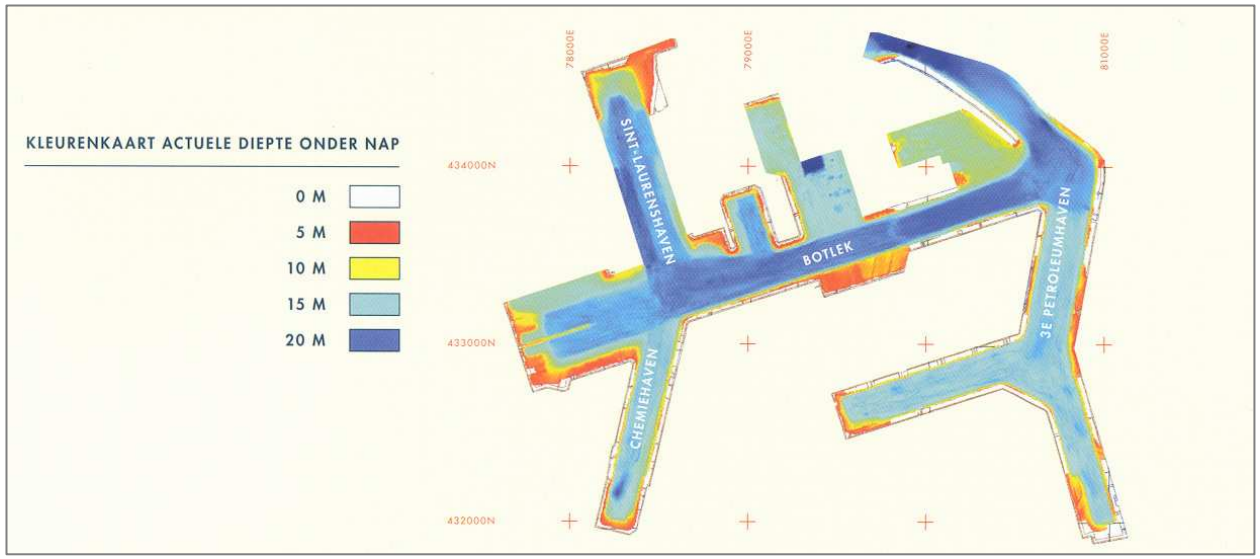
Illustration of sedimentation of port basin with mud sediments:seasonality at Binh Tri port, South Viet Nam



