Prediction of Metal Loadings from Groundwater to Tidal Waters

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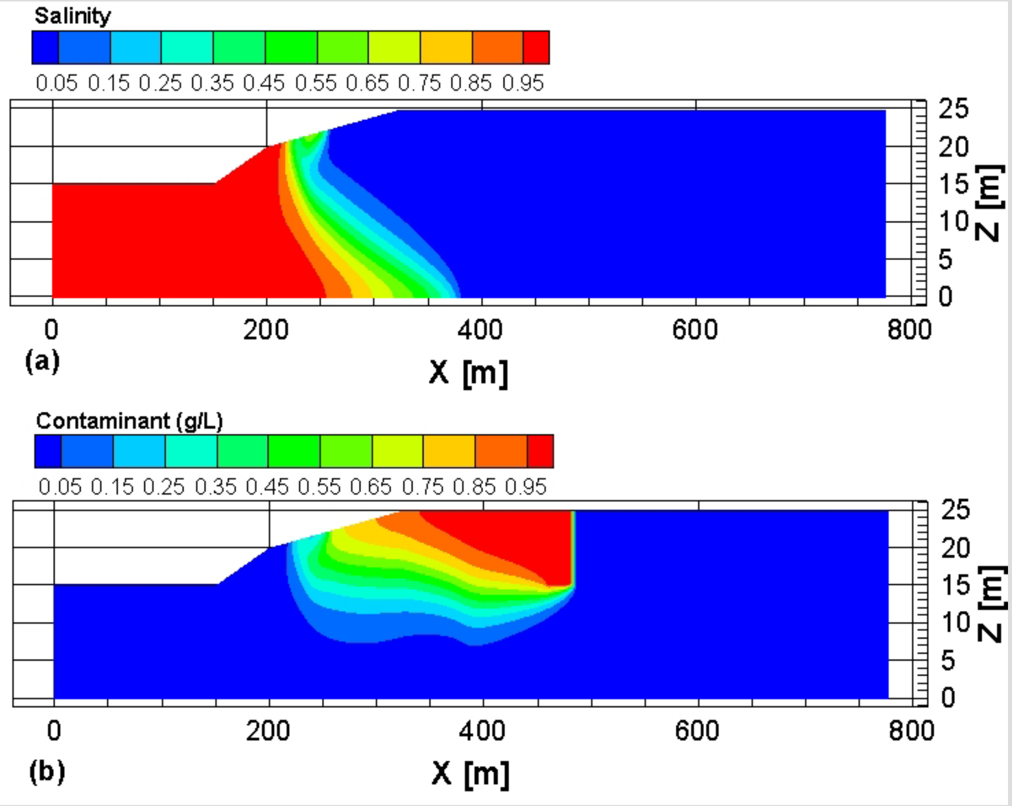
Overview

- Contaminant loadings to the near-shore marine environment and concentrations beneath the seabed
- Hydrologic studies and loading estimates for the Beach Dump at Island Copper Mine
- Synthetic case illustrating contaminant loading from an onshore source to discharge in the intertidal zone

Key Processes

- Transient variations in hydraulic head and groundwater velocity created by tidal cycle
- Location of the fresh water – salt water interface beneath the shoreline
- Migration of seepage face across intertidal zone
- Dilution beneath the intertidal zone as sea water mixes with fresh water

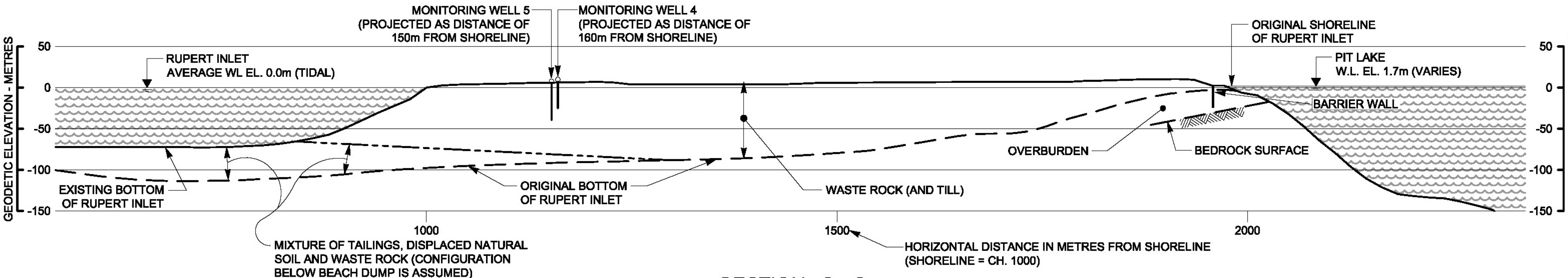
Salt Water Interface



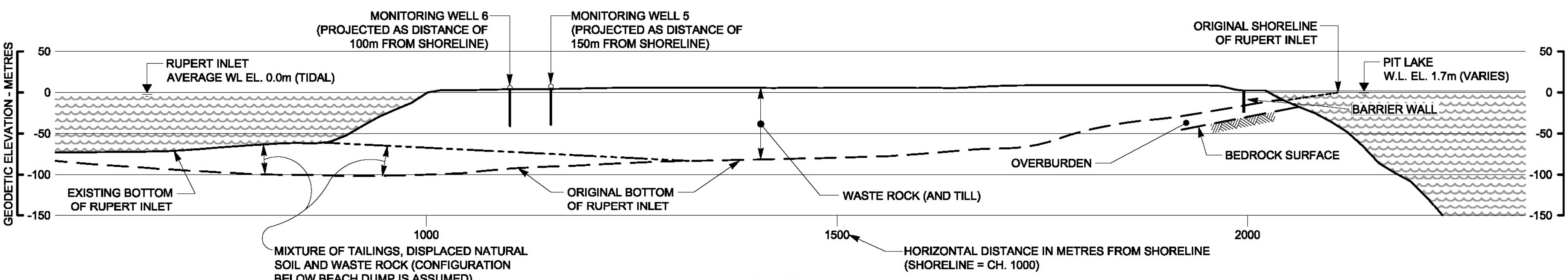
- Steady state estimate of solute load
- Variations in solute loading through the tidal cycle

Beach Dump

- Disposal of 560 M tonnes of waste rock, about 95% is below mean sea level
- Exfiltration pathway for Pit Lake, along with remnant flood channel
- Cap of unsaturated waste rock (forms zone 2–10 m thick) with a till cover



SECTION C–C
BEACH DUMP – BARRIER WALL IN SHALLOW WASTE ROCK



SECTION D–D
BEACH DUMP – BARRIER WALL IN DEEP WASTE ROCK

FIGURE E-4
SECTIONS OF BEACH DUMP AT BARRIER WALL

SCALE

50 0 50 100 150 200m

1 : 5 000

Groundwater Flow System

- Conceptual model of Beach Dump based on three zones reflecting different origins of water:

- Upper zone originating as rainfall infiltrating through surface of Beach Dump
- Middle zone transmitting surface water that exfiltrates from Pit Lake
- Lower zone containing seawater

- Based on salinity profiles in boreholes, sustained flow from surface infiltration and outflow from Pit Lake creates a net flow toward Rupert Inlet in the upper ~20 m of the Beach Dump

Estimated Average Annual Infiltration on Beach Dump

	Internal Drainage (153 ha)	External Drainage (112 ha)	Entire Surface
Annual ppte	1900 mm/yr	1900 mm/yr	
ET	530 mm/yr	530 mm/yr	
Runoff		420 mm/yr	
Infiltration	1370 mm/yr	950 mm/yr	
Volume	2.1 Mm^3/yr	1.1 Mm^3/yr	3.2 Mm^3/yr
Per Unit Area			1200 mm/yr

Water Balance Estimates for Beach Dump

Average annual inflow from Pit lake	6.5 Mm^3/yr
Infiltration from direct precipitation – 1200 mm of 1900 mm rainfall	3.2 Mm^3/yr
Infiltration pathways from North Dump	0.3 Mm^3/yr

Estimates of hydraulic gradient

- Accurate estimates of hydraulic gradient are challenging

  - high permeability implies low gradients

  - non-uniform fluid density

  - tidal fluctuations

- Average water levels calculated over tidal cycles

June 20-July 4 2001

	L	Δh	grad
W4 to shore	150	nil	nil
W5 to shore	150	8 cm	5E-4
W6 to shore	100	1 cm	1E-4
W10 to shore	330	nil	nil

June 11-13 2003

	L	Δh	grad
W4 to shore	150	0.6 cm	4E-5
W5 to shore	150	18.1 cm	1E-3
W6 to shore	100	9.7 cm	1E-3
W10 to shore	330	27.1 cm	8E-4

