10.4 Reproduction Analysis of Present Situation

10.4.1 Change of the Sea coast Line

(1) Analysis with Aerial Photographs

The change in topography was studied by analyzing aerial photographs.

The aerial photographs of Nadi in Fiji taken in four different years, 1986, 1994, 2009 and 2014, were collected and used in this analysis. Figure 10-46 and Figure 10-47 show the aerial photographs of the 25km-long coastal area among the collected photographs. Figure 10-48 and Figure 10-49 show the shoreline profiles interpreted on them.

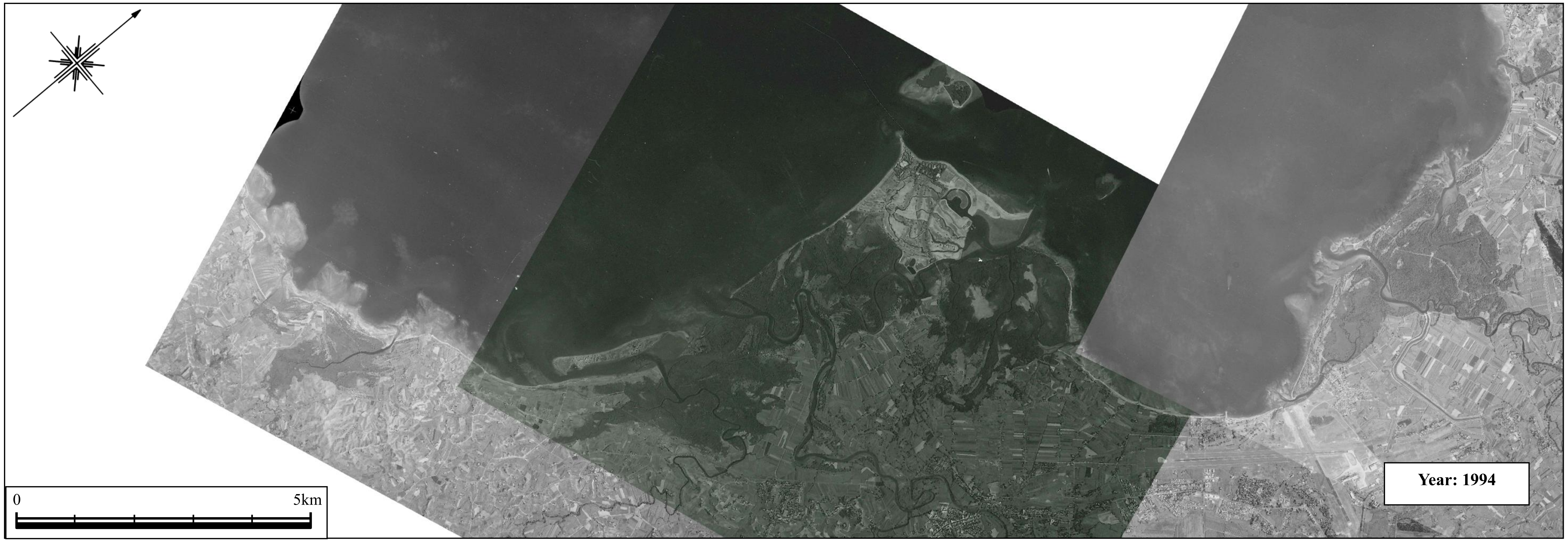


Figure 10-46 Aerial Photographs (taken in 1986 and 1994)

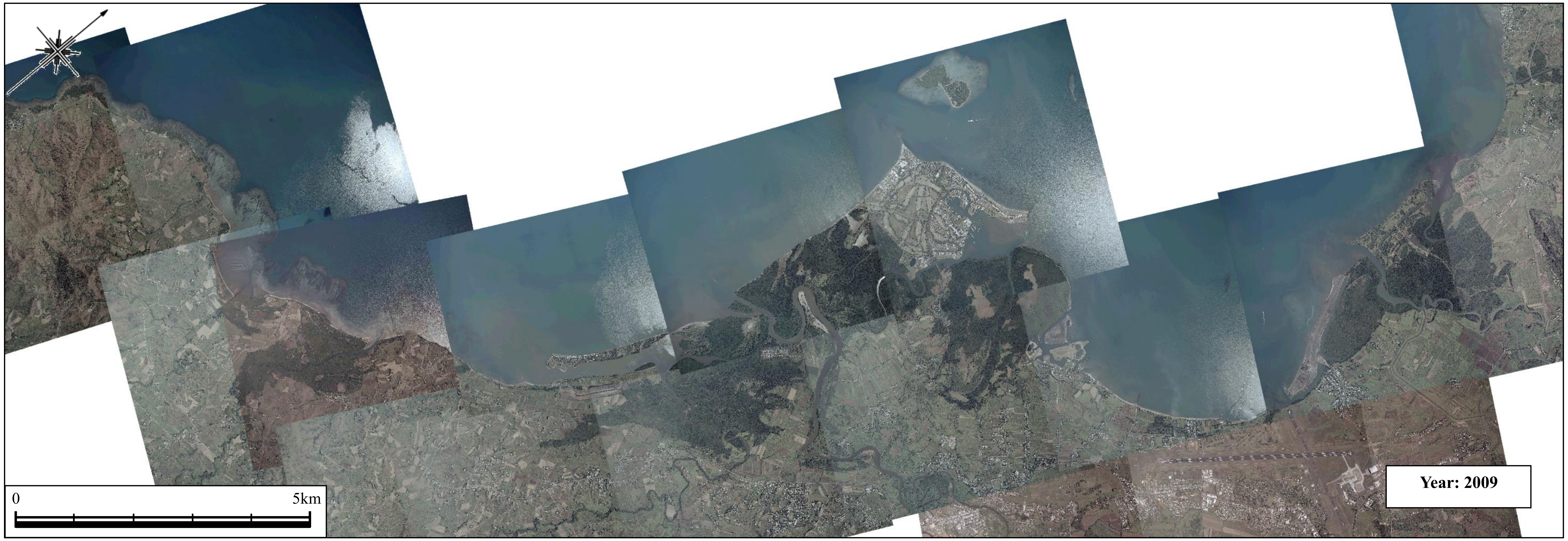


Figure 10-47 Aerial Photographs (taken in 2009 and 2014)

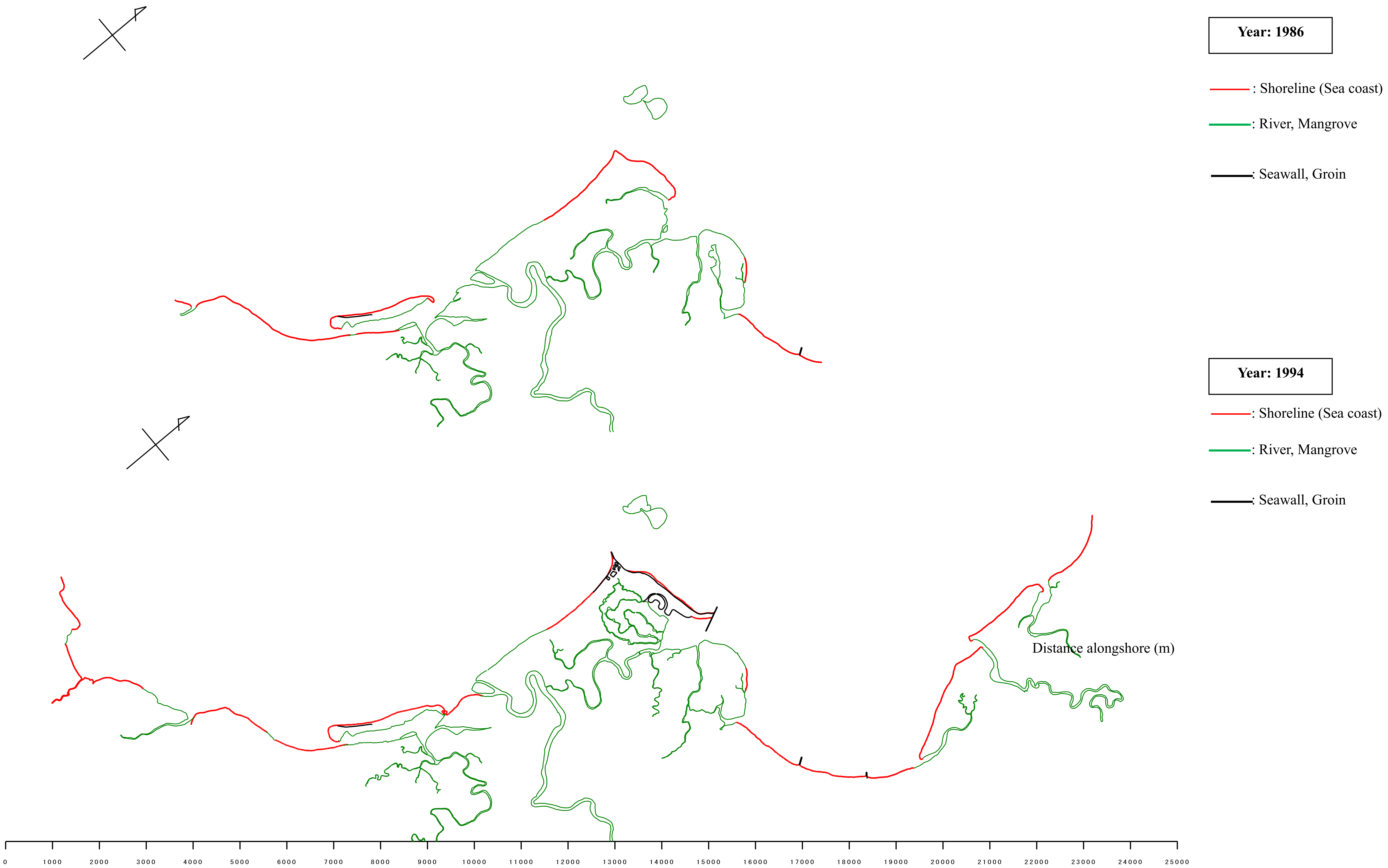


Figure 10-48 Sea coast Profiles Interpreted on Aerial Photographs (taken in 1986 and 1994)

Figure 10-49 Sea coast Profiles Interpreted on Aerial Photographs (taken in 2009 and 2014)

(2) Quantitative Changes of the Shoreline

1) Shoreline around the Estuary of the Nadi River

Figure 10-50 shows the quantitative changes of the shoreline around the estuary of the Nadi River between 1986 and 1994, between 1994 and 2009 and between 2009 and 2014.

Figure 10-51 shows the total quantities of the change of the shoreline between the reference year 1986 and 1994, 1986 and 2009, 1986 and 2014, and between the reference year 1994 and 2009, 1994 and 2014.

The conditions of the sea coast derived from these changes from 1994 are summarized in Table 10-22. The areas codes A1, A2 and A3 used in the table are shown in Figure 10-50.

Table 10-22 Changes of Shoreline around Estuary of Nadi River

	A-3	A-2	A-1
– 1994	The direction of the littoral drift sand transport was from north to south along the sea coast. The Nadi River is considered to have been the source of the sediment.	The sandbar located to the south of the estuary of the Nadi River was extended toward the estuary to the extent that it was almost connected to the main island.	Recession of the shoreline by erosion was observed southward from the tip of the cape. The direction of the littoral drift sand transport was from north to south along the sea coast.
– 2009	Partial recession of the shoreline caused by erosion was observed before 1994. No significant change seems to have occurred since 2009.	Recession of the shoreline by erosion was observed in the middle part of the sandbar.	The shoreline has moved a little toward the sea since 1994 presumably because of the sea coast nourishment implemented together with the construction of hotels.
– 2014		The sea coast nourishment was carried out together with the construction of hotels.	

2) Shoreline in Nadi Bay

Figure 10-52 shows the quantitative changes of the shoreline on the eastern side of Nadi Bay between 1994 and 2009 and between 2009 and 2014 and the total change between the reference year 1994 and 2009, 1994 and 2014.

The conditions of the sea coast derived from these changes are summarized in Table 10-23. The areas designated by the codes used in the table are shown in Figure 10-50 and Figure 10-52.

Table 10-23 Changes of Shoreline in Nadi Bay

	B-0	B-1	B-2	B-3	B-4
– 2009	Reclamation has extended the sea coast to the east and the sea coast nourishment implemented together with the reclamation has advanced the shoreline seaward since 1994.	Land development has been implemented.	A slight erosion of the shoreline was observed in the period between 1994 and 2009.	Erosion caused the recession of shoreline in the period between 1994 and 2009. The direction of the littoral drift sand transport was from north to south along the sea coast.	The direction of the littoral drift sand transport was from north to south along the sea coast.
– 2014			Little change in the shoreline has been observed since 2009.	The shoreline has been restored with the construction of a groin and sea coast nourishment. The sea coast downstream of a groin in the middle of the sea coast has been slightly eroded.	

3) Shoreline in Nadi Bay

The results of the bathymetric survey of current shoreline are shown in Figure 10-53 and Figure 10-54.