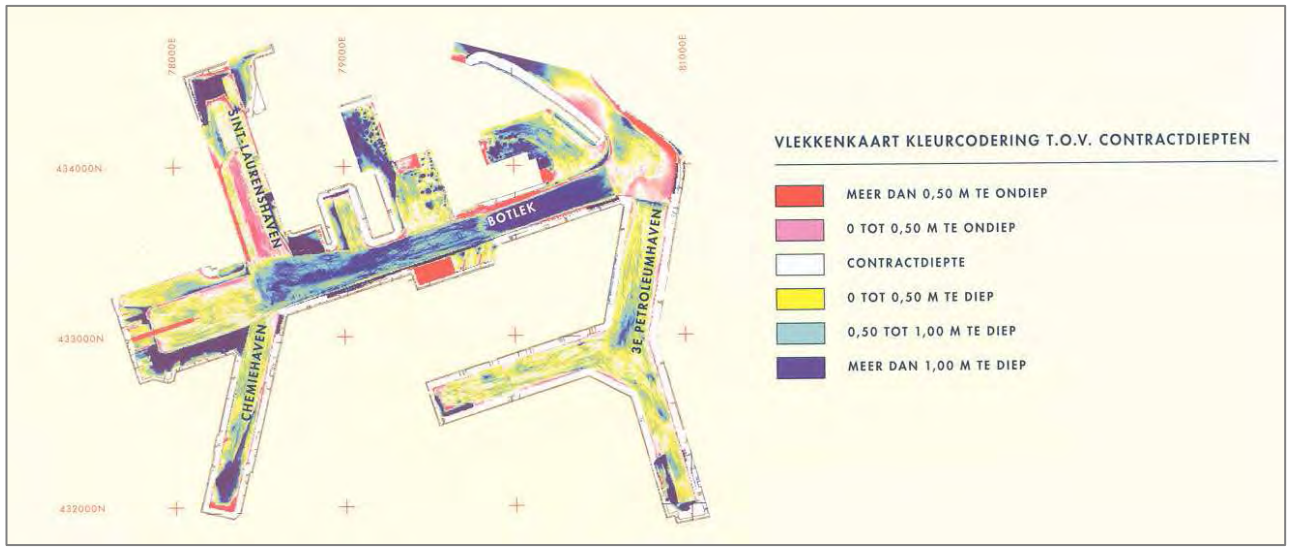
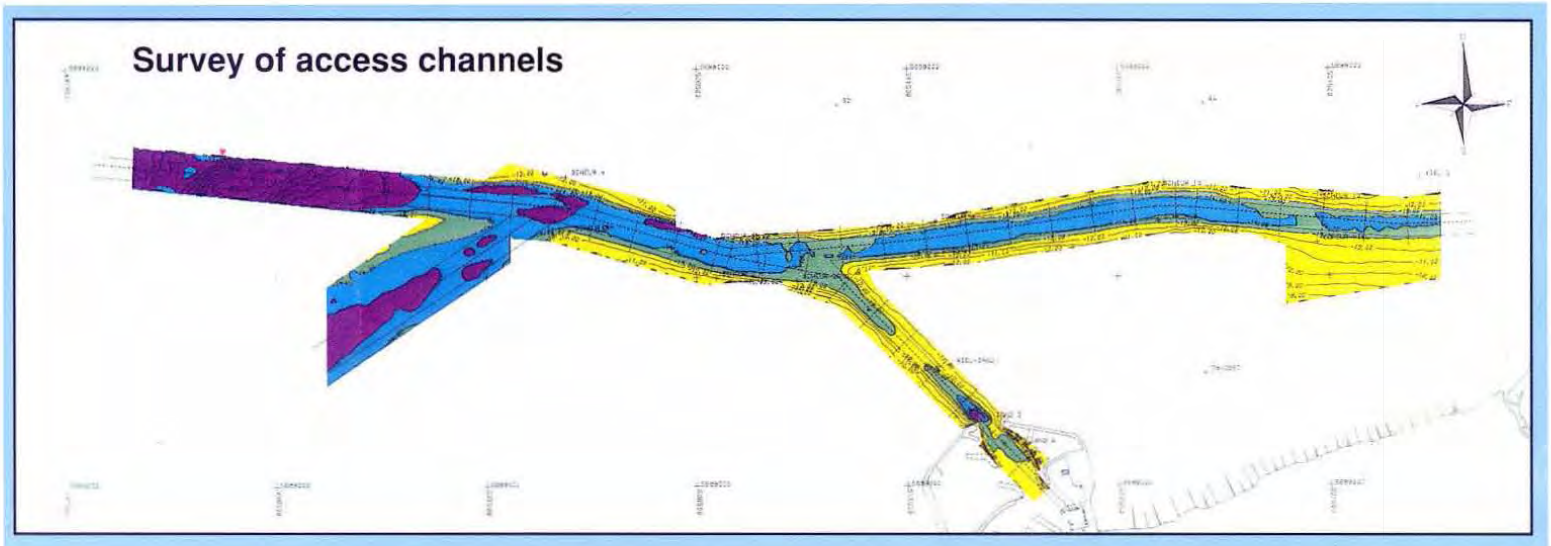
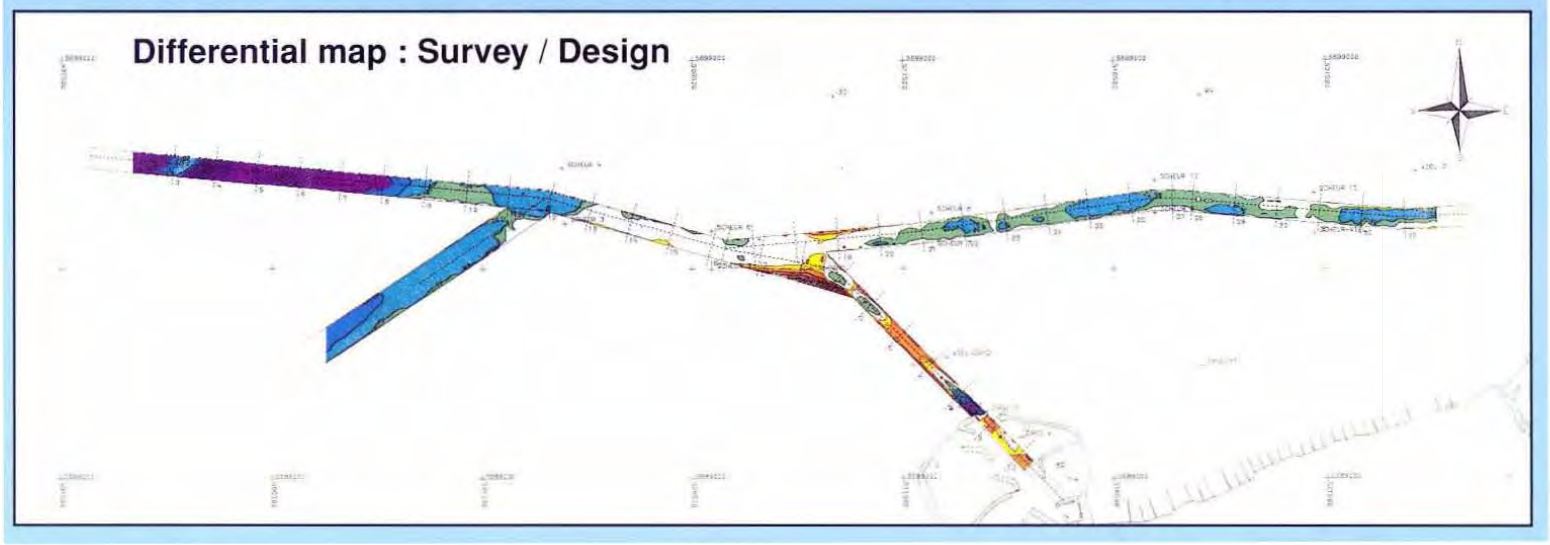
Port	Estuary/River	Sedimentation Rates m3/m2/month (m^3 in-situ)	Morphological variation : lateral shifts m/month	Sediment type
Nantes St. Nazaire	Loire	0,20 - 0,50		mud
Shanghai	Yangtze	0,10 – 0.30		mud
Zeebrugge	Port area Marit. Channel	0,5 - 1,1 0,2 - 0,7		Mud/fine sand
Montevideo	Rio de la Plata	0,1 - 0,5		mud
Hai Phong	Cam / Bach Dang	0,20 - 0,50		mud
Can Tho	Mekong / Bassac	0,10 - 0,60	10 - 70 m/month	mud/fine sand
Boma	Congo / Mateba		30-1000 m/month	sand
Houston - Galveston	Galveston Bay/Bayou	0,05 - 0,30		fine sand

Monitoring of Sedimentations and Deepenings

The hydrographic sounding and Digital Terrain Model (DTM)



The Differential Map Sounding – Design Depth: codification of dredging areas



Sediment and Maintenance Dredging Management by Monitoring the Channel Accretions/Erosions