Hydraulic Conductivity Estimate Based on Tidal Analysis

- Analyze three vertical sections though Beach Dump

- Use code SEEPW – considers only a uniform fluid density

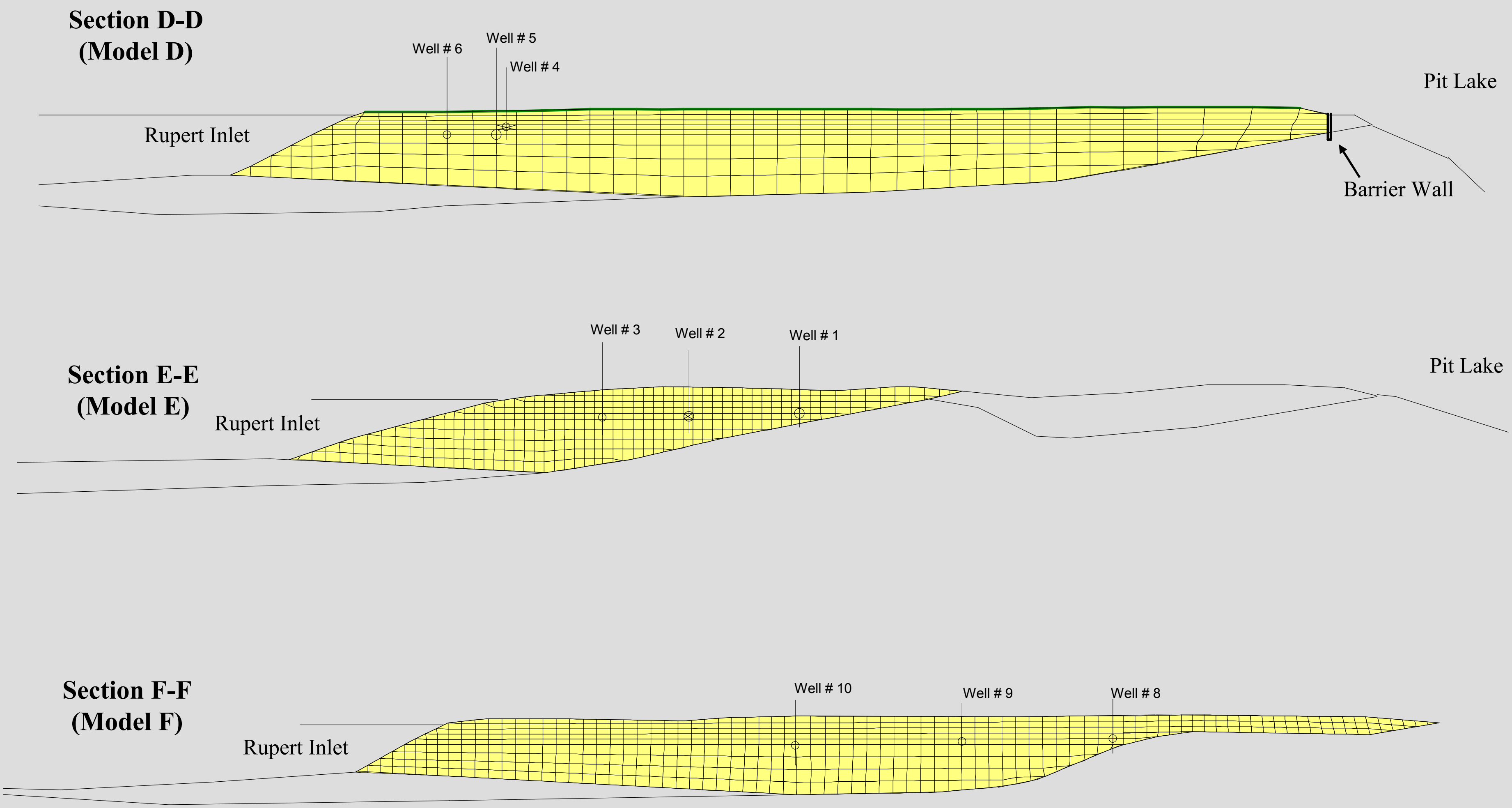


Figure E-8

Geometry and Mesh of Seepage Model

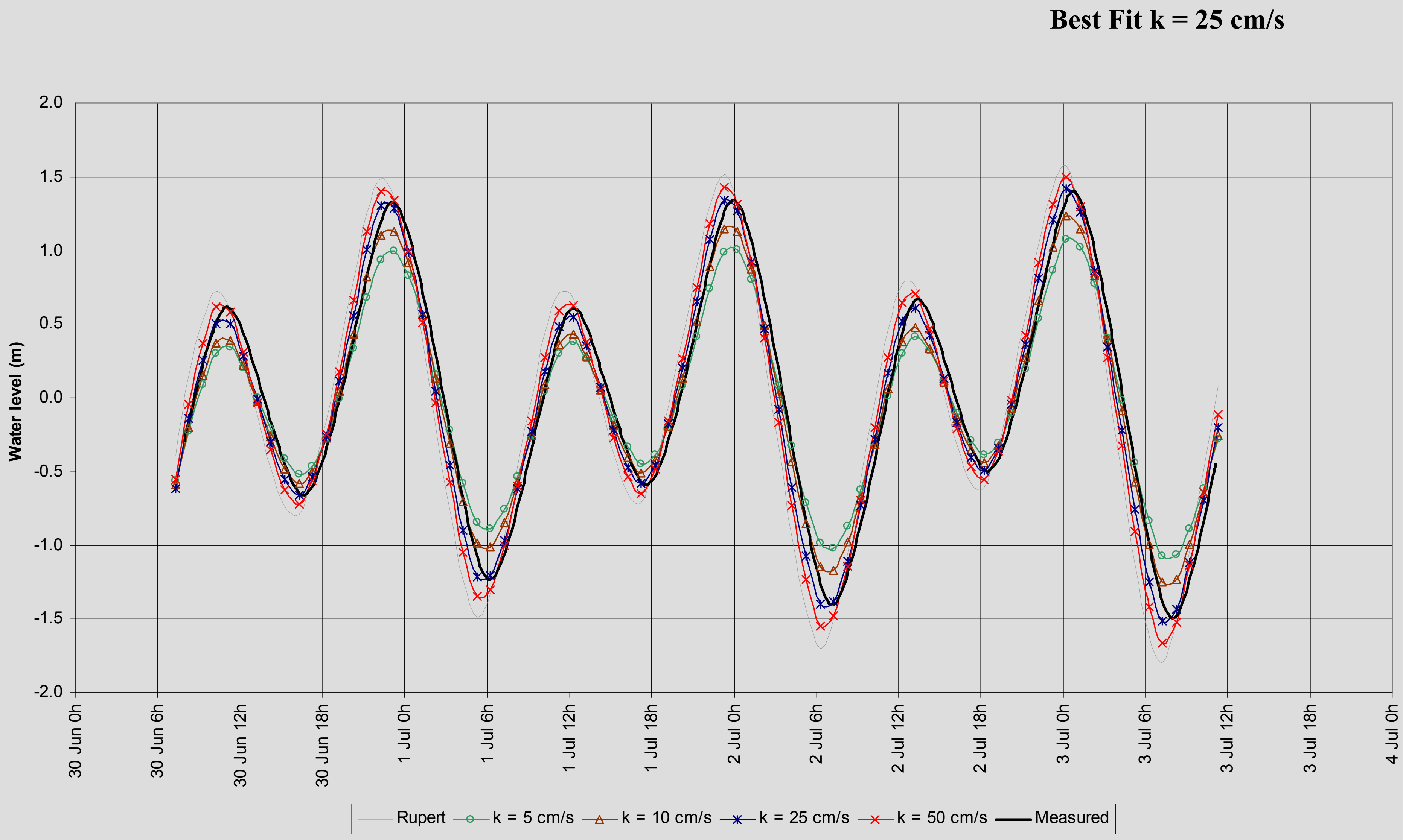


Figure E-9

Section D-D – Calibration of k Value at Well 4

Best Fit k = 40 cm/s

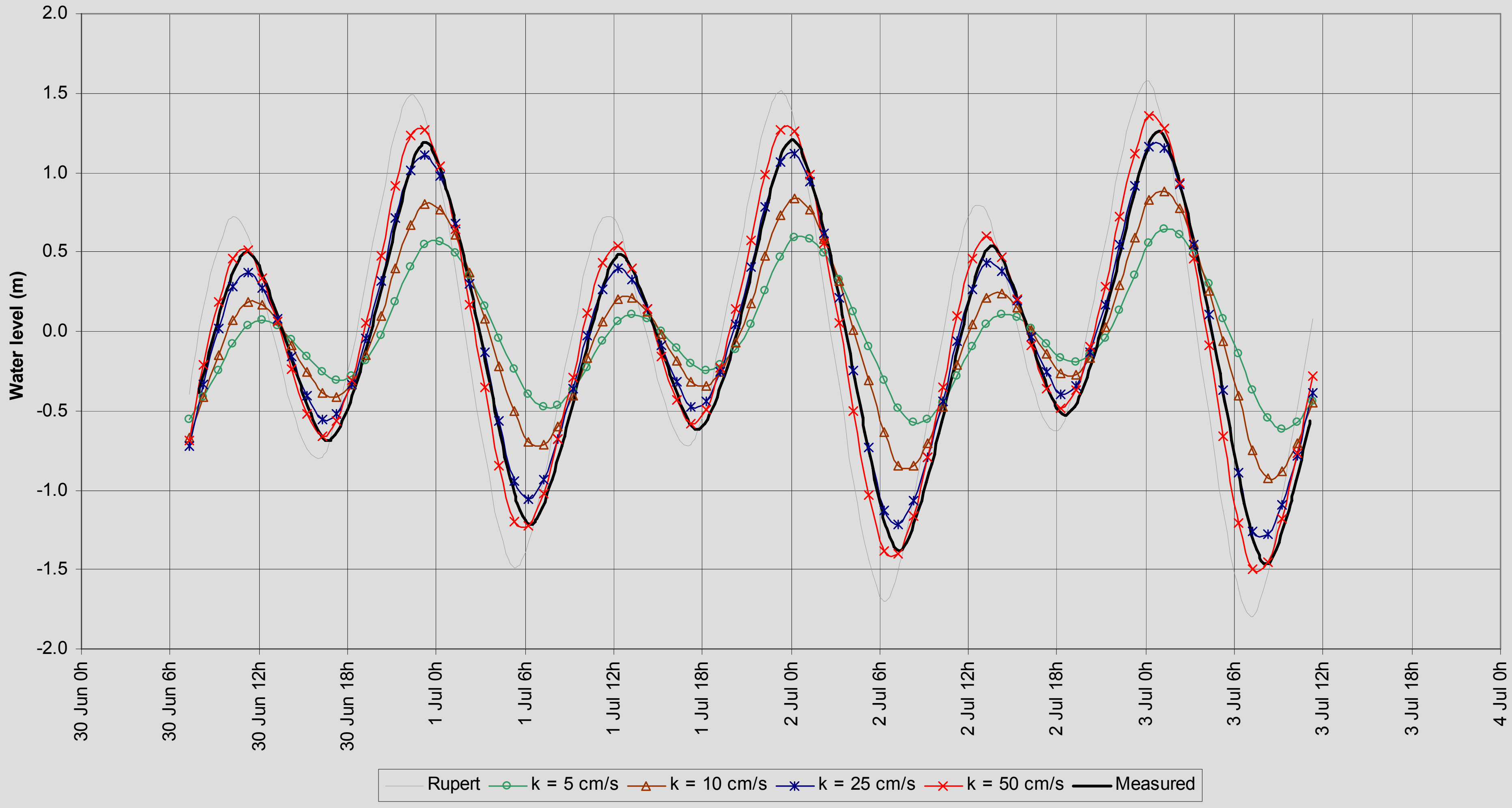


Figure E-17

Section F-F – Calibration of k Value at Well 10

Hydraulic Conductivity

- Estimated large-scale hydraulic conductivity of Beach Dump in the range from 10 - 40 cm/s
- This is a high-permeability system, with K on the order of 10^{-1} m/s

Variations in Flow Patterns in Beach Dump Due to Tides

- Base case hydraulic conductivty of 25 cm/s
- Assume water with uniform density throughout the dump
- Superposition of two solutions, one for a 20 m thick sustained flow, the second for tidal influences over full thickness of dump