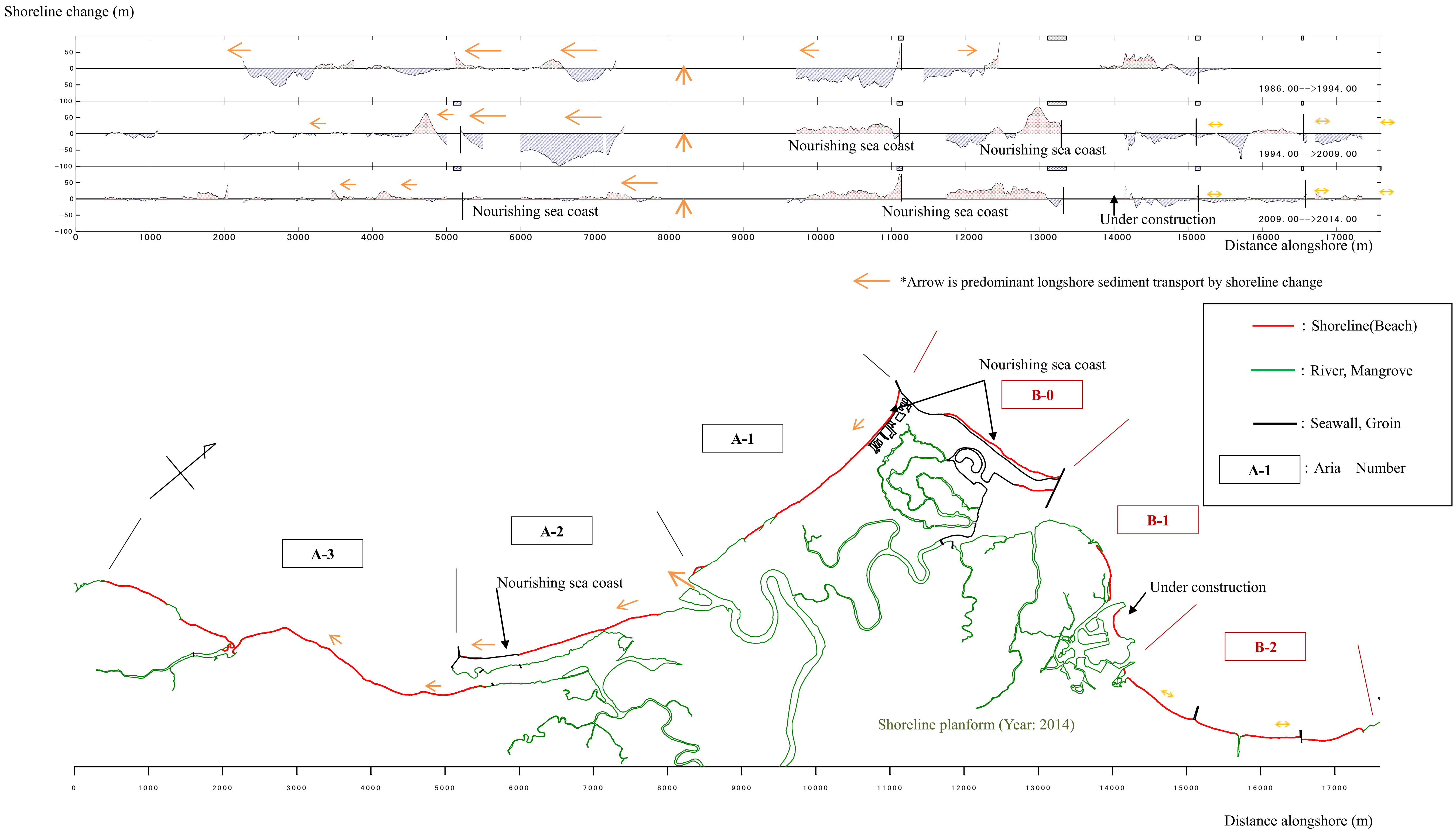


Figure 10-50 Quantitative Changes in Shoreline Detected with Aerial Photographs (near the estuary of the Nadi River: quantitative changes in shoreline between the years of the photography)

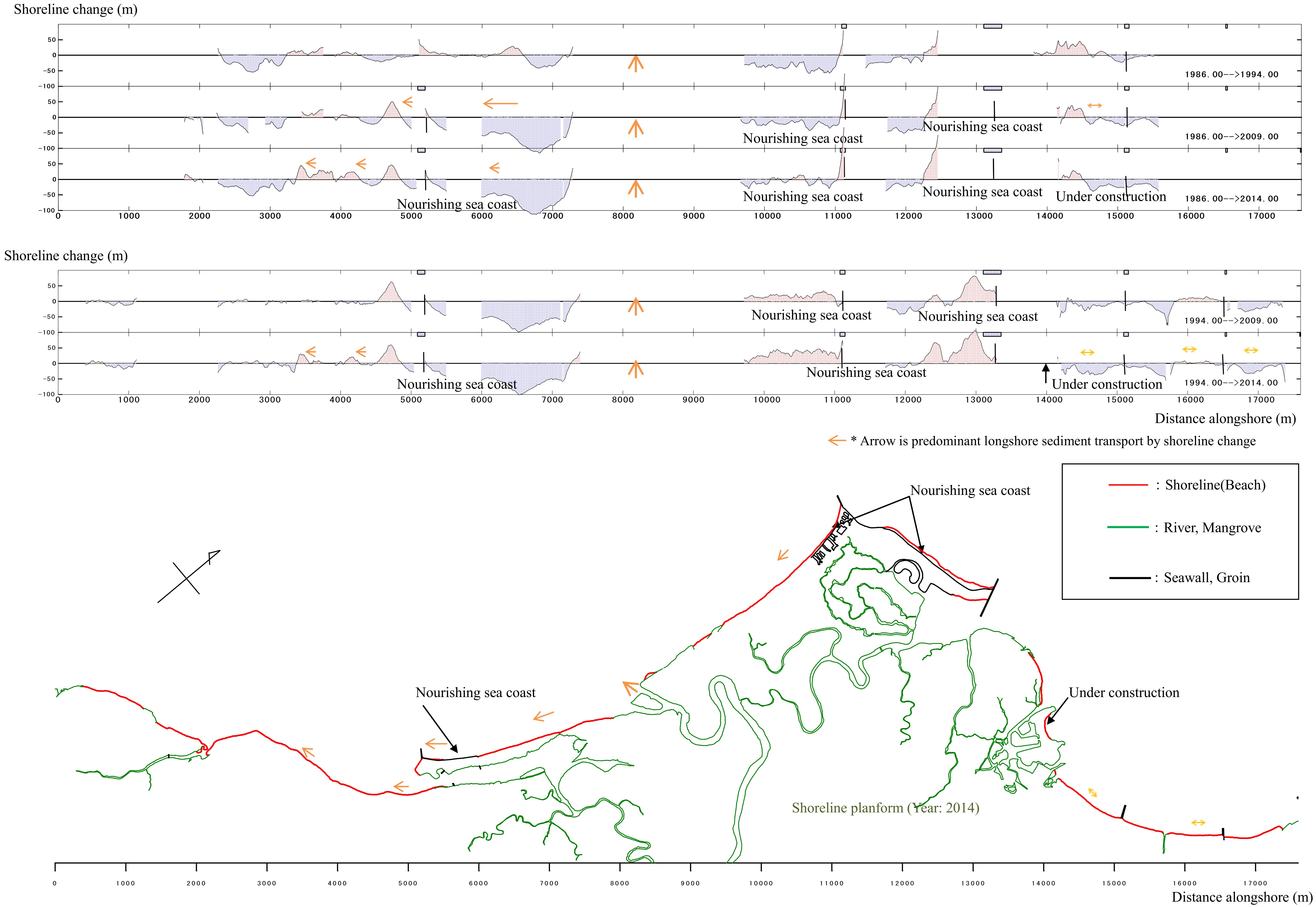


Figure 10-51 Quantitative Changes in Shoreline Detected with Aerial Photographs (near the estuary of the Nadi River: quantitative changes in shoreline since 1986 and 1994)

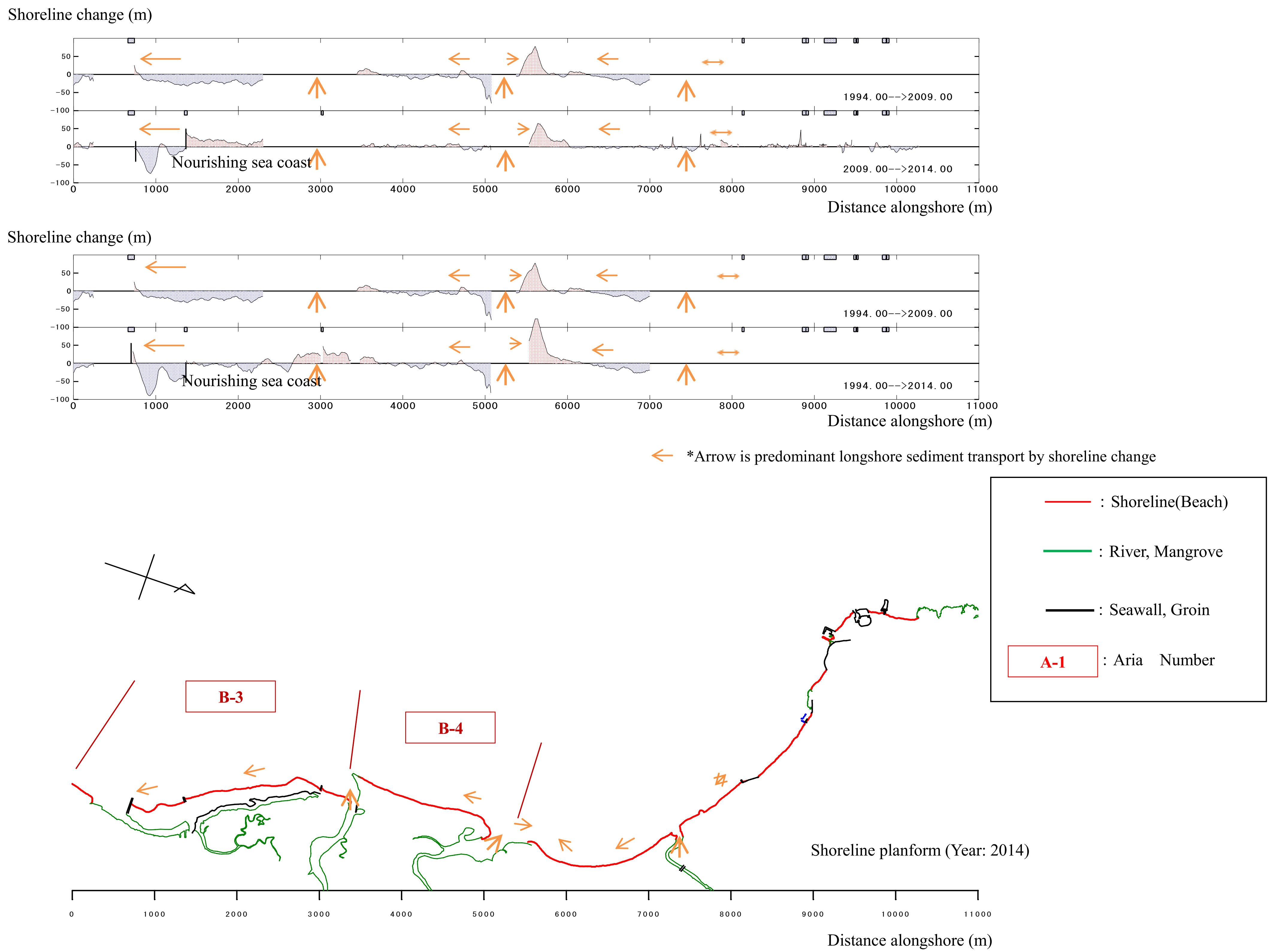


Figure 10-52 Quantitative Changes in Shoreline Detected with Aerial Photographs (in Nadi Bay: quantitative changes in shoreline between the years of the photography and since 1994)