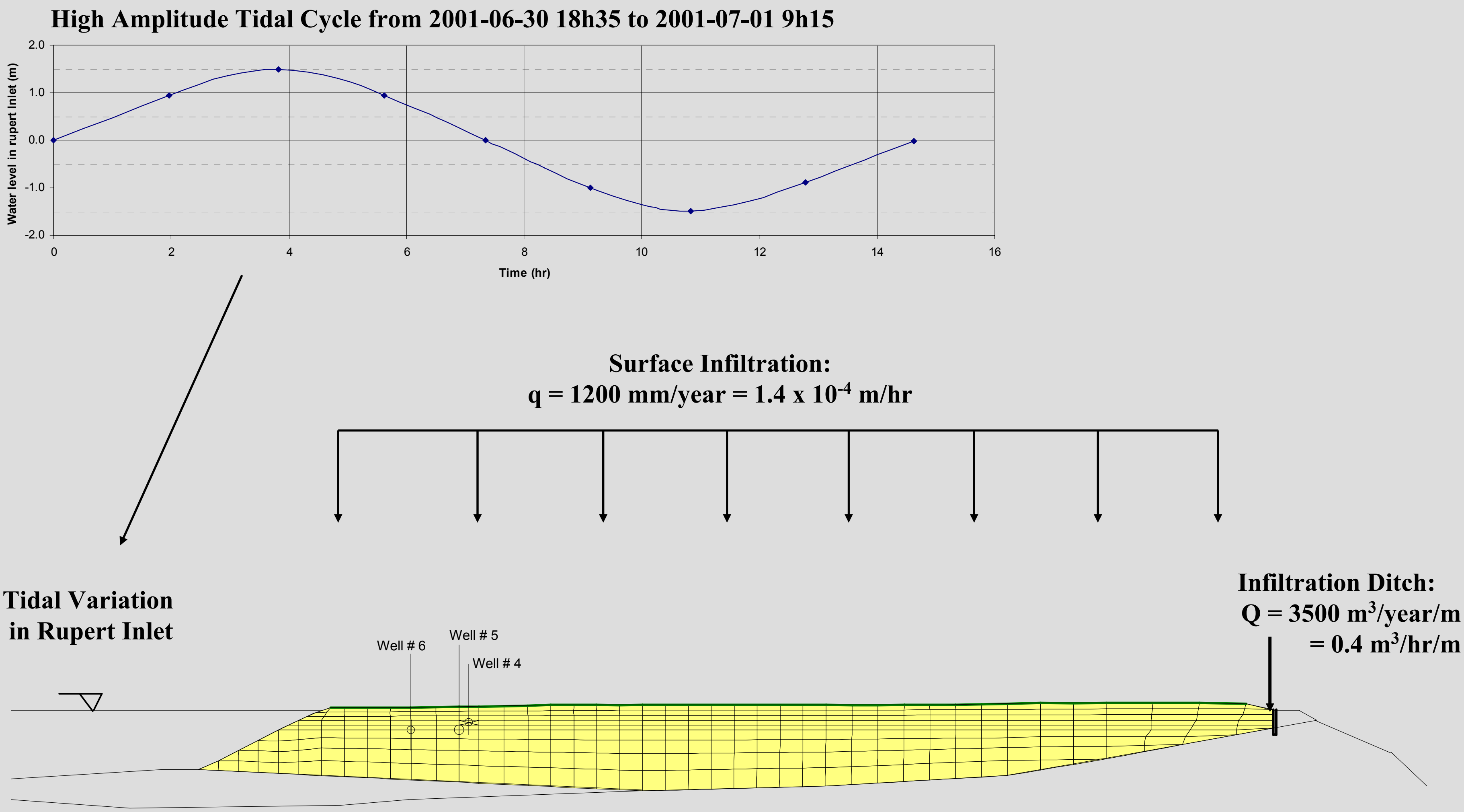


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Figure E-

Model D Case 2 Combined Mesh and Boundary Conditions

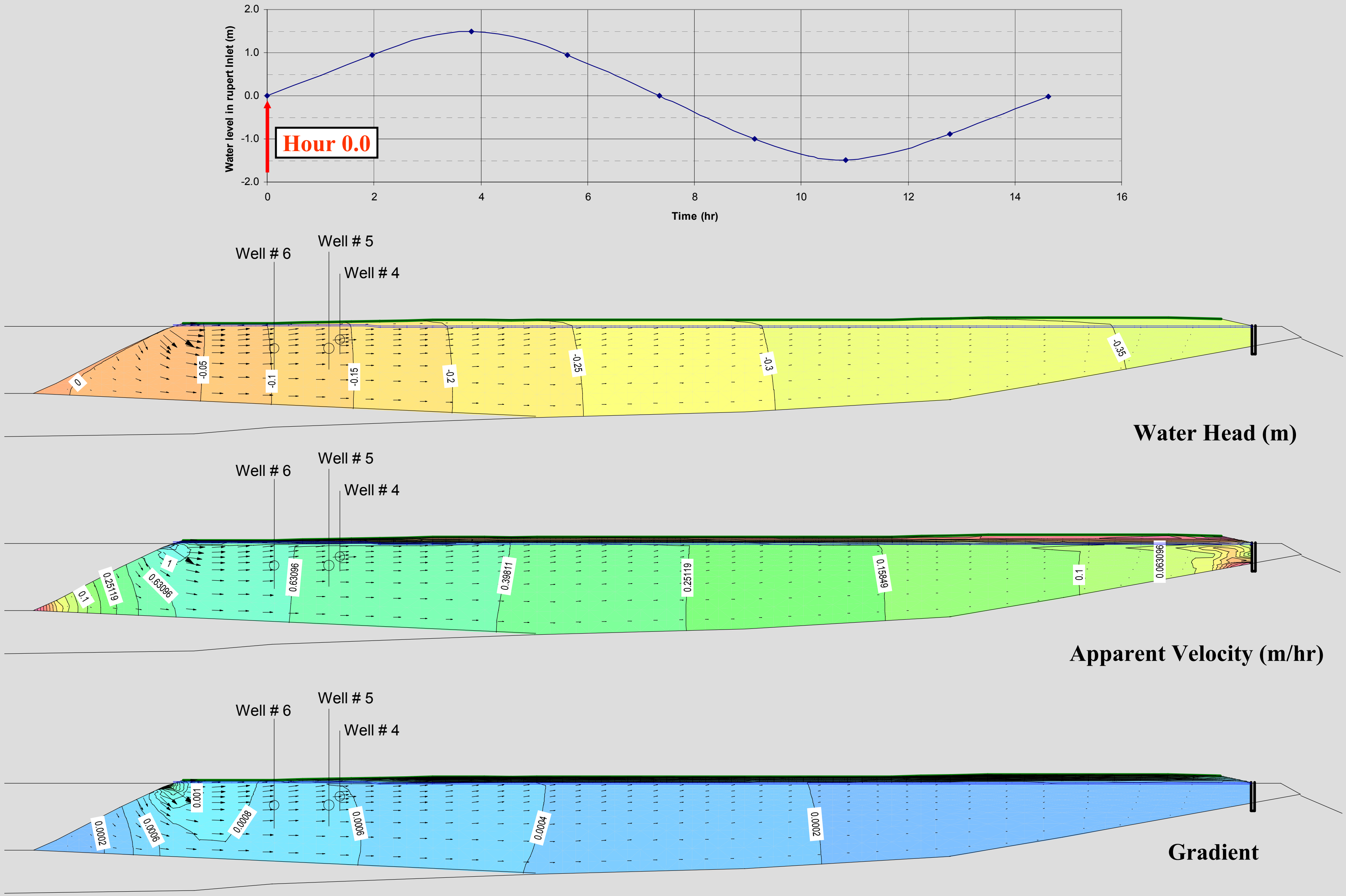

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Figure E-19

Model D Case 2 Combined Head, Velocity and Gradient at Hour 0

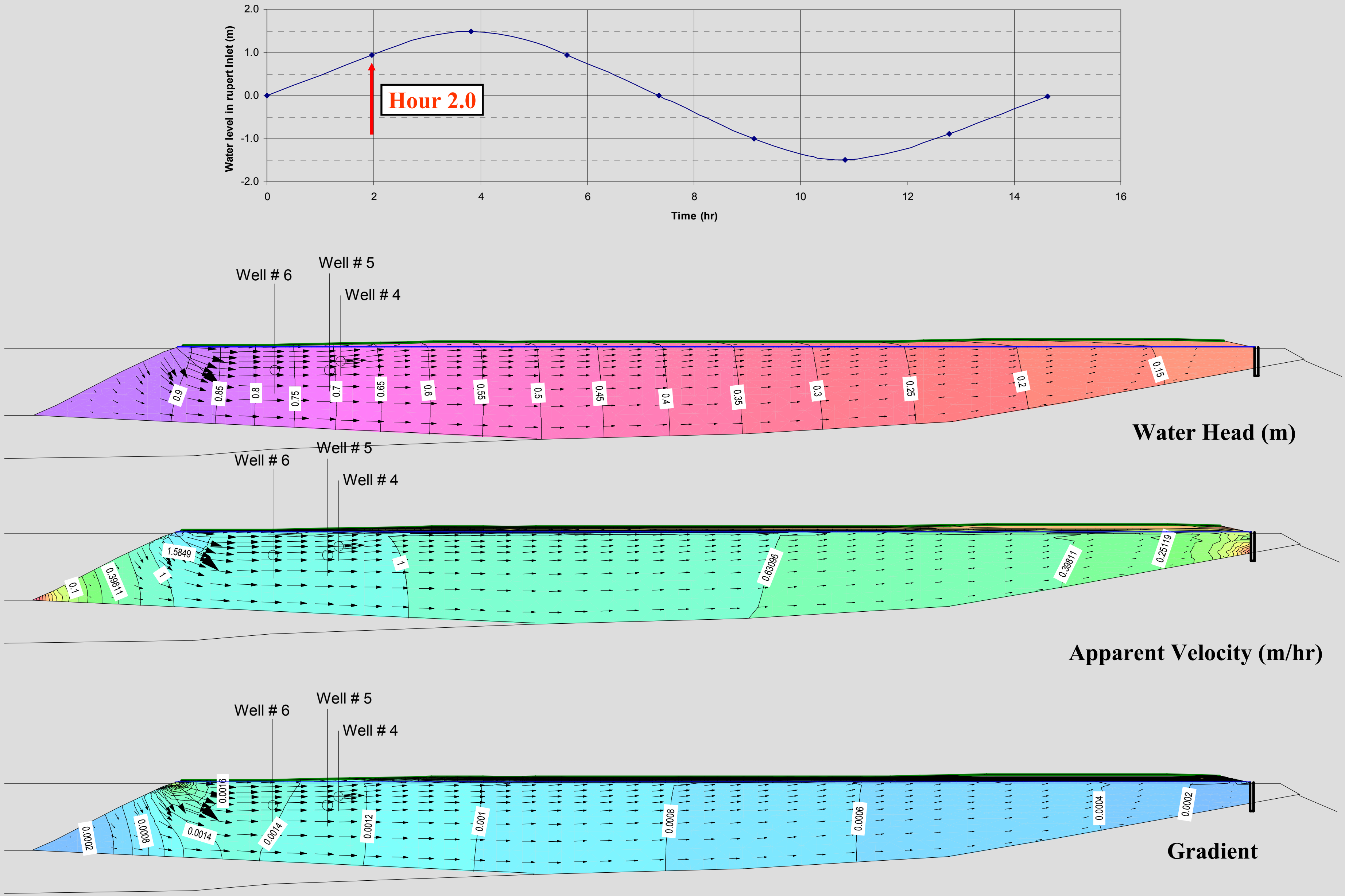

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Figure E-20

Model D Case 2 Combined Head, Velocity and Gradient at Hour 2.0

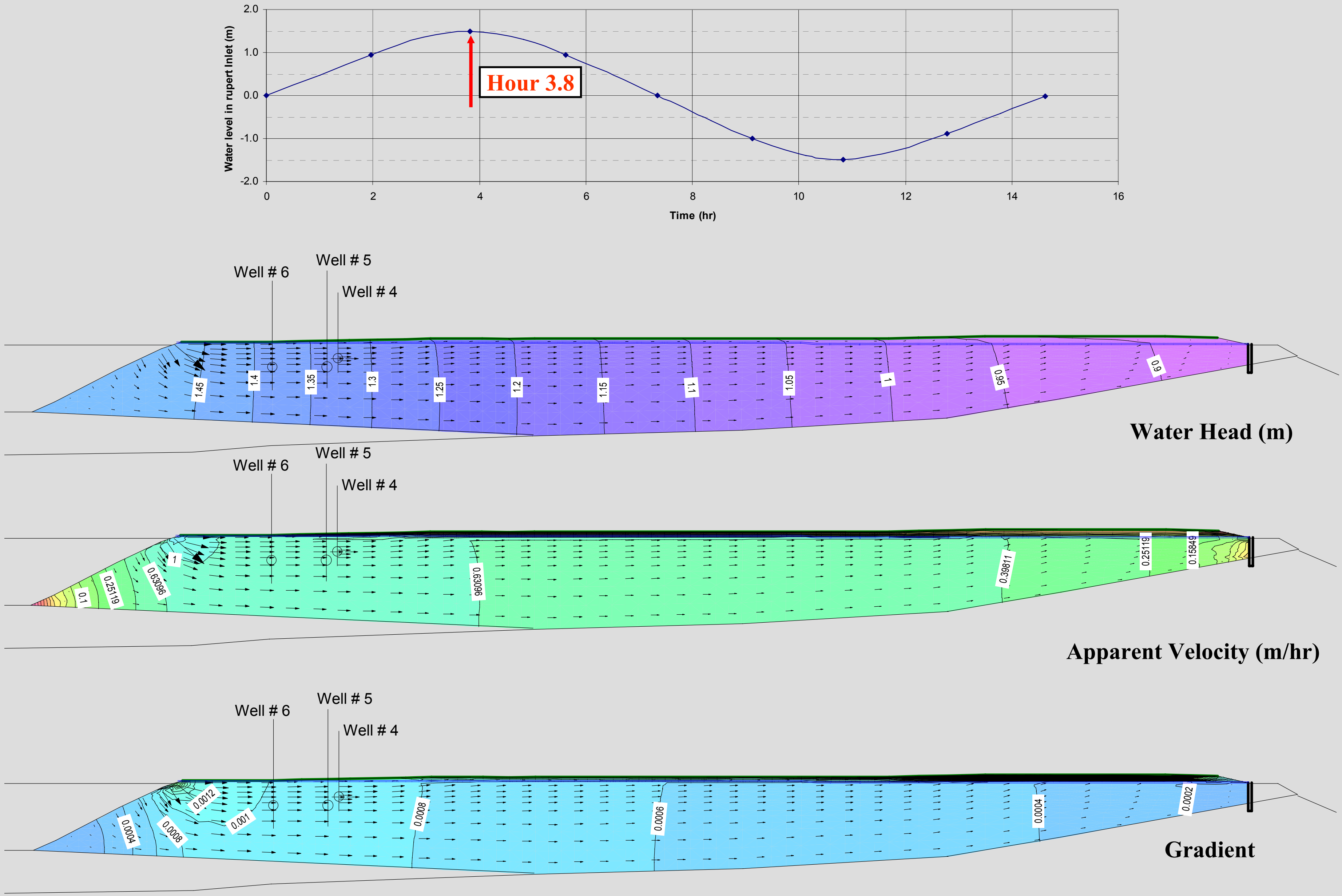

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Figure E-21

Model D Case 2 Combined Head, Velocity and Gradient at Hour 3.8

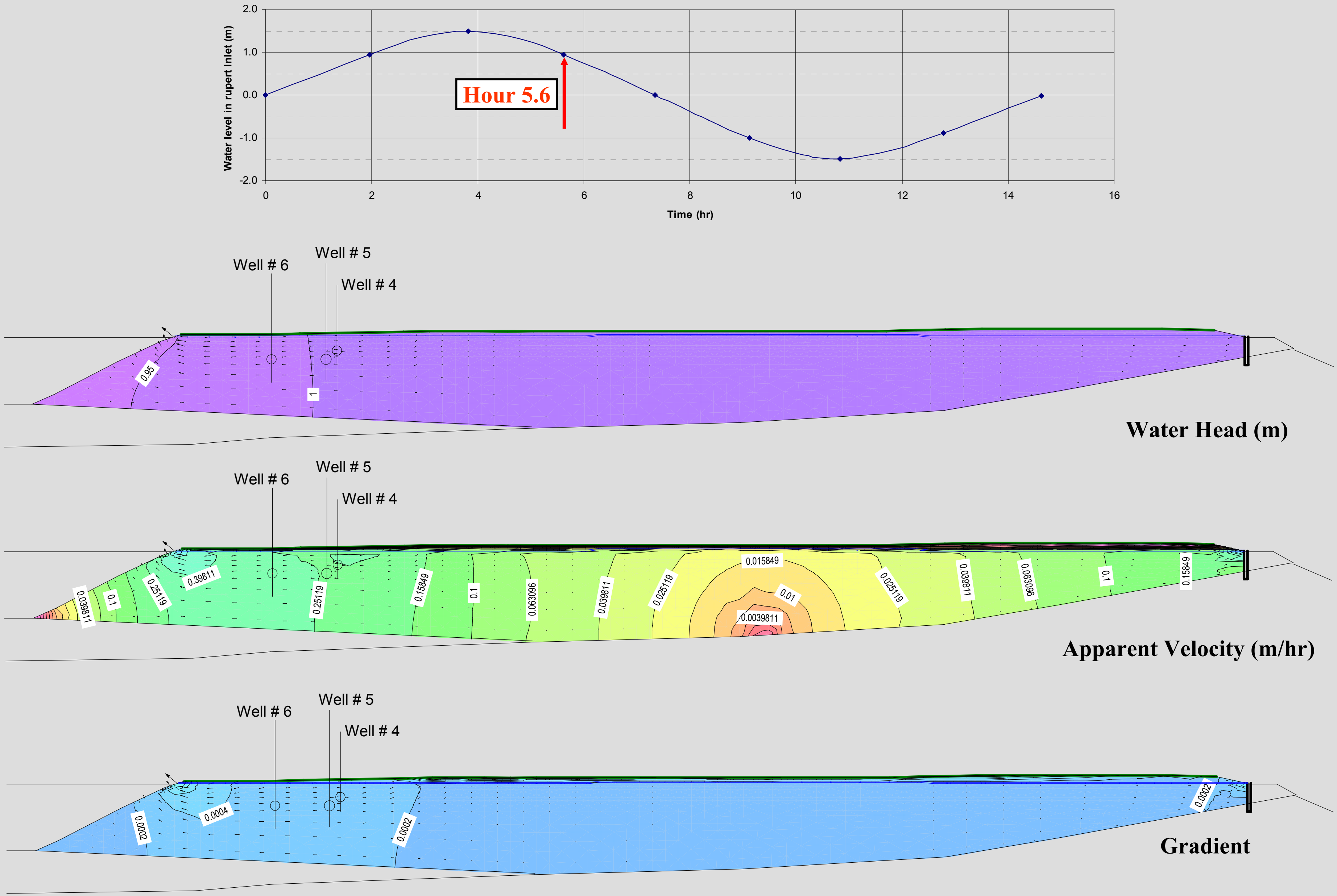

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Figure E-22

Model D Case 2 Combined Head, Velocity and Gradient at Hour 5.6

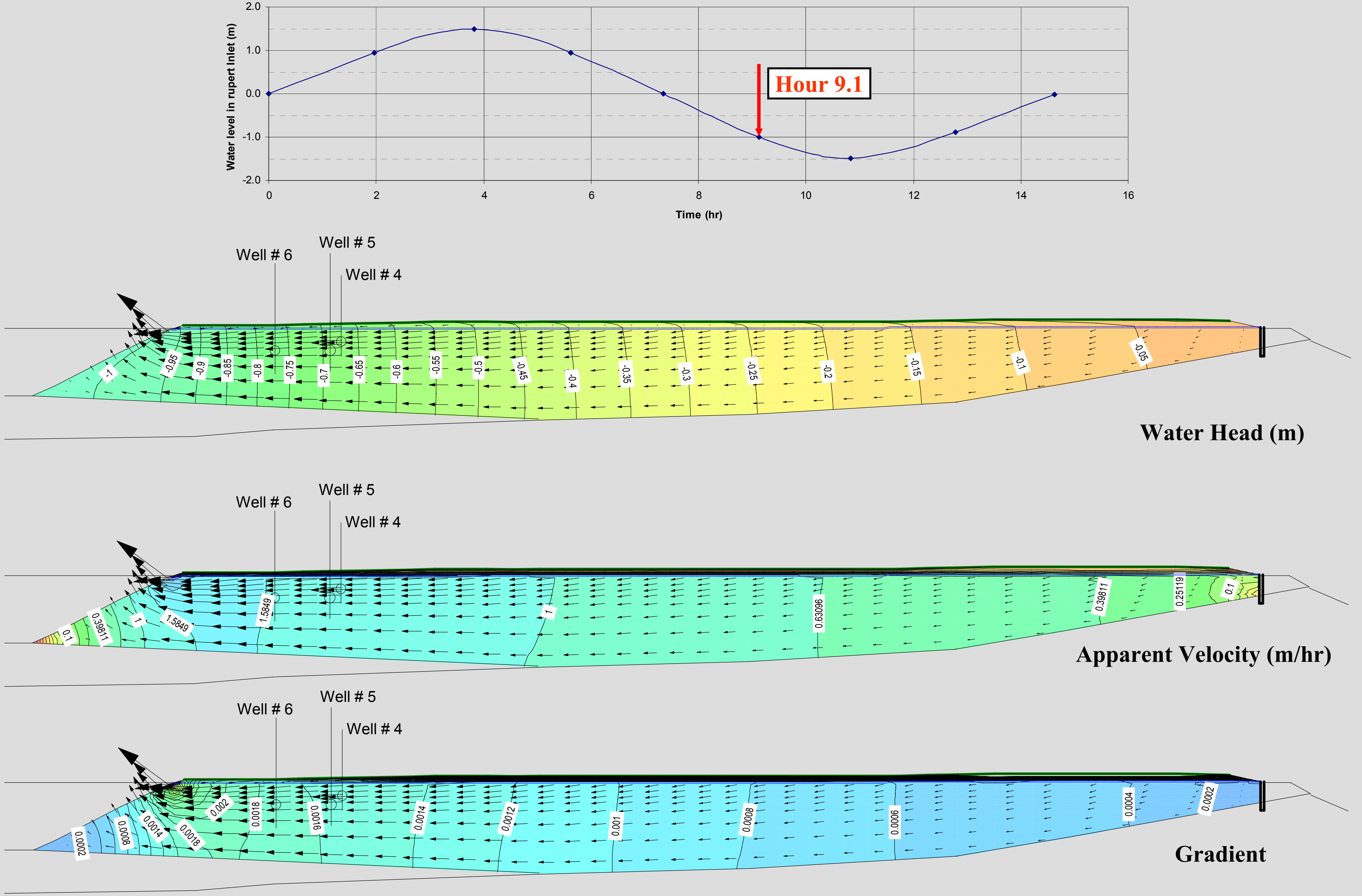

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Figure E-24

Model D Case 2 Combined Head, Velocity and Gradient at Hour 9.1

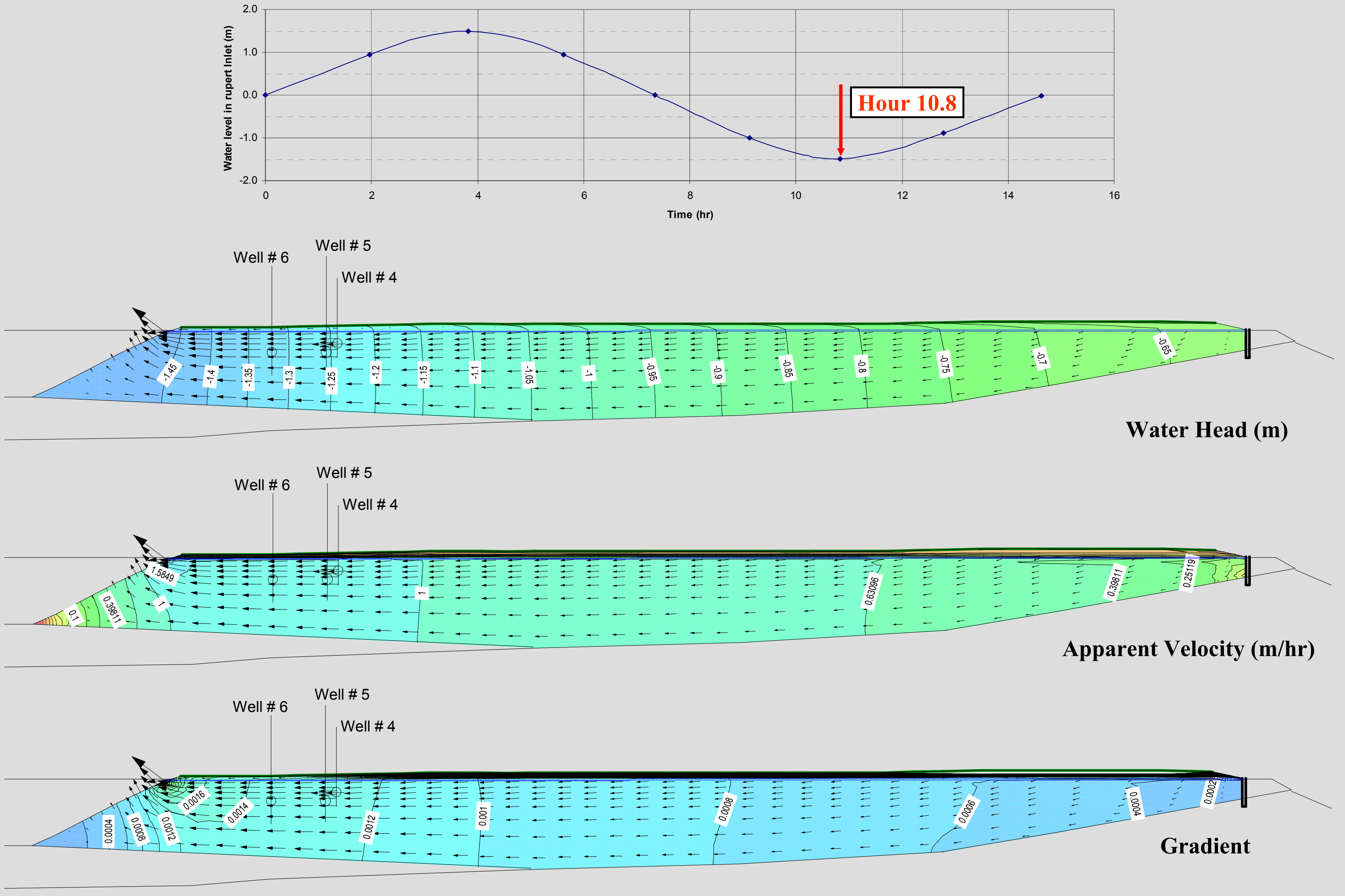

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Figure E-25

Model D Case 2 Combined Head, Velocity and Gradient at Hour 10.8

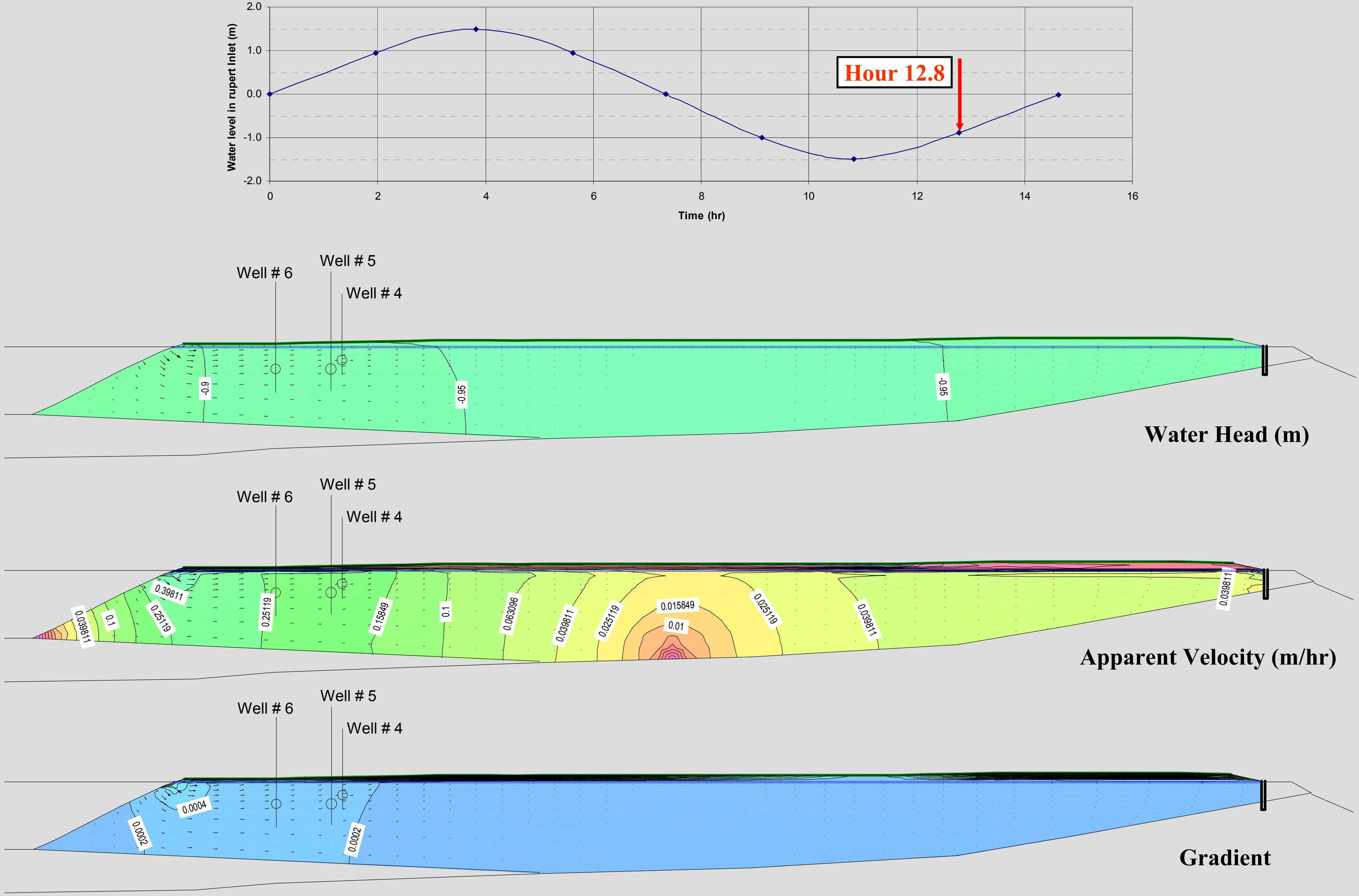

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Figure E-26

Model D Case 2 Combined Head, Velocity and Gradient at Hour 12.8