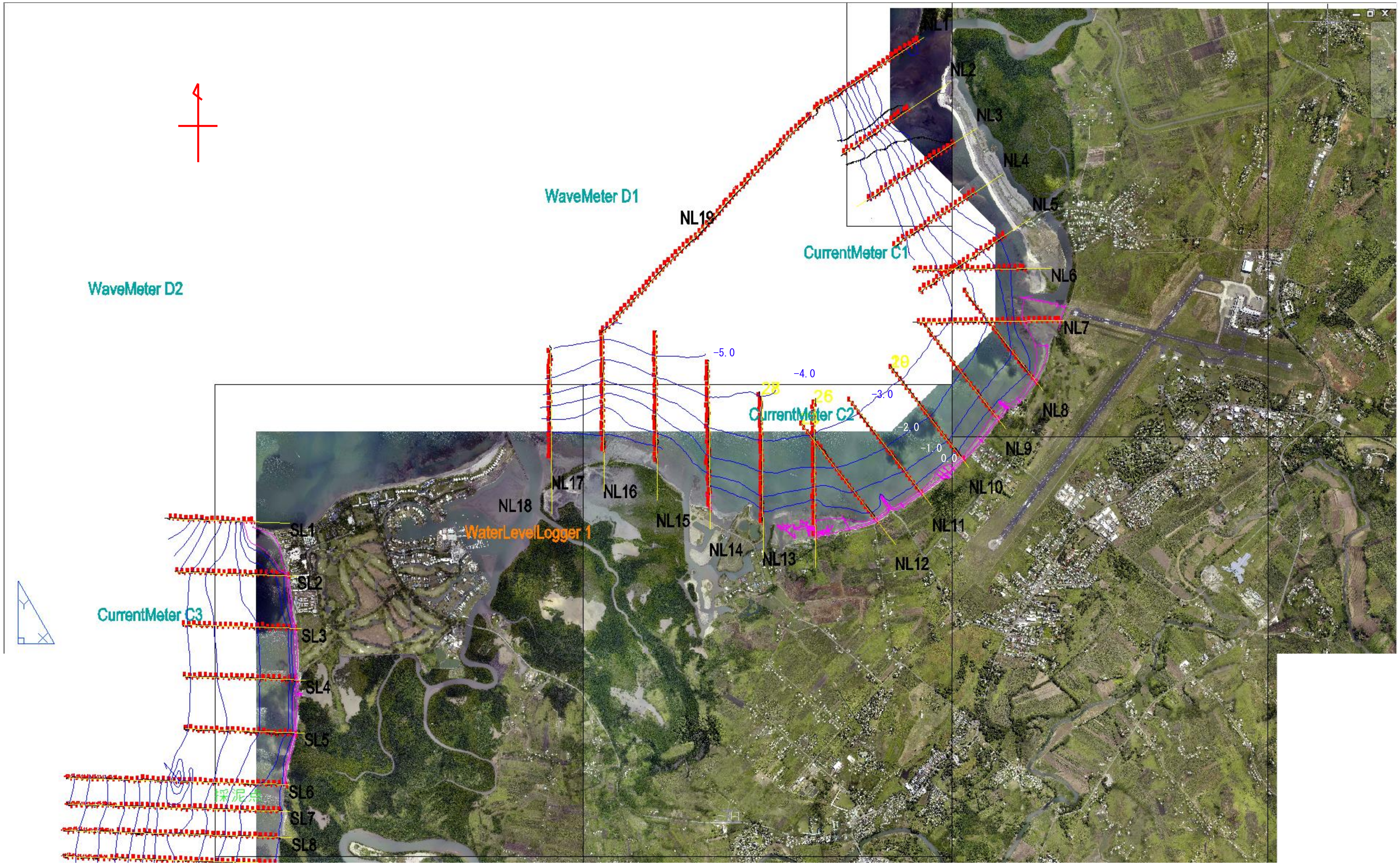


Figure 10-53 Bathymetric Chart of Nadi Bay

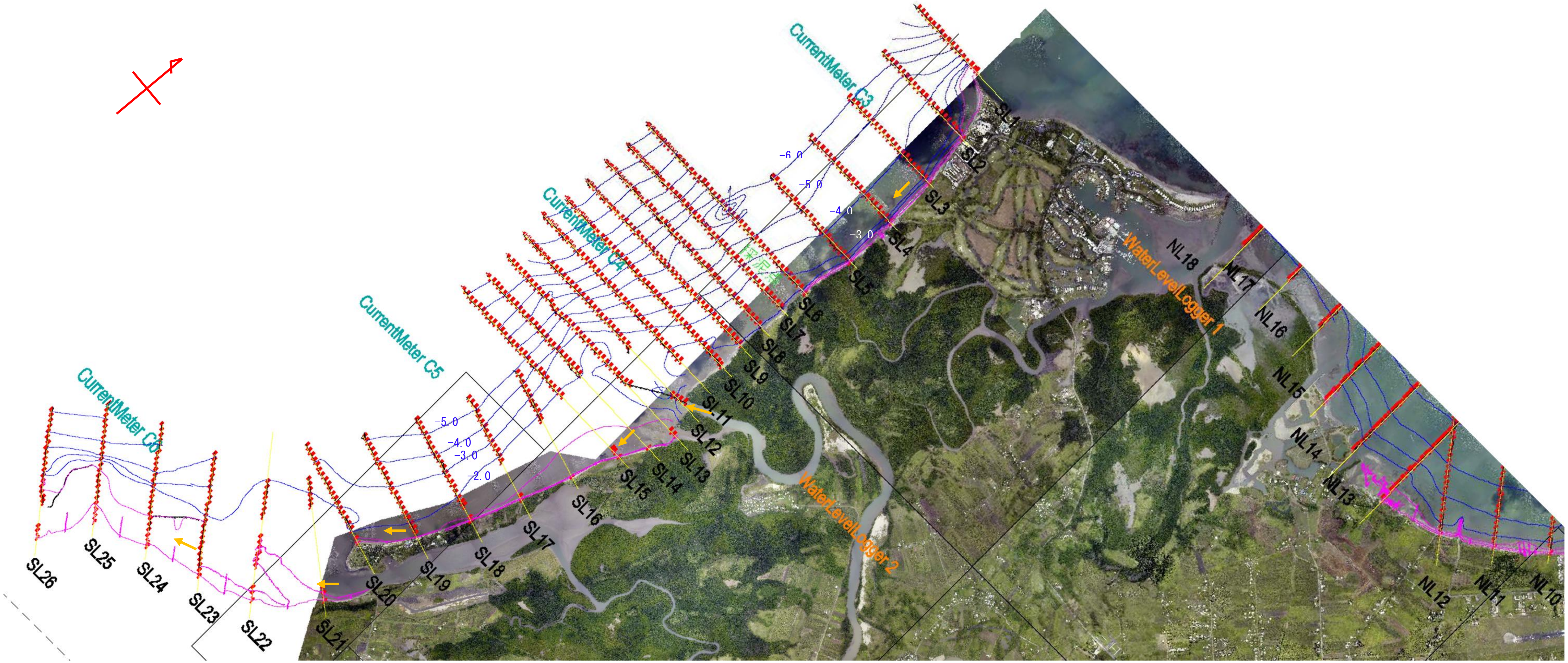


Figure 10-54 Bathymetric Chart near Estuary of Nadi River

10.4.2 Reproduction Analysis of Present Situation

(1) Sea coast Profile Change Model

1) Model Used in the Study

It was decided to forecast the change in the shorelines near the estuary of the Nadi River and in Nadi Bay with a sea coast profile change model, in order to examine the potential influence of flood control measures to be taken on the Nadi River on the shorelines.

"The Counter Line Change Model (N-line Model)" was chosen for the analysis because the model can forecast the long term sea coast profile change and evaluate the influence of sediment discharge from the river considering the particle distribution of seabed materials.

2) Outline of the Counter Line Change Model

The Counter Line Change Model (N-line Model) was originally proposed by Perlin and Dean (1978). Uda et al. have used this model to predict change on natural sea coasts, sea coasts with groins, sea coasts with seawalls and sea coasts behind large breakwaters by defining vertical distribution of the alongshore sediment transport with measured (and experimental) data (1990a,1990b, 1993 and 1996).

The Counter Line Change Model uses the procedures principally identical to those used in the 1-line model: An alongshore sediment transport rate is estimated from various wave breaking parameters. The cross-shore and along shore distribution of the estimated rate of transport are used for the estimation of sediment transport rate on each contour line. The rate on each contour line is used for the prediction of the change in the contour line. Equation (1) is the basic equation. The conceptual diagram and calculation flow are shown in Figure 10-55 and Figure 10-56, respectively.

$$h_k \frac{\partial y_k}{\partial t} + \left[\frac{\partial Q_k}{\partial x} - q \right] = 0$$ Equation (1),

where h, y, t, Q, x, q and k are vertical movement of sediment, contour line position, time, alongshore sediment transport rate, alongshore coordinate, supply/loss of sediment and contour line numbers (k = 1, 2, ·····N), respectively.

Vertical movement of sediment: $h_k = z_k - z_{k-1}$

Sediment transport rate at each water depth: $Q_k = \mu_k \cdot Q$

Coefficient giving an alongshore sediment transport rate at each water depth:

$$\mu_k = \int_{Z_k}^{Z_{k+1}} \xi(z)dz \Big/ \int_{-h_c}^{h_R} \xi(z)dz \text{ ,}$$

where ξ(z), z, hR and hC are a function giving the sediment transport rate at each water depth, elevation from the still water level, the limit of elevation on the landward sediment transport and the limit of water depth on the seaward sediment transport, respectively.

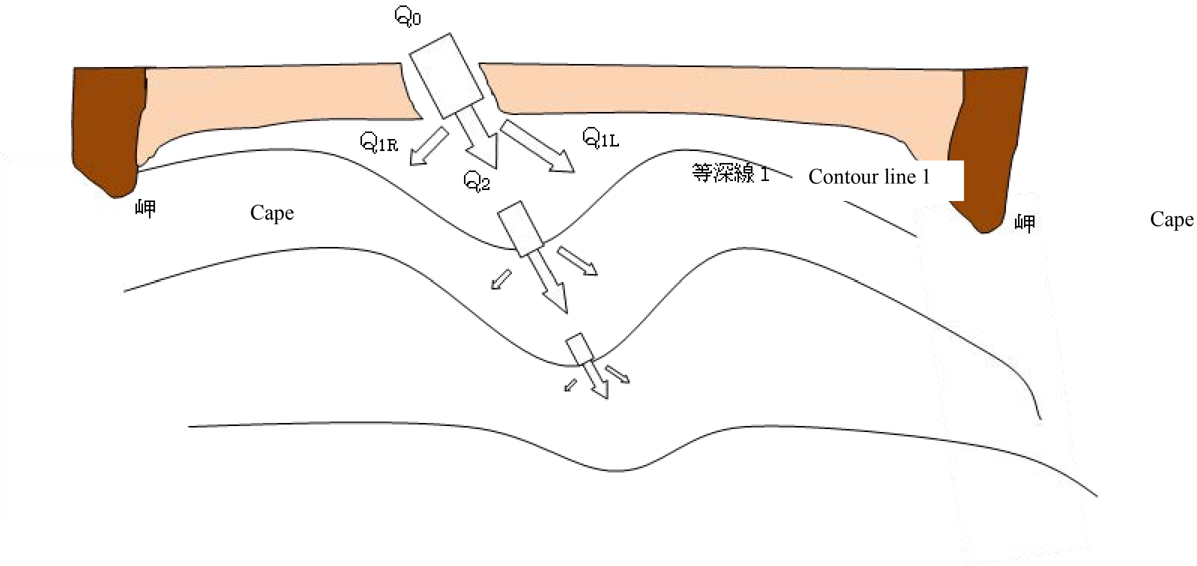


Figure 10-55 Conceptual Diagram of the Counter Line Change Model

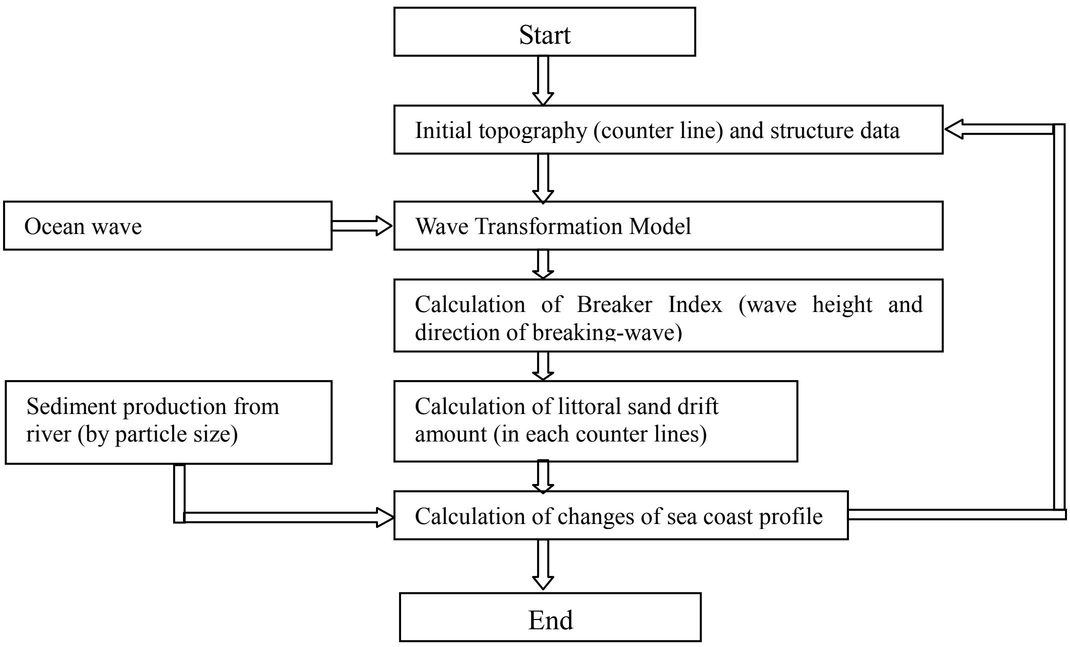


Figure 10-56 Calculation Flow of the Contour Line Change Model

3) Analysis Cases

The table below shows the two cases for which analysis was conducted. One was the case of reproduction of the current state and the other was the case of forecasting the changes without flood control measures.

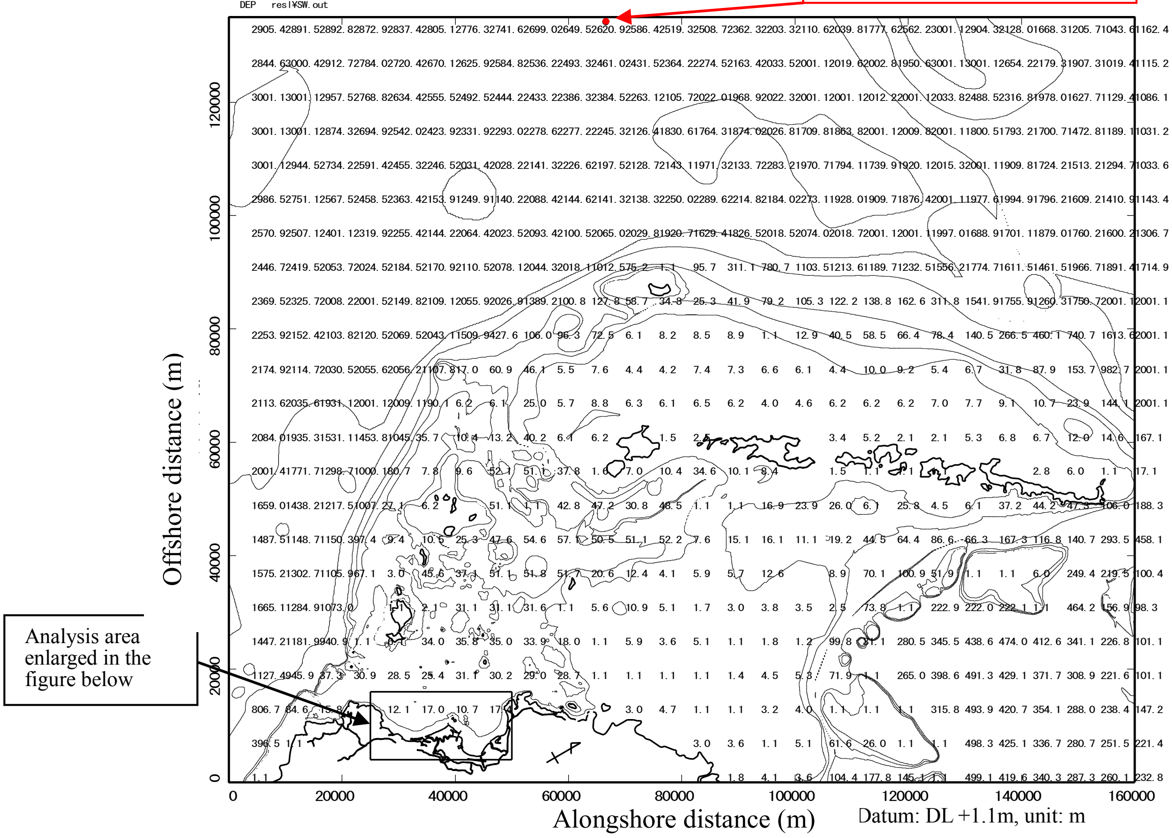
Table 10-24 Cases for Sea coast Profile Change Analysis