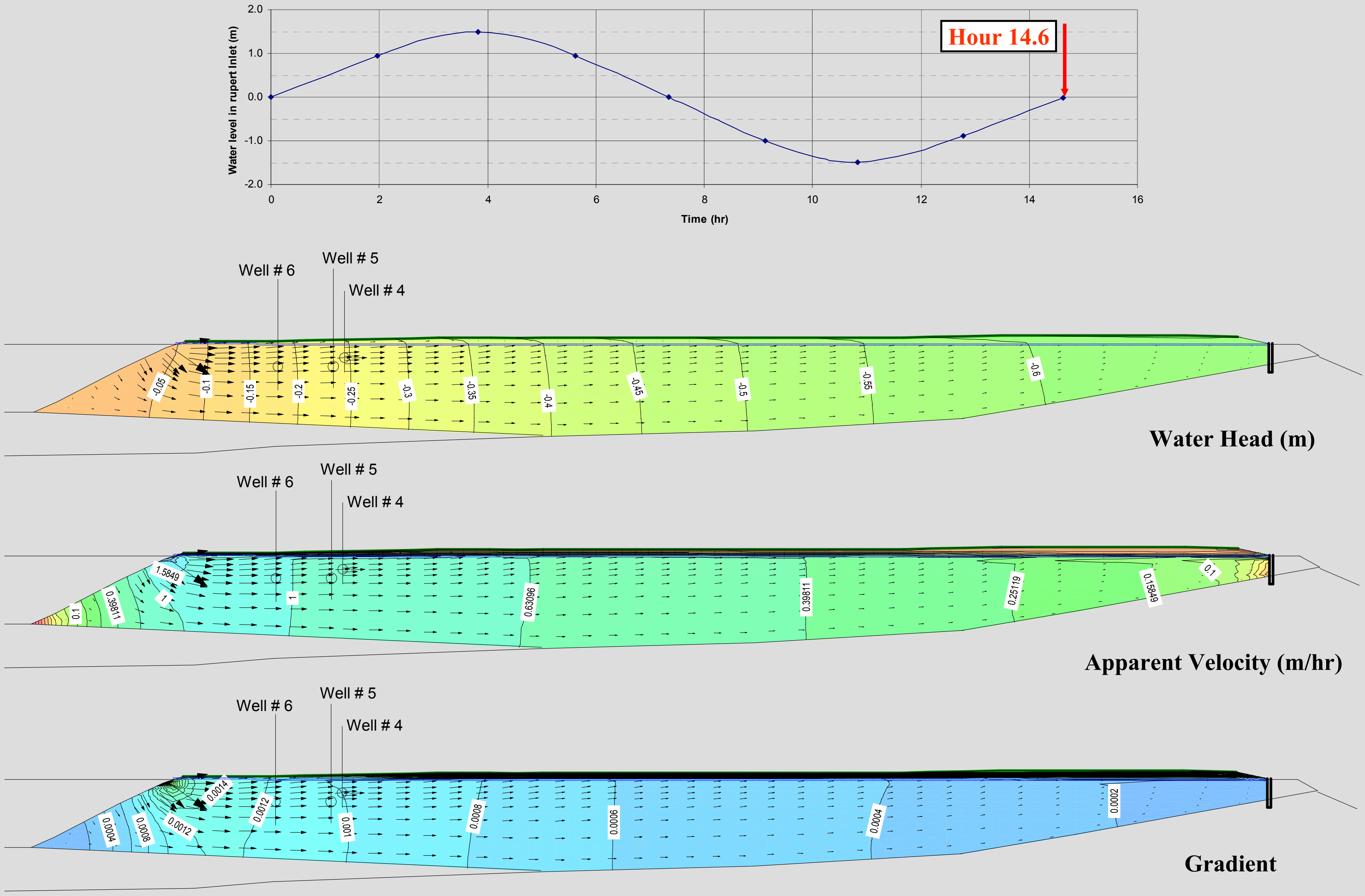

Figure E-27

Model D Case 2 Combined Head, Velocity and Gradient at Hour 14.6

Net Motion of Water Packets

- Representative sets of path lines followed by a water packet during the tidal cycle
- Sustained flow system above 20 m depth includes effects of both fresh water recharge and tidal oscillations
- Below 20 m depth, tidal oscillations

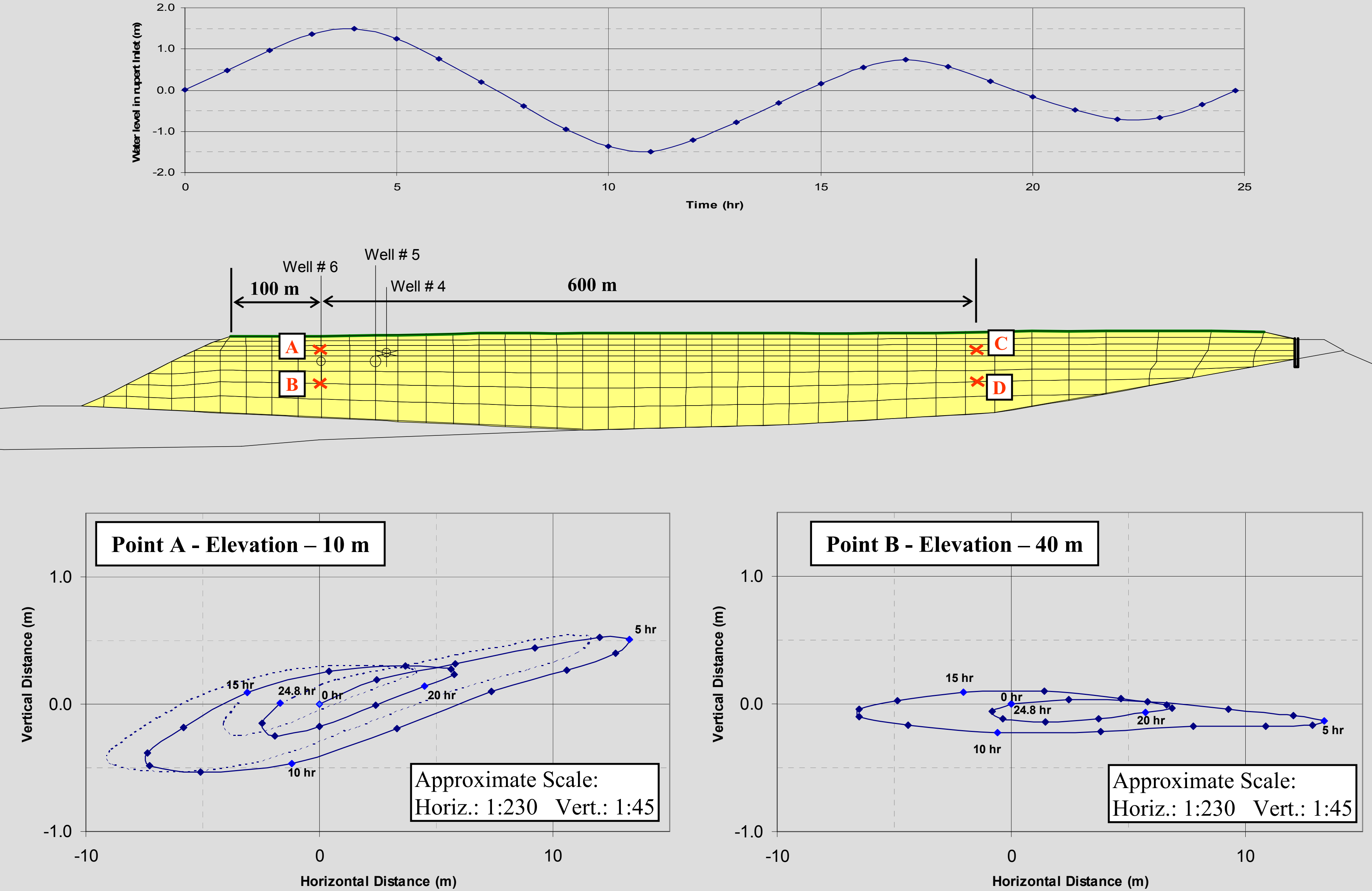

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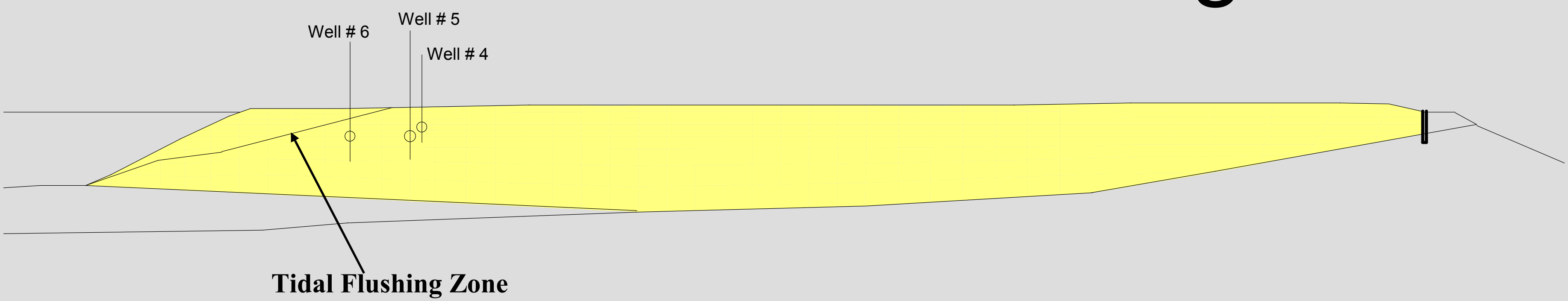
Figure E-30

Particle Track El.-10 m and –40 m at 100 m from Shoreline k = 25 cm/s

Travel Time Estimate from Pit Lake to Rupert Inlet via Beach Dump

- 1000 m flowpath, porosity of 0.35