Analysis case	Description	Remarks (Utilized Data)
Reproduction of the current state	Calculation for the reproduction of the sea coast profile change from the past to the present (for the verification of the model)	a) Current topography (hydrographic charts + bathymetry) Existing shorelines (shoreline surveying in Aug. 2014 and Feb. 2015) Hydrographic charts of the seas around the island b) Shorelines in the past Aerial photographs, partial (Sep. 2009) Aerial photographs, partial (Aug. 1994) Aerial photographs, small-range (1986, month unknown) c) Shoreline changes near a structure (groin) Depth difference at both sides of the groin Aerial photographs mentioned above (Groin N1 is on a photograph taken in 1986. Therefore, it was constructed before 1986.)
Case without flood control measures (forecasting)	Forecasting the changes with the existing conditions	Sediment discharge from Nadi River at its estuary: Utilize the result of Sediment Transport Analysis

(2) Conditions of Analysis of the Current State

1) Caliculation of Wave Transformation

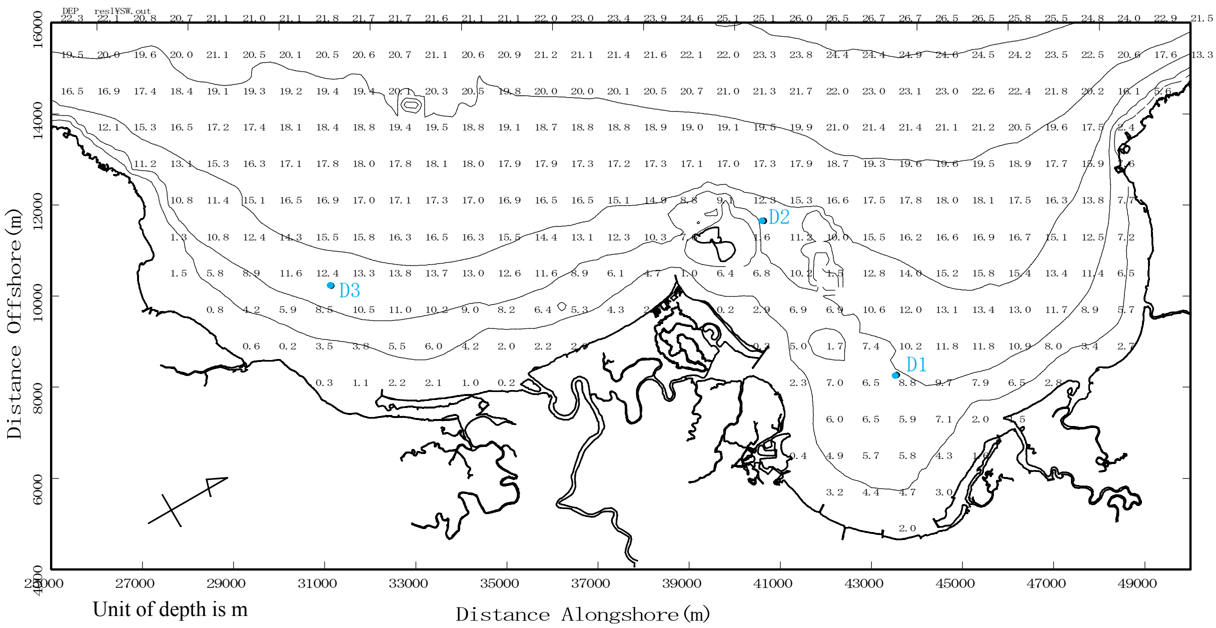
a) Analysis Area and Topographical Condition



Datum: DL +1.1m, unit: m

The contour lines in the figure represent isobaths.

Figure 10-57 Area for Wave Transformation Analysis and Bathymetric Chart (overall view)



Unit of depth is m

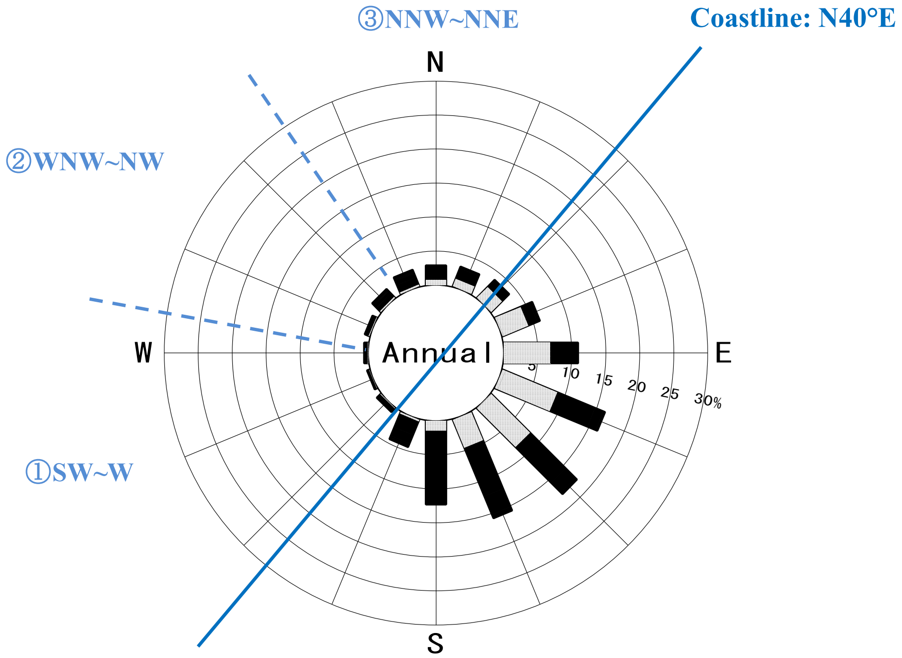
Contour line is depth

Figure 10-58 Area for Wave Transformation Analysis and Bathymetric Chart (analysis area enlarged)

b) Ocean Wave Conditions

Shore line changes are caused by waves from Ocean. Conditions of wave from Ocean are high in wave height and long cycle period components are included.

Energy-averaged waves representing annual wave energy and MSL are used in the Contour Line Change Model for long-term forecasting of sea coast profile changes. Figure 10-59 shows the representative ranges of the wave direction established with the ocean wave predicted data. An energy-averaged wave in each direction range was calculated.



	Direction	Mean Angle	Mean Height	Mean Period
①	SW～W	N241°E	2.60m	9.12s
②	WNW～NW	N312°E	2.85m	8.49s
③	NNW～NNE	N355°E	2.54m	8.95s

Figure 10-59 Representative Wave for Contour Line Change Calculation

Table 10-25 Monthly Incidence in Representative Ranges of Wave Direction

	SW～W					WNW～NW					NNW～NNE				
	Rate P1(%)	Height H(m)	Period T(s)	Energy Rate P2(%)	Action Days	Rate P1(%)	Height H(m)	Period T(s)	Energy Rate P2(%)	Action Days	Rate P1(%)	Height H(m)	Period T(s)	Energy Rate P2(%)	Action Days
Annual	1.66	2.60	9.12			2.43	2.85	8.49			7.76	2.54	8.95		
JAN	2.47	2.75	9.24	2.80	0.9	10.89	2.41	8.99	8.26	2.6	46.42	2.28	9.31	38.96	12.1
Feb	3.81	2.37	9.24	3.21	0.9	8.69	3.02	8.60	9.90	2.8	26.45	2.61	8.73	27.28	7.6
Mar	6.56	2.61	9.54	6.91	2.1	5.59	3.38	8.09	7.51	2.3	14.70	3.47	8.79	26.98	8.4
Apr	1.08	1.99	9.10	0.63	0.2	2.81	3.27	7.99	3.49	1.0	2.69	2.53	8.44	2.52	0.8
May	1.13	2.07	7.95	0.62	0.2	0.19	1.71	7.01	0.06	0.0	0.13	1.66	7.04	0.04	0.0
Jun	1.17	2.57	8.56	1.07	0.3	0.42	2.55	7.57	0.30	0.1	0.61	2.29	7.11	0.39	0.1
Jul	2.42	2.26	8.74	1.75	0.5	0.73	2.10	7.10	0.33	0.1	0.83	2.14	6.21	0.41	0.1
Aug	0.00	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.00	0.0
Sep	0.39	2.35	10.97	0.38	0.1	0.00	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.00	0.0
Oct	0.48	2.23	9.66	0.37	0.1	0.24	2.13	9.53	0.15	0.0	2.39	2.18	9.77	1.92	0.6
Nov	1.28	2.18	7.95	0.78	0.2	1.28	2.63	7.51	0.97	0.3	4.83	2.17	8.03	3.17	1.0
Dec	0.62	5.57	8.91	2.78	0.9	0.00	0.00	0.00	0.00	0.0	5.17	1.82	8.63	2.56	0.8
total					6.5					9.3					31.4

*）Energy Rate(P2)=（Power of Monthly Height×Monthly Period×Rate P1）／（Power of Annual Height×Annual Period）

Definition of Mean Wave

Energy-averaged Waves are calculated using the following equations:

$$\text{Height } \tilde{H} = \sqrt{\frac{\sum_{i=1}^{N}\left(H_i^2 \cdot T_i\right)}{\sum_{i=1}^{N} T_i}} \qquad \text{Period } \tilde{T} = \frac{\sum_{i=1}^{N}(T_i)}{N} \qquad \textit{Angle } \tilde{\theta} = \frac{\sum_{i=1}^{N}\left(\theta_i \cdot H_i^2 \cdot T_i\right)}{\sum_{i=1}^{N}\left(H_i^2 \cdot T_i\right)}$$

N: Number of data

The conditions for the analysis mentioned above are compiled in Table 10-26.

Table 10-26 Conditions for Wave Transformation Analysis

Item	Conditions	
Region for calculation	longshore	160km
	offshore	135km
Grid interval	ΔX = ΔY	200m
Wave	Angle① : N241°E, Ho=2.60m, T=9.12s, L_0=129.8, H_0/L_0=0.020	
	Angle② : N312°E, Ho=2.85m, T=8.49s, L_0=112.4, H_0/L_0=0.025	
	Angle③ : N355°E, Ho=2.54m, T=8.95s, L_0=125.0, H_0/L_0=0.020	
Tide	E.L.+0.00m (M.W.L)	
Spreading parameter	S_{max} = 25	
Segment of direction	36 (Δα = 5°)	
Segment of frequency	5	

The relationship between the wave spread parameter, Smax, and wave steepness, Ho/Lo, is shown in the table below as reference.

Wave steepness and Smax

	Wave steepness	S_{max}
Wind waves	H_0/L_0>0.03	S_{max}=10
Swell with short decay distance	0.03≧H_0/L_0>0.015	S_{max}=25
Swell with long decay distance	0.015≧H_0/L_0	S_{max}=75

Reference) "Guideline of design for fishing harbor facilities" 2003
National association of fisheries infrastructure

c) Reproducibility of Calculation Results

The heights and directions of the waves at the wave observation points D1, D2 and D3 calculated on the condition of the energy-averaged representative waves (refer Figure 10-59) being incident on the analysis area shown in Figure 10-57 and the heights and directions of the waves actually observed at these observation points were compared.

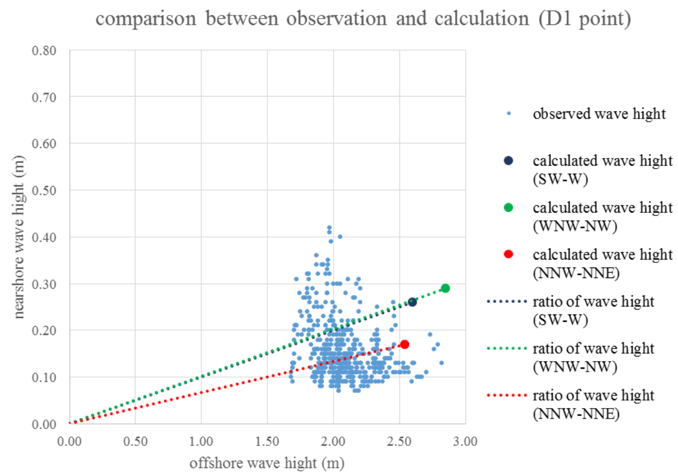
The wave transformation analysis with the representative waves has revealed that the deep-water waves reach the sea coast in the project area after being attenuated by reefs and small islets. While the deep-water waves have a height of 2.5m – 2.8m offshore, the waves have a height of 0.4m or less when they reach the waters in front of the target sea coast. The wave direction also changes to WSW – NNW, a direction almost perpendicular to the shoreline, there. When waves come closer to the sea coast, they change the course again to the direction more perpendicular to the shoreline.

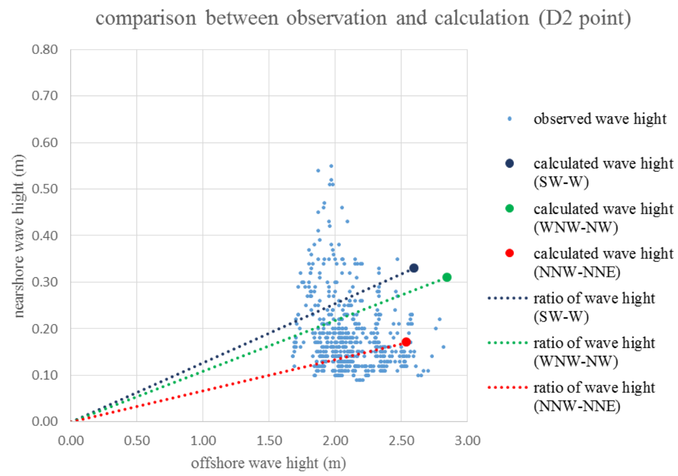
Figure 10-60, Figure 10-61 and Figure 10-62 show the comparison between the results of the wave transformation analysis and field observation data. Figure 10-60 shows the relationships between the heights of the deep-water waves obtained from the prediction database and the heights of the actual near-shore waves (observed at the observation points D1, D2 and D3). The figure also shows the wave heights and wave height ratios of the energy-averaged waves obtained in the wave transformation analysis. The figure suggests that the wave height ratios between the energy-averaged waves and the deep-water waves generally represent those between the observed waves and the deep-water waves, although the deviation of the latter ratios is somewhat large.