- Estimate of travel time derived from water balance is 1.4 year
- Overflow at barrier wall began February 1999
- Infer Pit Lake water may have reached Rupert Inlet in mid to late 2000
- Recent inflows from Pit Lake are a minor contributor to metal loading

Tidal Mixing Zone



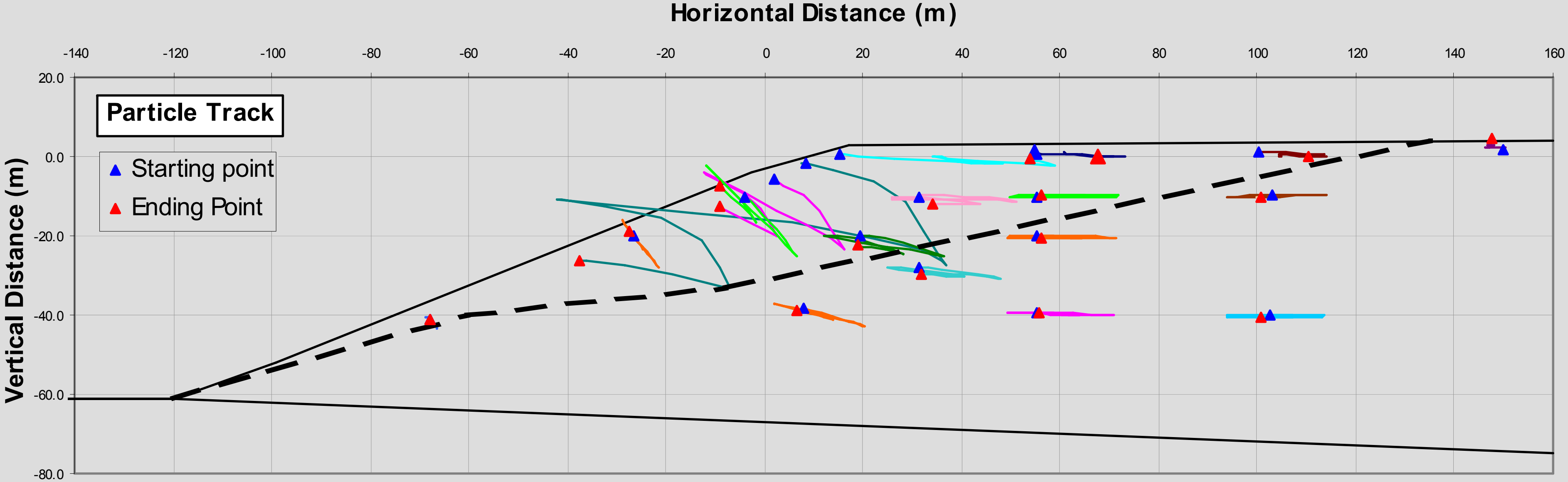


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Figure E-36

Configuration of Tidal Flushing Zone for k = 25 cm/s

Concentration Data (1998-2002) Upper 20 m of Beach Dump

Zinc - mg/l	well	range	average	upper bound
	4	0.3 - 1.0	0.4	0.8
	5	0.1 - 0.5		
	6	0.1 - 0.7		
Copper - mg/l				
	4	0.005 - 0.04	0.015	0.03
	5	0.002 - 0.02		
	6	0.003 - 0.02		