In Figure 10-61, the directions of the deep-water waves in the hindcasting database are plotted against the directions of nearshore waves (observed at the observation points D1, D2 and D3) and the wave direction obtained in the results of wave transformation analysis. The directions of most of the observed nearshore waves are in the range between WNW and NW. The wave directions obtained in the wave transformation analysis approximately represent the directions of the waves observed at the observation points, although the deviation is large.

Figure 10-62 shows the relationships between the frequency distributions of the observed waves and the result of the wave transformation analysis on the wave direction at the three observation points (D1, D2 and D3). The figure shows that, while the directions of the waves observed at the three observation points are predominantly WNW to NW, the wave direction in the result of the analysis converges to the same direction as the analysis points near the sea coast.

On the basis of the above-mentioned observations, it can be concluded that the nearshore waves calculated with the assumed energy-averaged offshore waves represent actual nearshore waves well.





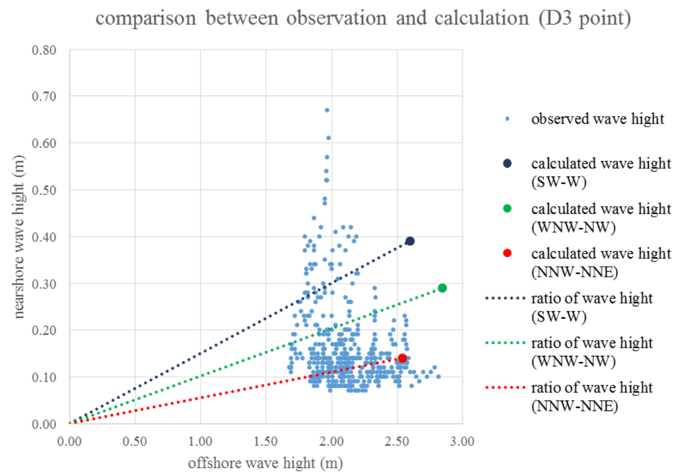


Figure 10-60 Comparison of Wave Height between Field Observation Data and Result of Wave Transformation Analysis

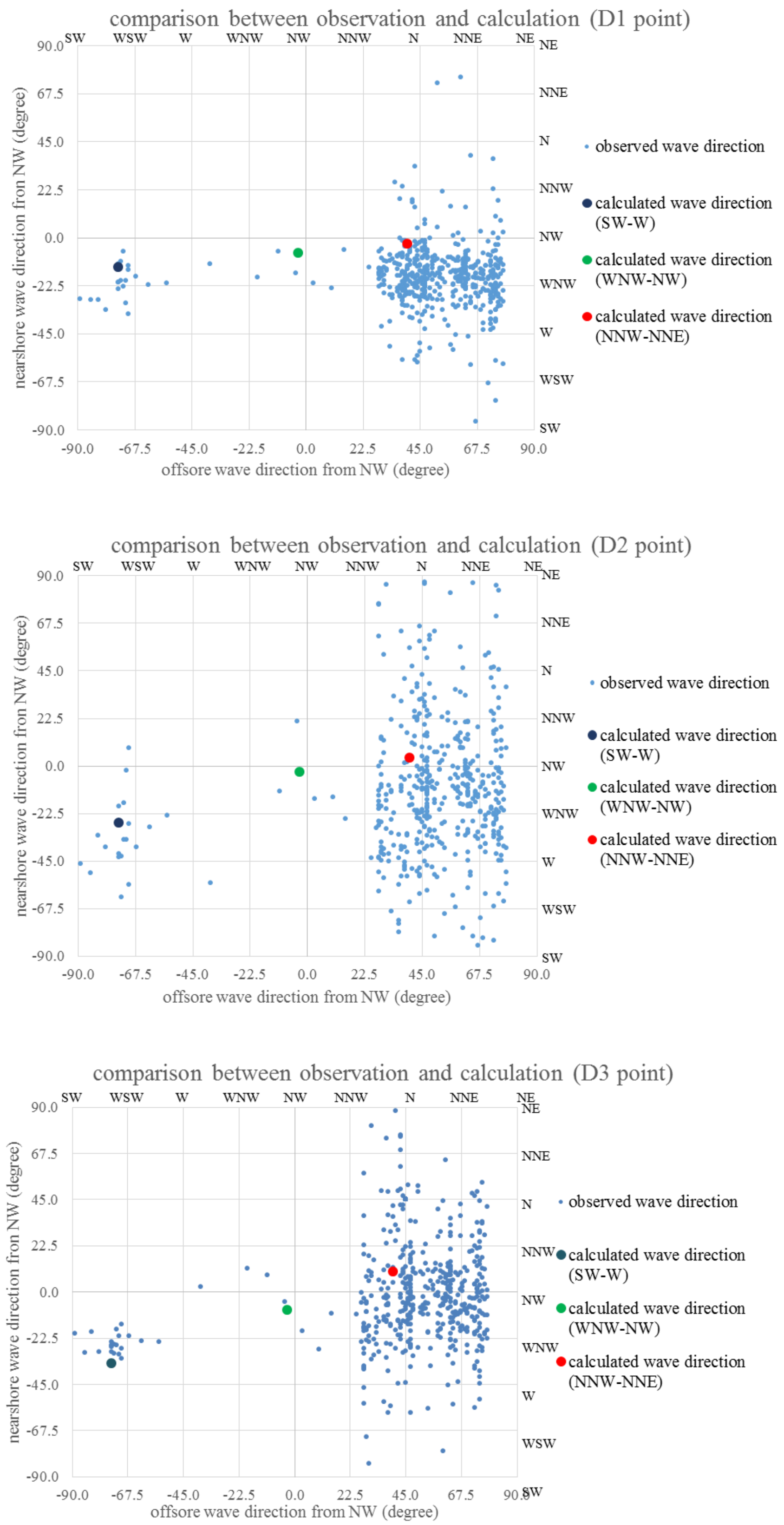
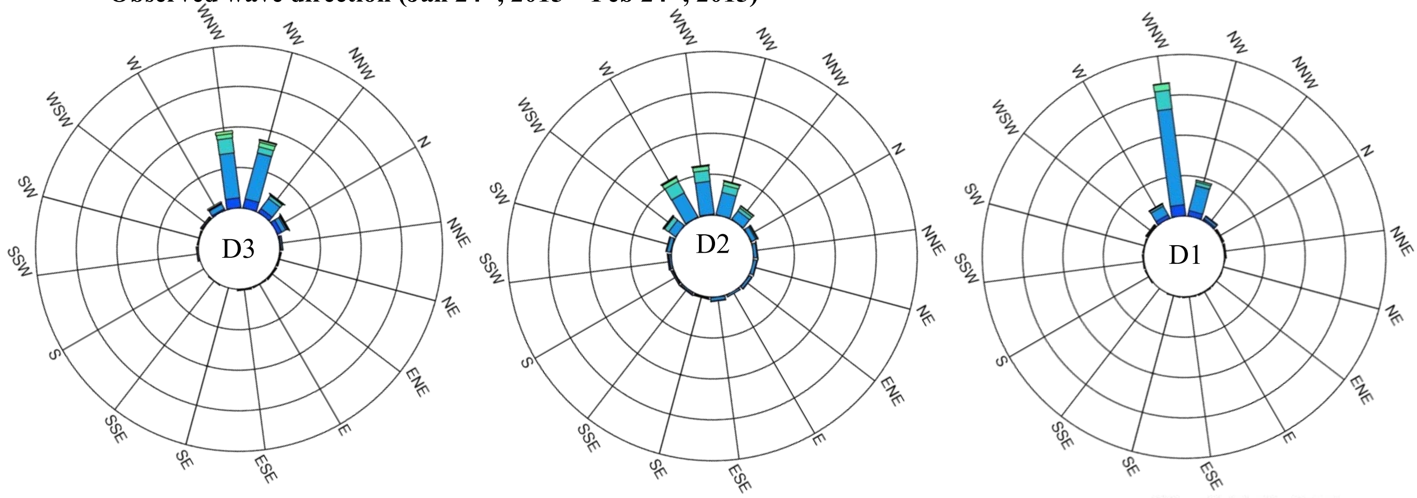
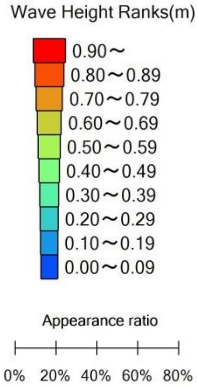


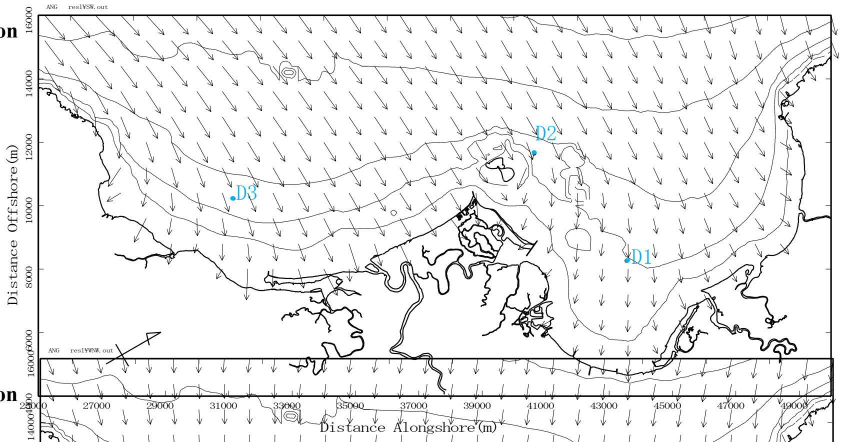
Figure 10-61 Comparison of Wave Direction between Field Observation Data and Result of Wave Transformation Analysis

Observed wave direction (Jan 24th, 2015 – Feb 24th, 2015)

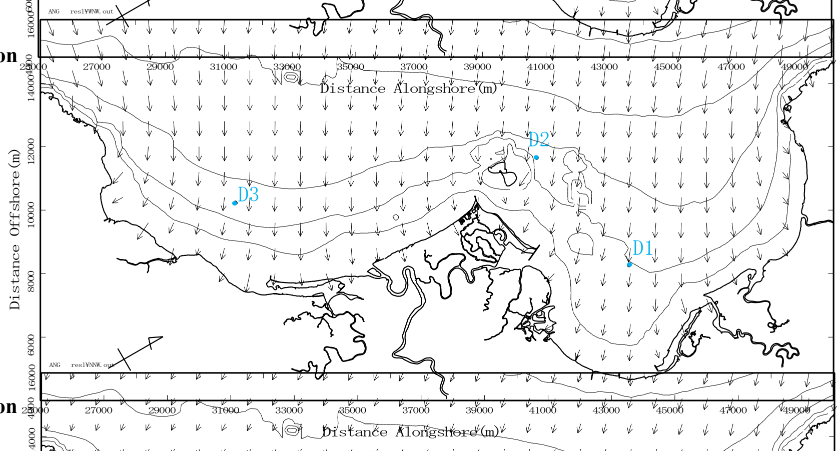




Calculated wave direction (SW – W)



Calculated wave direction (WNW – NW)



Calculated wave direction (NNW – NNE)

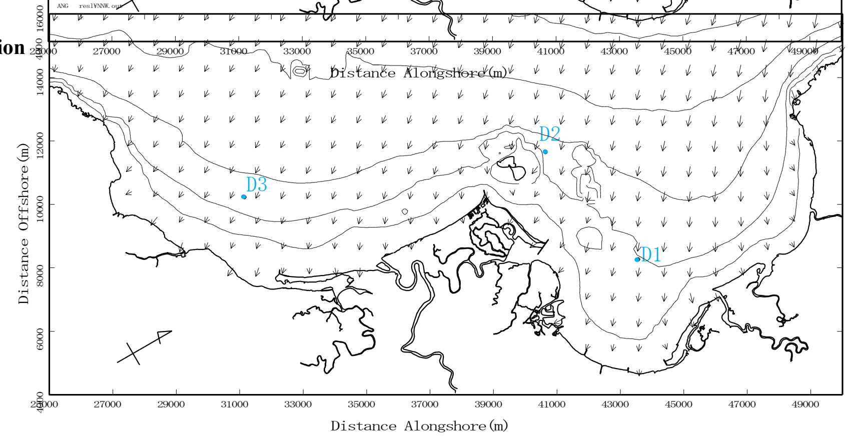


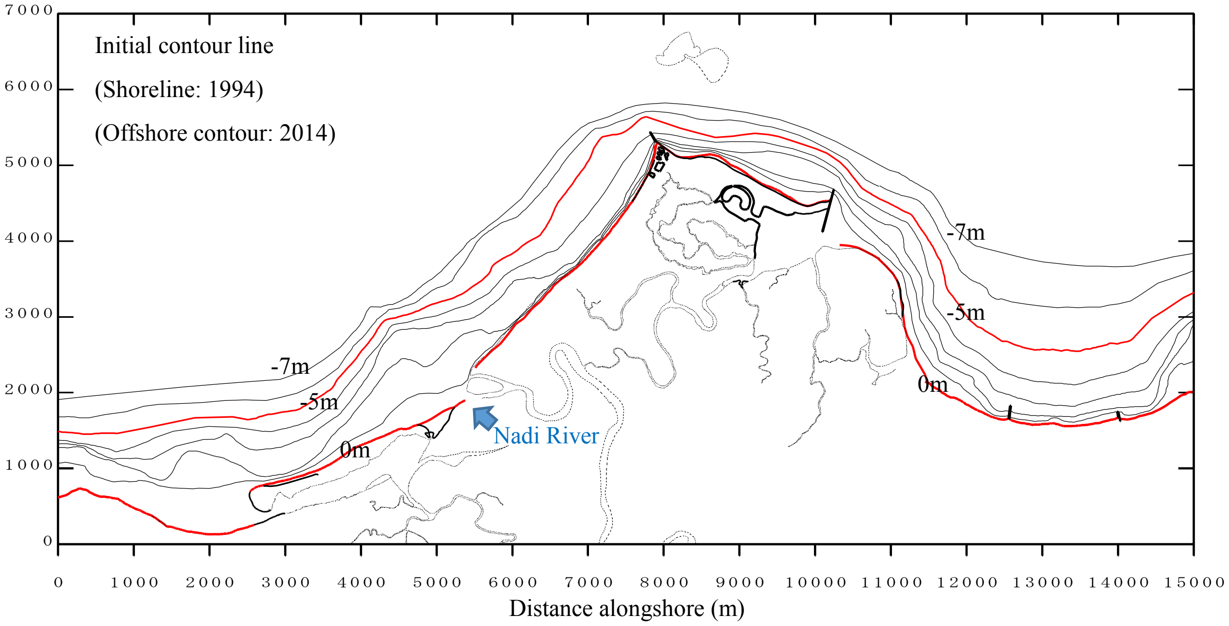
Figure 10-62 Comparison of Wave Direction between Field Observation Data and Result of Wave Transformation Analysis

2) Calculation of Contour Line Change

a) Condition of Reproduction Calculation

Figure 10-63 shows the area for which the model calculation was performed and the shape of the initial contour lines (those in 1994).