Beach Dump Seeps

- Sampled at end of a low tide in June 2003
- Two seeps collected just above the water line
  - zinc 0.1 and 0.11 mg/l
  - copper 0.0004 and 0.001 mg/l
- Indication of tidal dilution: zinc conc. 2 – 6 times smaller than values measured in the upper 5 m of boreholes, copper conc. about 10 times smaller

Steady State Approximation to Loadings to Rupert Inlet

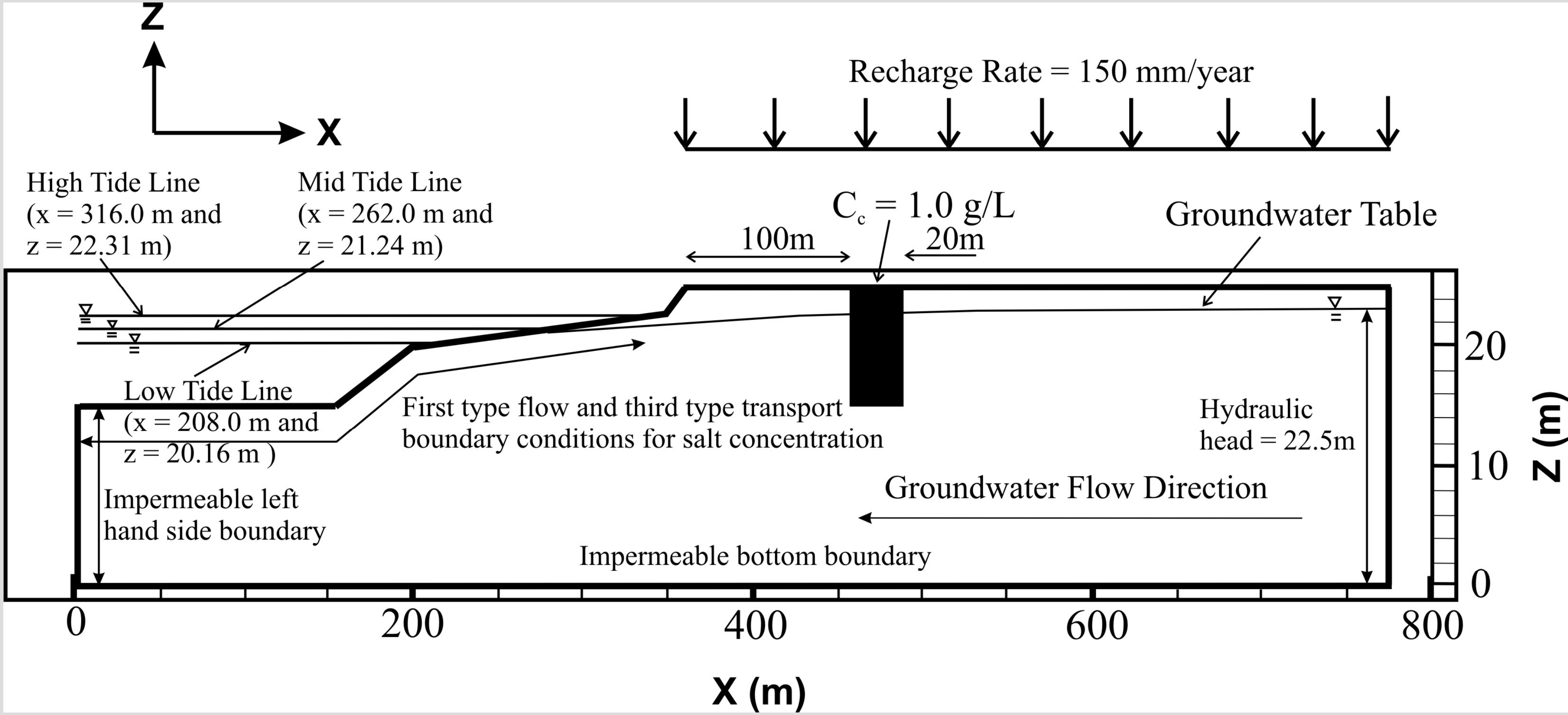
- Flow derived from Pit Lake water balance and infiltration estimates (sustained flow system) = 10 Mm^3/yr
- C_{AVG} based on average values measured in upper 20 m of wells in the Beach Dump

Steady State Estimate of Loadings to Rupert Inlet

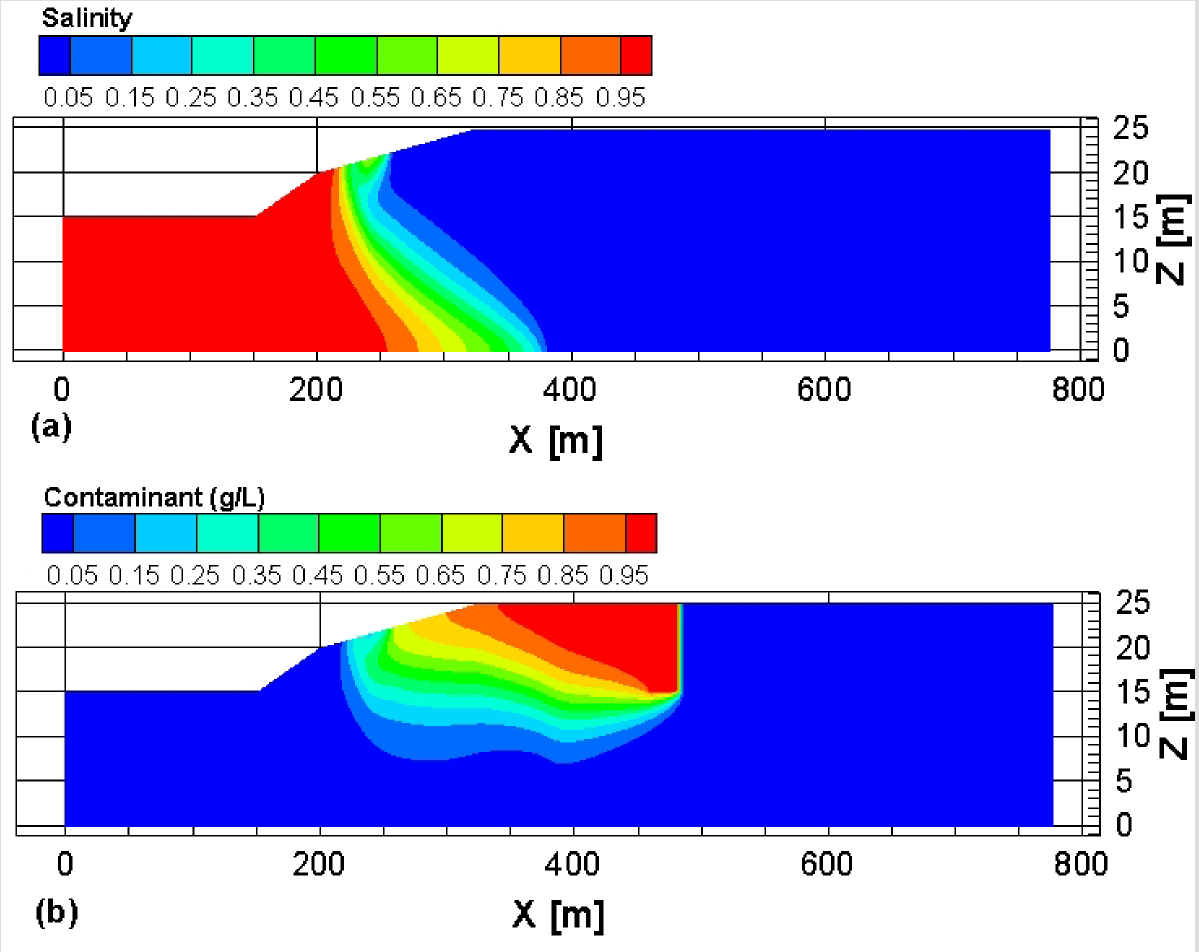
(kg/year)