A trial calculation was conducted to set the conditions to estimate the changes in the shoreline and the predominant directions of the sediment transport to reproduce the current state with the state in 2014 assumed as the current state. Table 10-27 shows the conditions for the estimation in the Counter Line Change Model.



The contour lines in red show those at 0 m and -5 m.

Figure 10-63 Area of the Calculation and Initial Contour Lines

Table 10-27 Conditions of Reproduction calculation model

Item	Condition
(1)Region for calculation	Longshore:15000m、 DX=20m
(2)Wave condition (wave condition is offshore)	Angle① : N241°E, Ho=2.60m, T=9.12s Angle② : N312°E, Ho=2.85m, T=8.49s Angle③ : N355°E, Ho=2.54m, T=8.95s Wave field using in N-line model is extracted form computitation nearshore wave
(3)Term for calculation	1994～2014（20 years）
(4)Contour data	Initial : Shoreline:1994,Offshore:2014
(5)Sediment data	Data :Observed data in this investigation. Division of grain size is six .(mean grain size:0.074mm,0.137mm、0.326mm,0.601mm,1.304mm,6.164mm)
(6)Depth of closure and Cross-shore distribution of sediment transport	Depth of closure is -7m. Cross-shore distribution of sediment transport is used calculation formula by Uda et.al(1996).
(7)Coefficuent of sediment transport formula	K1=0.77、 K2=1.62K1（K1:Komar(1970), K2:Ozasa・Brampton(1980))
(8)Boundary conditions	Longshore $Q_1=Q_2$, $Q_N=0$ Cross-shore NADI River : 113,490m^3/year (without Mud)

b) Grain Size Distribution

Grains in the sediment were empirically classified by the sizes of the openings of sieves stipulated in the Japanese standards for sieves. The representative grain size set for each grain size range is shown in Table 10-28.

Table 10-28 Grain Sizes for the Classification of the Sediment

Grain size class (mm)	mean Φ $(\Phi 1+\Phi 2)/2$	mean grain size(mm)	Classification
19.0 - 2.0	-2.624	6.164	Gravel
2.0 - 0.85	-0.383	1.304	Coarse snad
0.85-0.425	0.734	0.601	Medium sand
0.425-0.25	1.617	0.326	Medium sand
0.25-0.075	2.868	0.137	Fine sand
under 0.075			Silt, Clay

* Grain size d and Φ *scale* : $\Phi = -\log_2 d$ 、 $d = (1/2)^{\Phi}$

c) Sediment Discharge form Nadi River

The average annual sediment discharge from the Nadi River at its estuary is approx. 113,490m^3/year (excluding clay, or the grains with a size of 0.005mm or below). Table 10-29 shows the estimated grain size distribution of the sediment. The grains with a size of 0.005mm or below (clay) in the sediment discharged from the river were excluded from the calculation because most of such grains were suspended in the water and carried away to the offshore zone and do not contribute to the topographic change.

Table 10-29 Annual Sediment Discharge from the Nadi River and Grain Size Distribution

Grain size (mm)	amount(m^3/year)	Rate(%)
0.005- 0.075	85,889	75.68
0.075- 0.25	26,545	23.39
0.25- 0.425	318	0.28
0.425- 0.85	465	0.41
0.85- 2.00	182	0.16
2.00-19.00	91	0.08
total	113,490	100.00

(Chapter 9. Riverbed Variation Analysis for Comprehensive Sediment Control, Calculation for the Reproduction of the Current State 1998 - 2014)

Table 10-30 shows the grain size distributions by depth in Nadi Bay and near the estuary of the Nadi River. The sediment discharged from the river at its estuary is sorted by grain size in the water and the sorted grains are deposited on the seabed at different depths.

Table 10-30 Grain Size Distributions (%) by Depth in the Bay (NL13) and near the Estuary (SP13-17)

SP13-17	Depth (m)								
Grain size (mm)	1.0	0.0	-1.0	-2.0	-3.0	-4.0	-5.0	-6.0	-7.0
0.005 - 0.075	2.03	2.03	14.94	15.07	28.96	42.85	56.74	70.62	84.51
0.075 - 0.250	8.46	8.46	67.25	38.37	32.18	25.99	19.81	13.63	7.44
0.250 - 0.425	5.37	5.37	16.35	29.76	24.83	19.91	14.98	10.06	5.14
0.425 - 0.85	22.21	22.21	0.74	9.15	7.64	6.13	4.63	3.11	1.60
0.85 - 2.00	41.13	41.13	0.25	5.05	4.21	3.38	2.54	1.71	0.88
2.00 - 19.00	20.80	20.80	0.47	2.61	2.18	1.74	1.30	0.87	0.44
total	100	100	100	100	100	100	100	100	100

d) Distribution of the Longshore Sediment Transport Rate by Depth

The model used in this calculation assumed that the sediment discharged from the river at its estuary precipitated and was deposited on the seabed as shown in the grain size distributions by depth at first and, then, was transported alongshore by the force of waves. The energy-averaged waves were used as the waves in the model. Figure 10-64 shows the rate of the longshore sediment transport amounts by these waves at given depths.

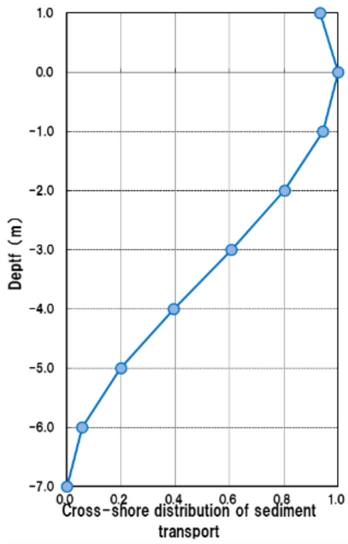


Figure 10-64 Longshore Sediment Transport Rate by Depth (Uda, et al. (1996))

e) Target of Reproduction (Changes in Longshore line and direction of sediment Transport)

Current characteristics of longshore line are explained by historical changes of longshore line and predominant direction of shore line sediment transportation. Figure 10-65 shows historical shoreline changes by the result of aerial photos analysis. The range of graph is same as the area of contour line changes calculation. Upper graph shows the long shore line changes from 1994 to 2014, lower graph shows dominant direction of shoreline sediment transportation. Partially discontinued line in the upper graph was caused by undetected shoreline under mangrove forest canopies

These shoreline changes and dominant direction are set as the target of reproduction calculations in the next session.

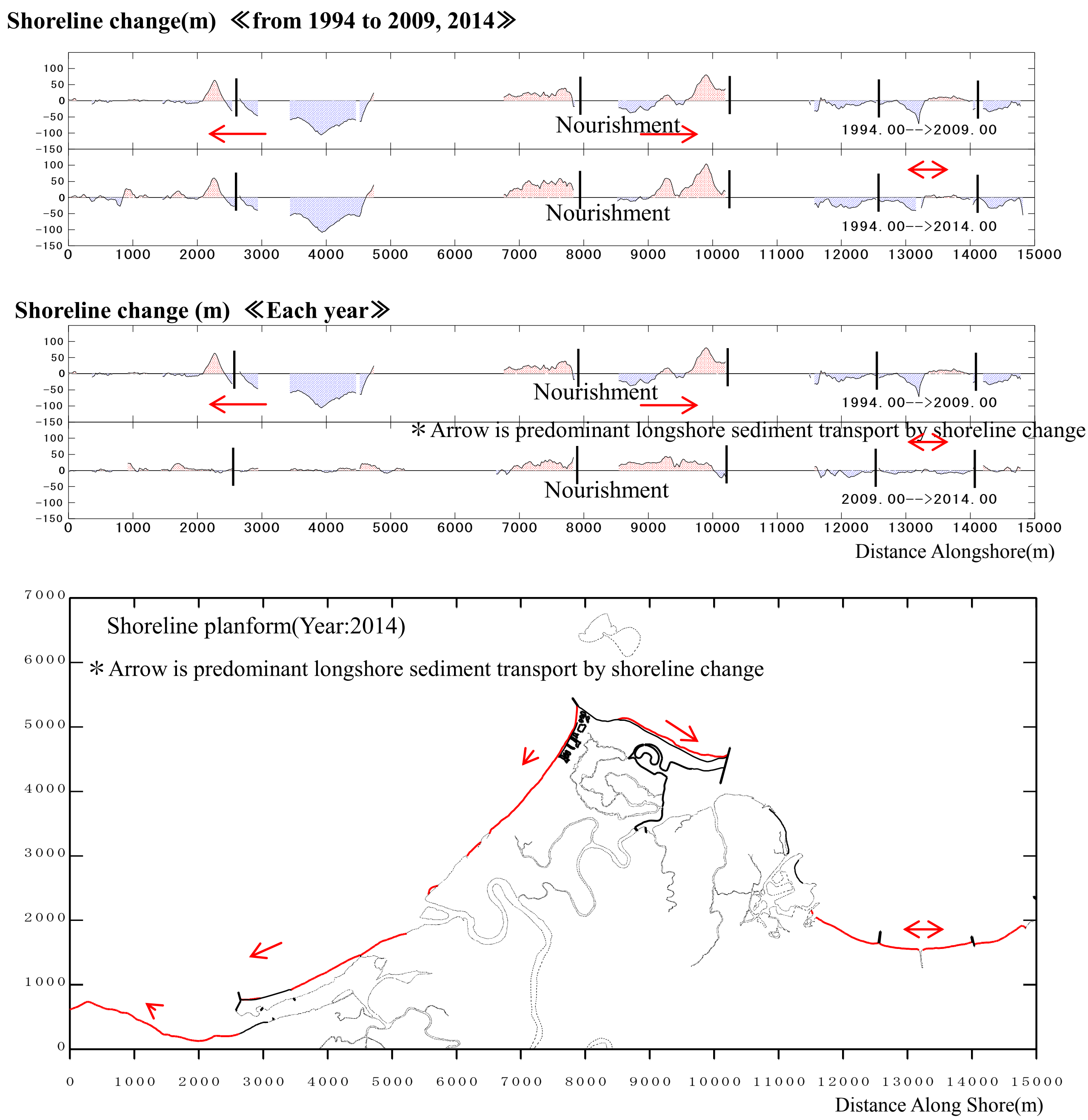


Figure 10-65 Changes in the Shoreline and Predominant Directions of the Longshore Sediment Transport between 1994 and 2014

(3) Calculation for the Reproduction of the Current State

1) Calculation of the Contour Line Changes for the Reproduction

In the reproduction calculation, one twelfth of the annual sediment discharge from the river at its estuary shown in the Table 10-29 above was used for the calculation of the monthly changes in the contour lines.

2) Calculation Results

a) Shore Line Changes and Direction of Sediment Transportation

Figure 10-66 shows the results of the calculation. Upper graph shows the contour line changes between the reference year of 1994 and 2009/2014 for the reproduction of the states in 2009 and 2014, respectively. Middle graph shows amount of annual sediment transportation, lower plan shows contour lines of initial, 1994 and current reproduction. In the plan, also shows dominant direction of longshore sediment transportation. According to the hearing from Denarau Corporation, both side of Denarau Cape have implemented artificial sea coast nourishment. From the findings of aerial photo analysis, the gaps of shape of shorelines in the term of 1994 to 2014 are high. So, it is considered that sea coast nourishment had implemented between 1994 and 2014. Therefore, the calculation reproduced the sea coast nourishment during the term.

The results of contour line calculations, case of from 1994 to 2009 and from 1994 to 2014, well reproduce the changes of shoreline which analyzed for aerial photos which shown in Figure 10-65.

Regarding the direction of sediment transport, dominant direction of the area of south of Denarau Island is “South”, also north of Denarau Island is “North”. These results also well reproduce the actual conditions.

It is consider that the applicability of the conditions for re-production calculation is high from these results.

b) Loss of Sediment Discharge to Offshore

Table 10-31 shows the amount of the sediment discharge of one year from the Nadi River and the amount of discharged sediment deposited at the depth of each contour line. Total volume of sediment discharge includes the amount of the sediment carried away from the analysis area with diameter below 0.005mm. The table also shows the estimated proportion of the sediment discharged from the Nadi River which has contributed to the change in the contour lines (contribution ratio).

The values in the table suggest that approx. 28 % of the sediment discharge of total discharge of 160,600m3/year from the Nadi River contributed to the changes in the shoreline and contour lines and that the remaining 72 % of 116,200 m3/year was carried away from the river at its estuary to the offshore zone.

Table 10-31 Amount of Sediment Deposited at each Contour Line and Contributed Ratio by Reproduction Calculation

Contour line (m)	Discharge from the river at its estuary (m^3/year)	Contribution ratio	Amount of deposit at the depth of the contour line (m^3/year)	Amount of the sediment carried away to the offshore zone (m^3/year)
1.0	1,819	1.00	1,819	0
0.0	1,819	1.00	1,819	0
-1.0	12,129	0.90	10,916	1,213
-2.0	8,810	0.70	6,167	2,643
-3.0	11,800	0.50	5,900	5,900
-4.0	14,790	0.40	5,916	8,874
-5.0	17,781	0.30	5,334	12,447
-6.0	20,769	0.20	4,154	16,615
-7.0	23,759	0.10	2,376	21,383
Amount of the sediment carried away from the analysis area	47,100	0.00	0	47,100
Total	160,576	0.28	44,401	116,175

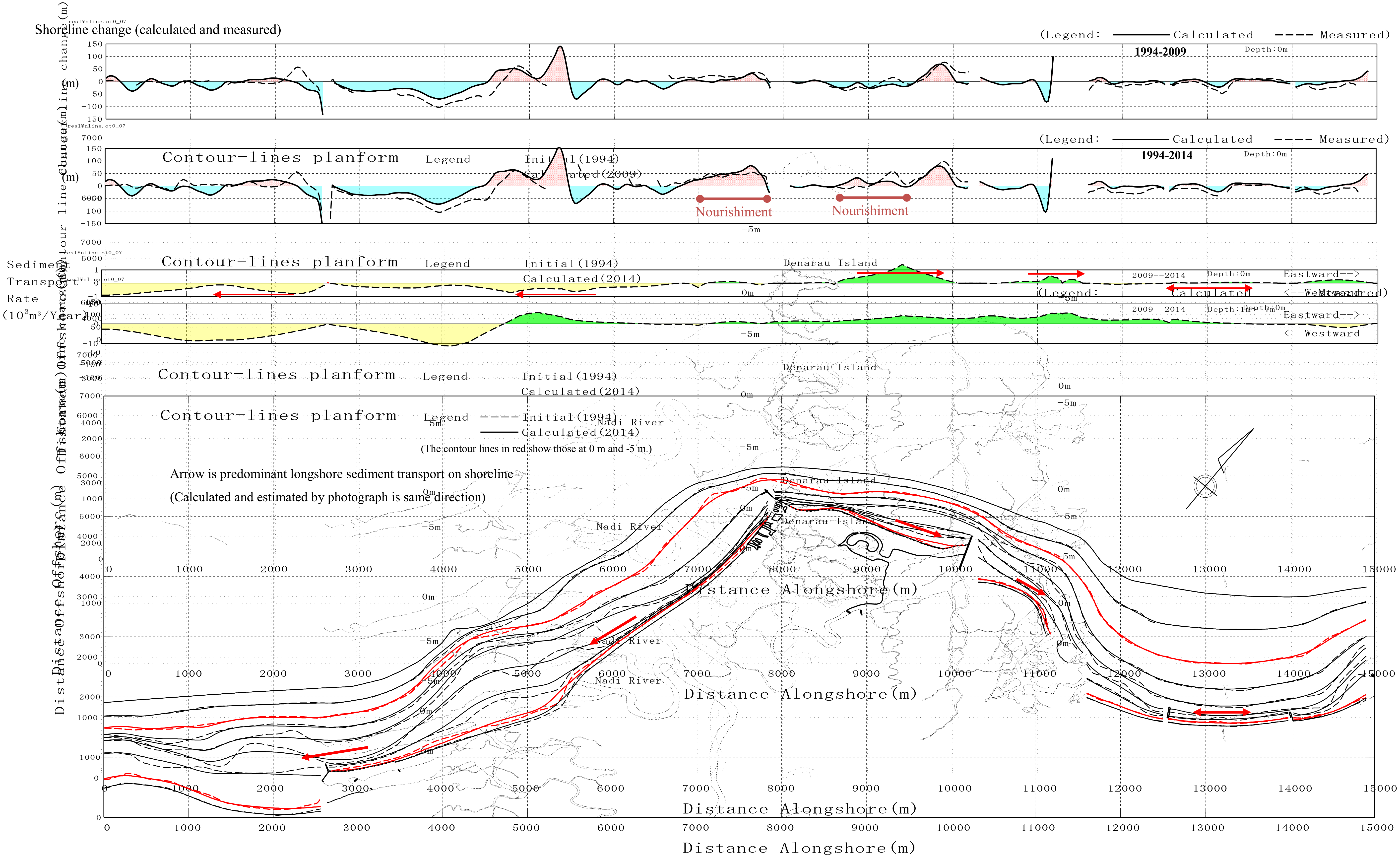


Figure 10-66 Calculation Results of Reproduction Contour Line Changes (shore line change amount and predominant direction of drift sand （1994 to 2009、1994 to 2014））

10.4.3 Forecasting Present Situation without Flood Control Measures

(1) Calculation Conditions

The objective of this calculation is to forecast present situation after long period without flood control measures to compare the future situation with and without flood control measures. Therefore, the forecasting of the changes in the contour lines was conducted on the assumption that there would be no change in structures near the sea coast and in the calculation conditions at present exclusive of the sediment discharge from Nadi River. The basic calculation conditions used in the reproduction calculation were used in the forecasting (refer to Table 10-33). The changes in the shoreline and contour lines in the periods of 10, 20, 30 and 50 years from the reference year of 2014 were estimated.

The shoreline and contour lines of 2014 obtained in the reproduction of the current state were used as the reference shoreline and contour lines in the forecasting. The contribution ratios of the sediment discharge from the Nadi River, or the proportion of the sediment contributing to the changes in the contour lines, used in the reproduction were used in the forecasting. In this calculation, sediment discharge form other rivers is not considered. Also, execute the calculation without the sea coast nourishment at both sides of Denarau cape.

The sediment discharge of Nadi River obtained in the forecasting in the riverbed variation analysis was used in the forecasting of the changes in the contour lines (refer to Table 10-32). Also, grain size for the calculation is the component of more than 0.005mm, excluding clay, same as in case of current reproducing.

Table 10-32 Annual Sediment Discharge from the Nadi River and Grain Size Distribution (without Flood Control Measures)

Grain size (mm)	amount(m^3/year)	Rate(%)
0.005- 0.075	75,196	77.41
0.075- 0.25	21,332	21.96
0.25- 0.425	175	0.18
0.425- 0.85	262	0.27
0.85- 2.00	117	0.12
2.00-19.00	58	0.06
total	97,140	100.00

(Chapter 9. Riverbed Variation Analysis for Comprehensive Sediment Control - Forecasting Results)

Table 10-33 Calculation Conditions for the Forecasting of the Contour Line Changes (without Flood Control Measures)

Item	Condition	
(1)Region for calculation	Longshore: 15000m、 DX=20m	
(2)Wave condition (wave condition is offshore)	Angle① : N241°E, Ho=2.60m, T=9.12s Angle② : N312°E, Ho=2.85m, T=8.49s Angle③ : N355°E, Ho=2.54m, T=8.95s Wave field using in N-line model is extracted form computitation nearshore wave	
(3)Term for calculation	50 years	
(4)Contour data	Initial : Current Situation(Final Conotour line by verification)	
(5)Sediment data	Data :Observed data in this investigation. Division of grain size is six .(mean grain size:0.074mm,0.137mm、0.326mm,0.601mm,1.304mm,6.164mm)	
(6)Depth of closure and Cross-shore distribution of sediment transport	Depth of closure is -7m. Cross-shore distribution of sediment transport is used calculation formula by Uda et.al(1996).	
(7)Coefficuent of sediment transport formula	K1=0.77、K2=1.62K1 (K1:Komar(1970), K2:Ozasa・Brampton(1980))	
(8)Boundary conditions	Longshore	$Q_1=Q_2$, $Q_N=0$
	Cross-shore	NADI River : 97,140m^3/year (without Mud)

* Item(1)、(2)、(5)、(6)、(7) is same as verification.

(2) Forecasting Results

1) Changes in the Contour Lines

Figure 10-67 to Figure 10-70 show the results of the forecasting of the changes in the 10-, 20-, 30- and 50-year periods respectively on the assumption that there will be no change in the existing facilities and the meteorological and oceanographic conditions.

These figures show that the predominant directions of the sediment transport will remain the same as those observed in the reproduction of the current state. In reality, a large quantity of sediment is discharged from the river at its estuary at the time of flooding. However, it was assumed that sediment was discharged evenly throughout the year in the forecasting. Therefore, the changes in the contour lines were forecast to be gradual and uniform so that no significant changes were forecast in the 10- and 20-year periods (refer to Figure 10-68). Therefore the forecast in 50-years is examined to be understandable in Figure 10-70.

a) Nadi River Mouth

The result forecasts (Figure 10-67) the trend that continuous deposition of sediment discharged from the Nadi River at the River mouth terrace continually to offshore direction. Dominant sediment transport direction of South of Cape Denarau is south, this situation makes erosion of shoreline continually in the area of south of Cape Denarau.

b) Regression of Shoreline around Cape Denarau

Tourism development around cape Denarau is active so that sand beach is important as tourism resources. The nourishment of beach is likely to be conducted in recent year. According to the forecast, shoreline (depth 0 m) at south and north side of the cape has a tendency of erosion gradually. In the calculation future nourishment of beach is not considered.

There are no major changes in North shore of Cape Denarau, but it is considered that the seabed materials in the north shore of the Cape will transport to northern side. At the north edge of the Cape, there is one jetty. The transported seabed materials will accumulate behind of the jetty.

c) Nadi Bay

The changes of Nadi Bay area are smaller than Nadi River mouth. Localized erosion of shoreline is observed, but in total, location of shore line is not changed. Gradual sediment accumulation is observed in the deeper area, where the area of less than -2m.

As the purpose of this forecasting was to study the influence of the Nadi River on the changes in the topography of the sea coast, the influence of the sediment discharged from other rivers flowing into Nadi Bay was ignored in the forecasting. Therefore, it should be noted that the sediment deposition in Nadi Bay may have been underestimated in this forecasting.

2) Amount of the Sediment Carried away to the Offshore Zone

Table 10-34 shows the data including the forecast annual average sediment discharge from the Nadi River at its estuary and the amount of sediment carried away to the offshore zone. The values in the table forecast that approx. 27 % of the sediment will contribute to the changes in the contour lines, while the remaining approx. 73 % will be carried away to the offshore zone.

Table 10-34 Amount of Sediment Deposited and Contribution Ratio

Contour line (m)	Discharge from the river at its estuary (m^3/year)	Contribution ratio	Amount of deposit at the depth of the contour line (m^3/year)	Amount of the sediment carried away to the offshore zone (m^3/year)
1.0	1,449	1.00	1,449	0
0.0	1,449	1.00	1,449	0
-1.0	10,034	0.90	9,031	1,003
-2.0	7,339	0.70	5,137	2,202
-3.0	10,017	0.50	5,009	5,009
-4.0	12,695	0.40	5,078	7,617
-5.0	15,374	0.30	4,612	10,762
-6.0	18,051	0.20	3,610	14,441
-7.0	20,729	0.10	2,073	18,656
Amount of the sediment carried away from the analysis area	42,200	0.00	0	42,200
Discharge from the river at its estuary	139,337	0.37	37,448	101,889

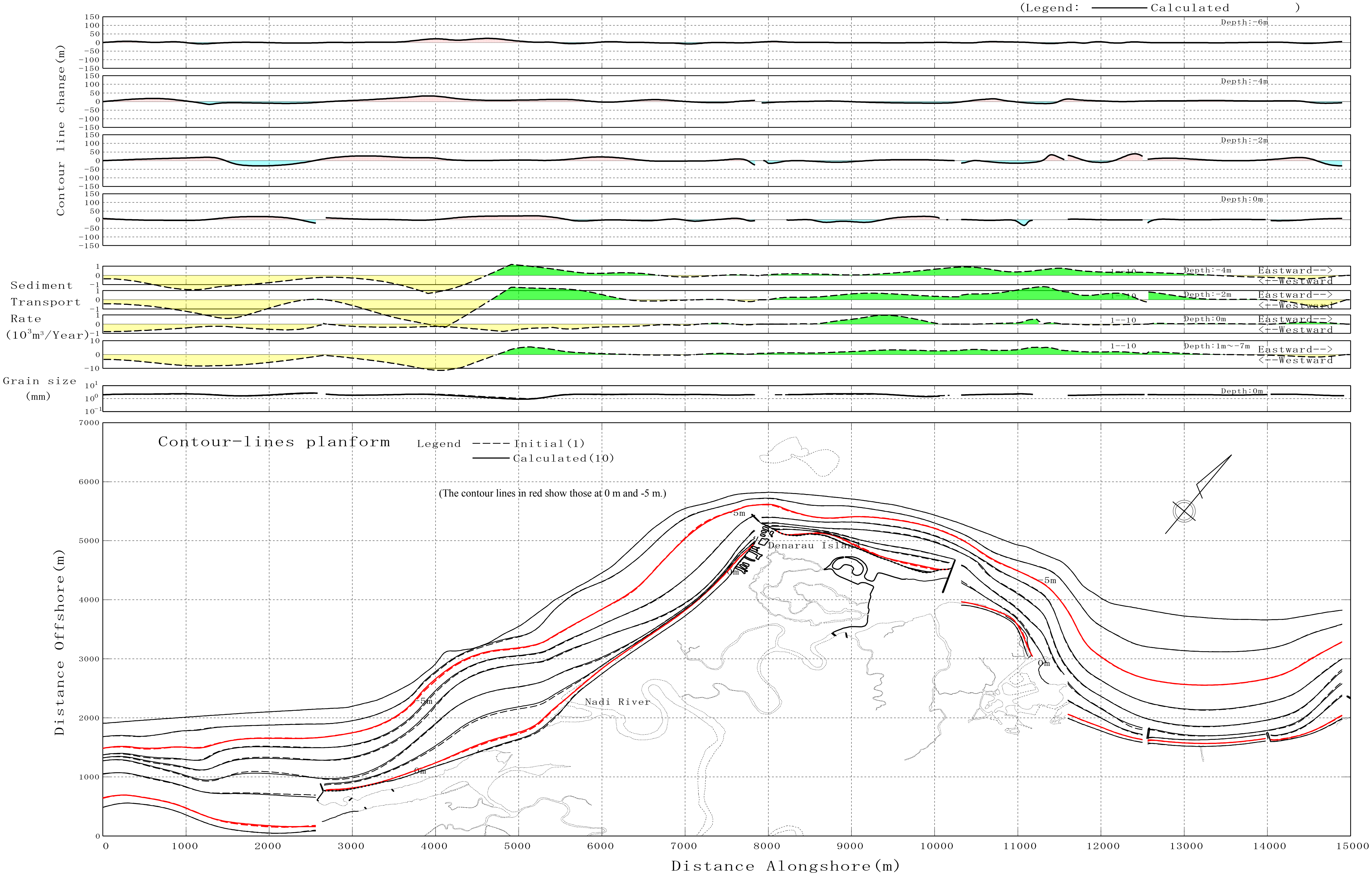


Figure 10-67 Result of the Forecasting of the Contour Line Changes (in the 10-Year Period)