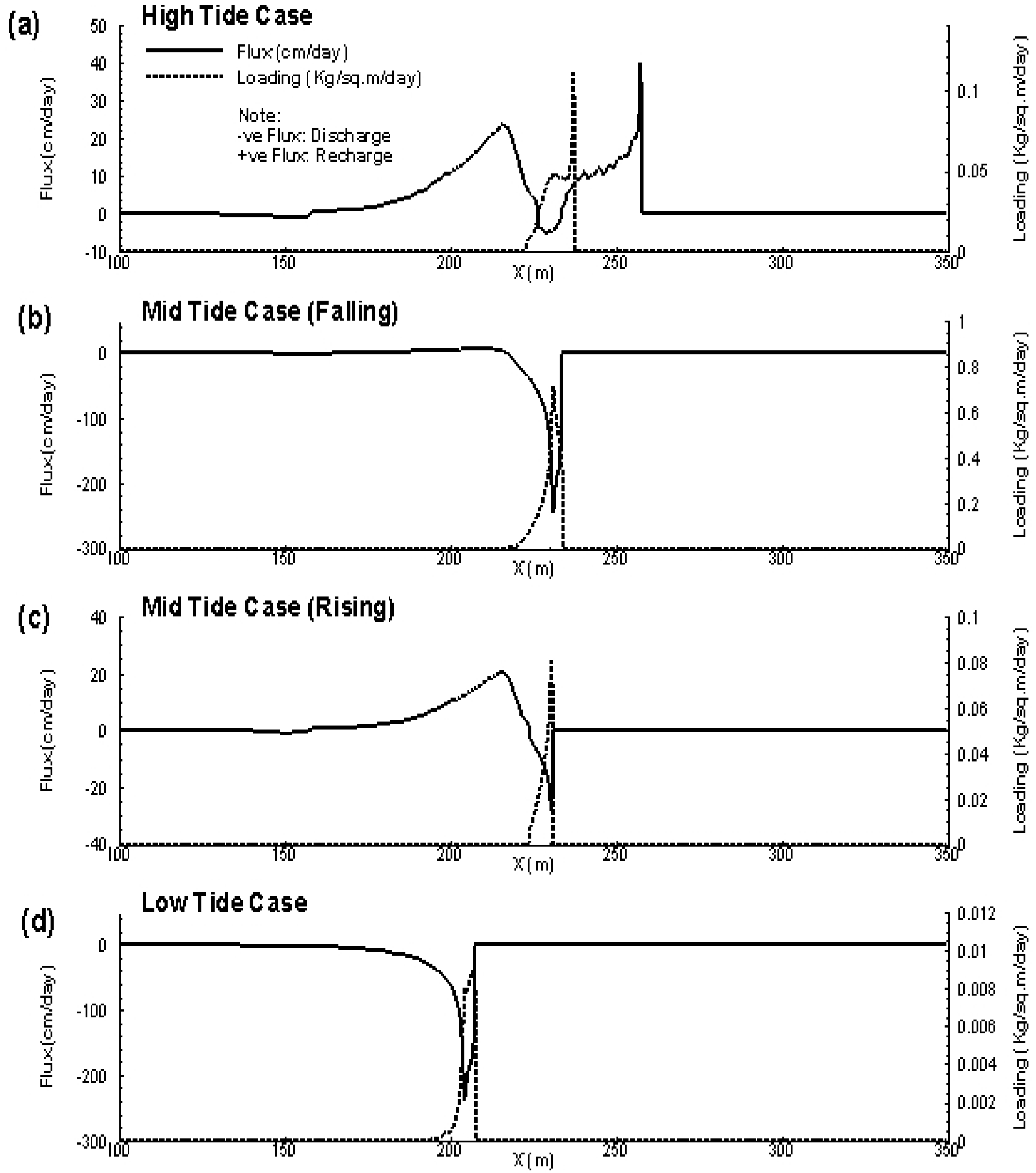
	Average	Upper Bound
Zinc	4000	8000
Copper	150	300

Synthetic Simulations



Salt Water Interface





(a)
High Tide Case
Flux(cm/day)
Loading (Kg/sq.m/day)
Note:
-ve Flux: Discharge
+ve Flux: Recharge
50
40
30
20
10
0
-10
100
150
200
250
300
350
X(m)
0.1
0.05
0
Flux(cm/day)
Loading (Kg/sq.m/day)
(b)
Mid Tide Case (Falling)
0
-100
-200
-300
1
0.8
0.6
0.4
0.2
0
(c)
Mid Tide Case (Rising)
40
20
0
-20
-40
0.1
0.08
0.06
0.04
0.02
0
(d)
Low Tide Case
0
-100
-200
-300
0.012
0.01
0.008
0.006
0.004
0.002
0

Dilution Factors at Seepage Face for Scenario Shown Here

- Averaged over the tidal cycle and calculated relative to the source concentration

High tide line	1.6
Mid-tide line	3.5
Low tide line	560

Summary

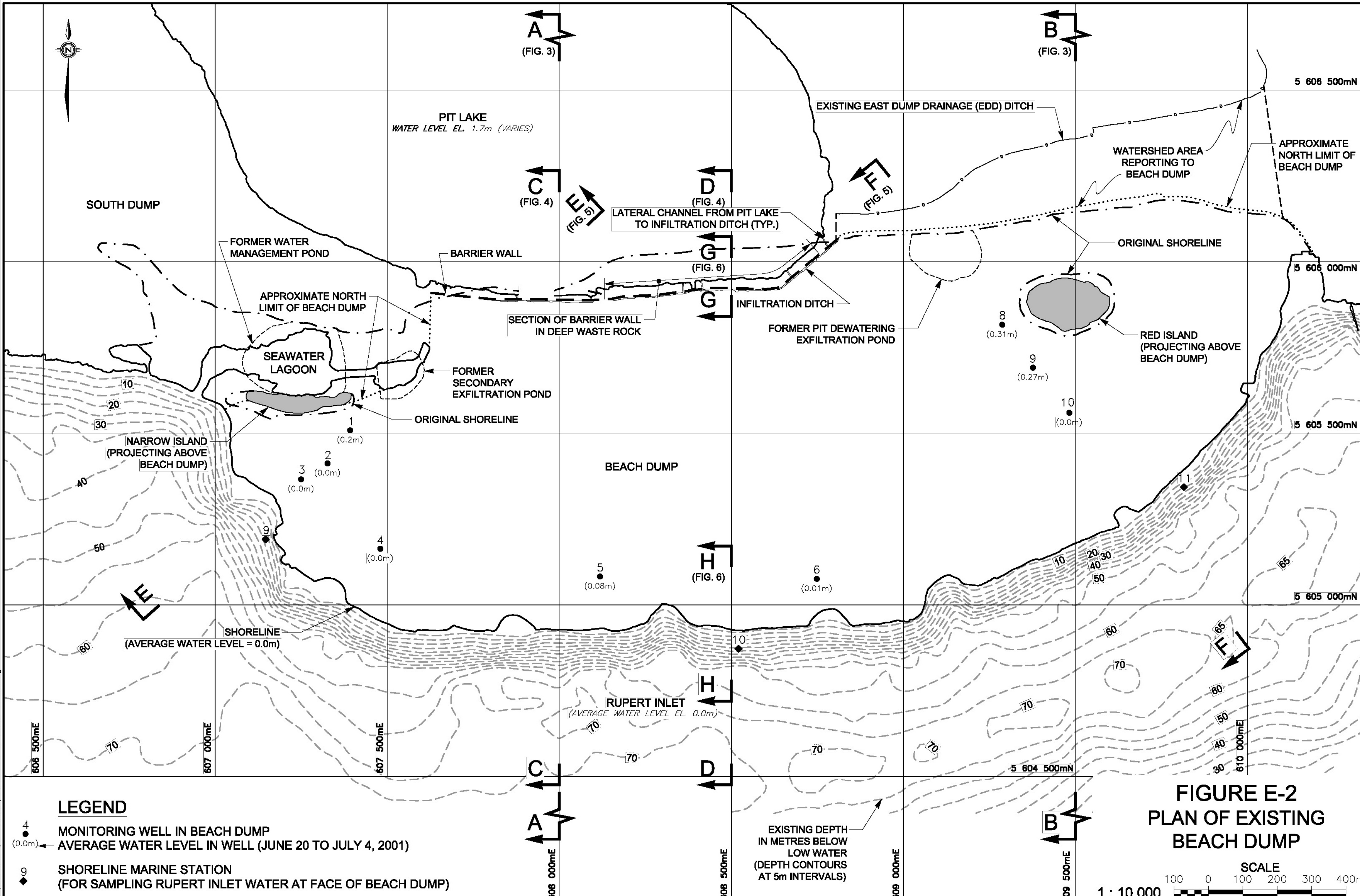
- In general, tidal water sites are challenging systems to monitor and analyze due to complex hydrodynamics and salinity effects

- Reliable estimates of steady state loading at Island Copper Mine have been developed by focusing on large-scale behaviour

Summary

- Modeling suggests the majority of contaminants discharge across the intertidal zone, not below the low tide line
- The variation in loading during a tidal cycle is strongly dependent on the interaction of the migrating seepage face across the intertidal zone with the spatial distribution of mass within the groundwater plume

Acknowledgements: BHP Billiton, NSERC



LEGEND

4 (0.0m) — MONITORING WELL IN BEACH DUMP; AVERAGE WATER LEVEL IN WELL (JUNE 20 TO JULY 4, 2001)

9 ◆ — SHORELINE MARINE STATION (FOR SAMPLING RUPERT INLET WATER AT FACE OF BEACH DUMP)

FIGURE E-2
PLAN OF EXISTING BEACH DUMP

Water Quality

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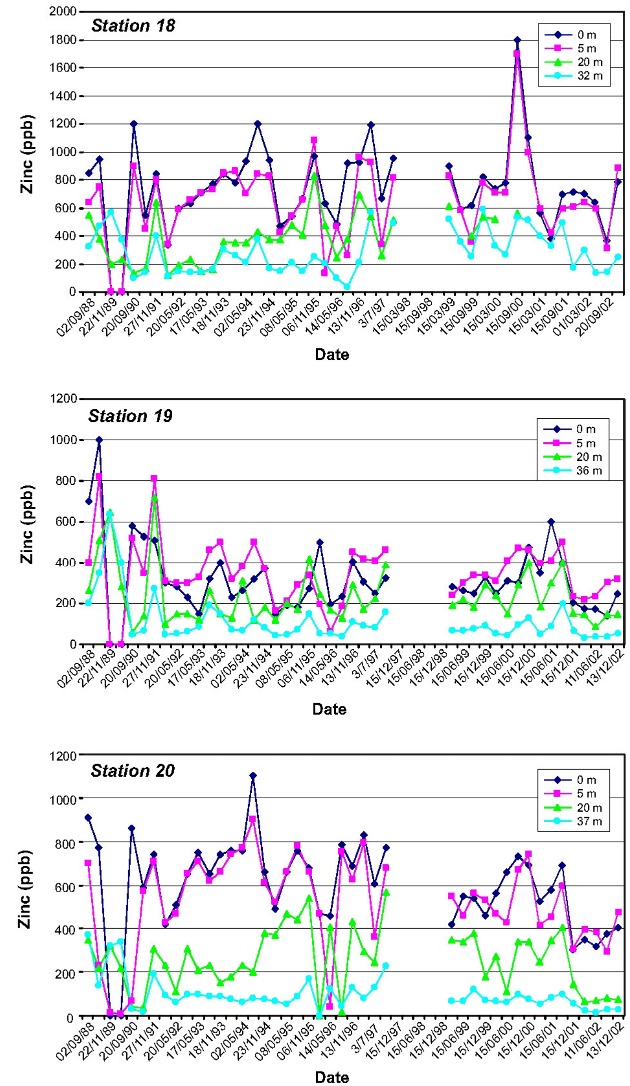

FIGURE E-38

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Historical Zinc Concentrations for Beach Dump Wells at Stations 18, 19 and 20, 1988 - 2002