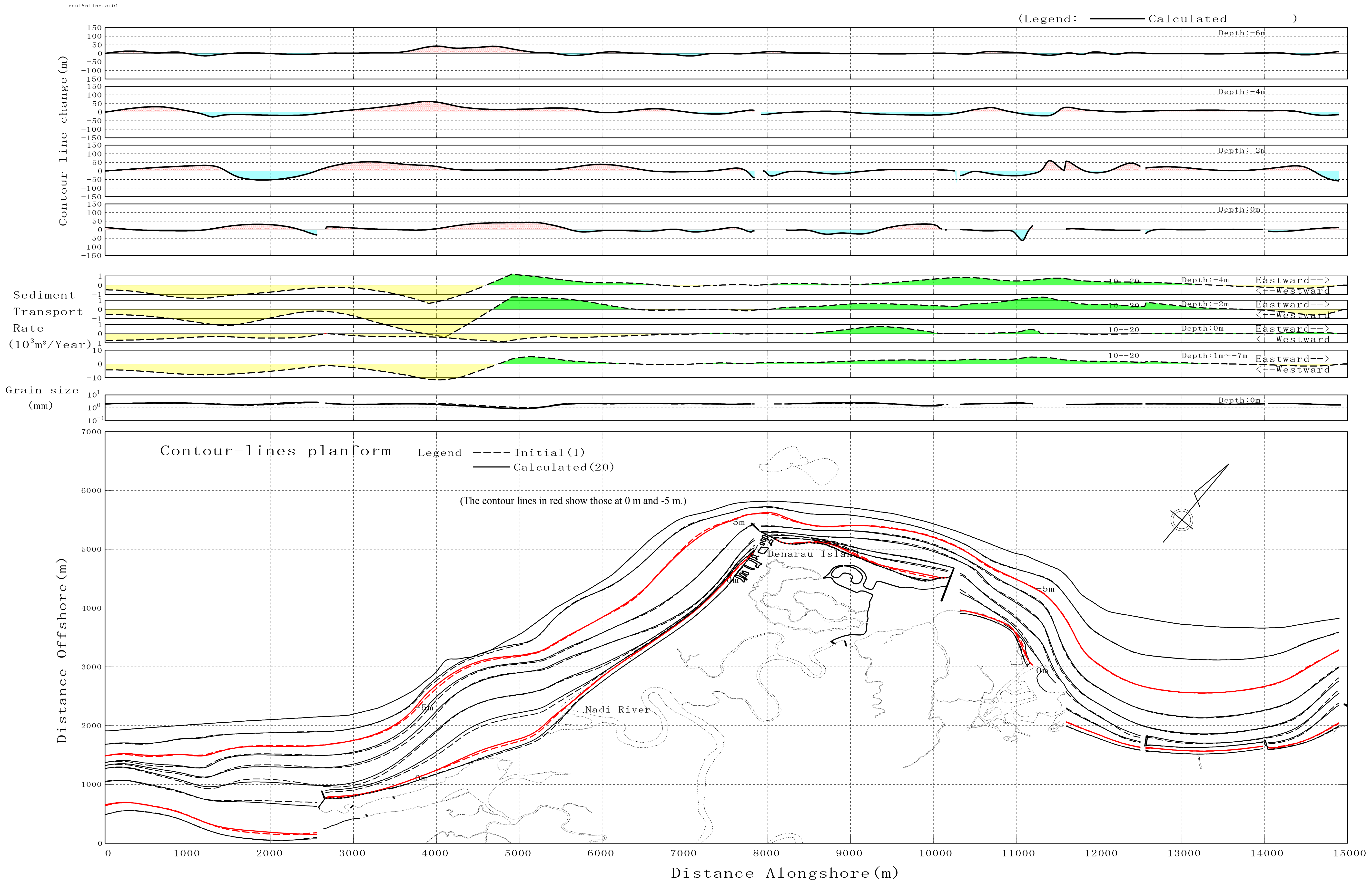


Figure 10-68 Result of the Forecasting of the Contour Line Changes (in the 20-Year Period)

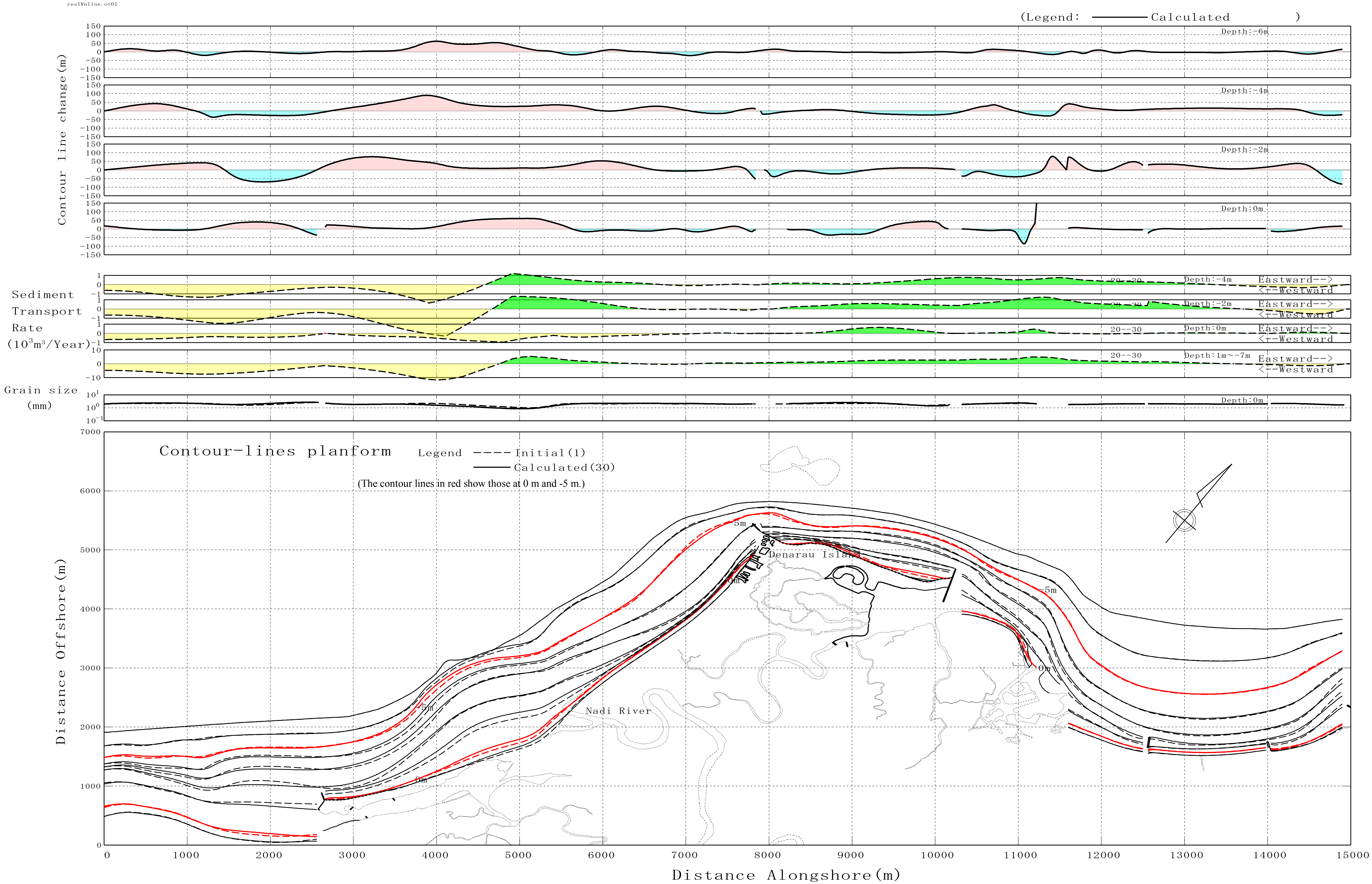


Figure 10-69 Result of the Forecasting of the Contour Line Changes (in the 30-Year Period)

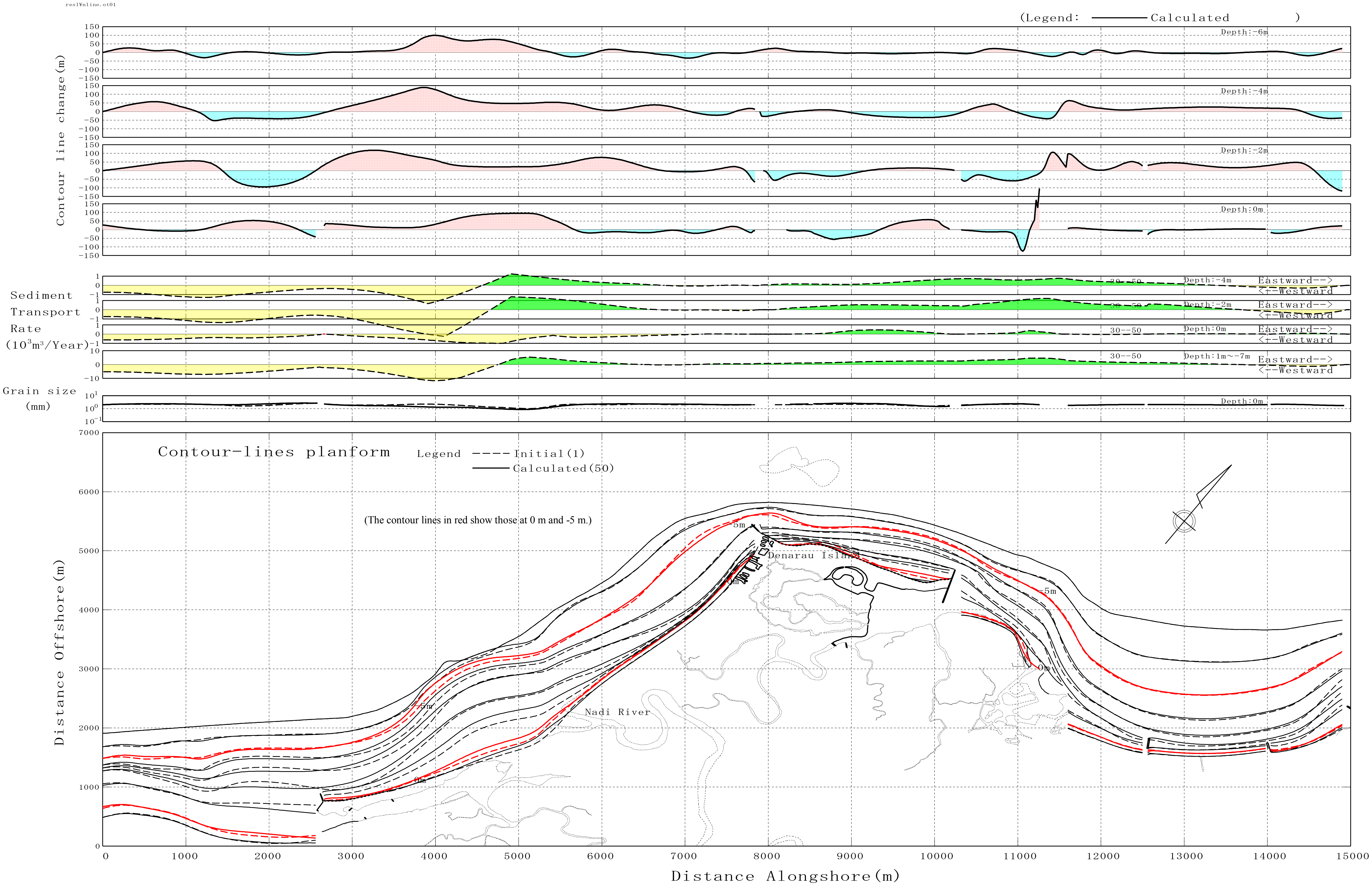


Figure 10-70 Result of the Forecasting of the Contour Line Changes (in the 50-Year Period)

10.5 Comparison and Evaluation of Flood Control Countermeasures

10.5.1 Viewpoints in Comparison and Evaluation

The following viewpoints are to be focused in the comparison and evaluation of the flood control countermeasures.

(1) River Mouth of Nadi River

The sediment discharge from Nadi River will be accumulated continuously at the river mouth so that the terrace around river mouth has tendency to expand to the offshore gradually. Since the terrace expanding is fluctuated depending on the sediment discharge from Nadi River, "the fluctuation of depth contour line of river mouth terrace" is pointed out one of viewpoint in evaluation

(2) Recession of Seashore Line around Cape of Denarau

The tourism development progress around Cape of Denarau, The beach around there is important tourism resources. As development of seashore, the beach nourishment has been implemented recently. The future "erosion and sedimentation of seashore around the cape" is pointed out one of viewpoint of evaluation.

(3) Nadi Bay

The sediment discharge from rivers in Nadi Bay is likely to be less than that of Nadi River mouth so that the variation of sea shore line is small. However the sediment with small particles such as fine sand and less than silt is observed in the seabed with depth less than－2.0m. Therefore "sediment tendency at depth contour line less than-2.0m" is pointed out one of viewpoint of evaluation.

10.5.2 Comparison and Evaluation Case

As the master plan of flood control structures, 4 alternatives were proposed by the JICA Study Team. They were examined at 2nd and 3rd JCC in June 2015. As the flood control structures in the middle stream section of Nadi main stream, the diversion channel, root-2 , (M-3) and the river improvement(enlargement of river channel)(M-1) were presented (refer to chapter 7), the latter was finally adopted in 3rd JCC.

Hereafter the above 2 alternatives and the case without any flood control structures are analyzed for seashore topographic variation.

The comparison and evaluation cases are as shown in the Table 10-35

Table 10-35 Comparison Case and Sediment Discharge Volume

Case	Solution	Sediment Discharge Volume	Related Section	Evaluation
Case-1 without Structures	Present river channel	Nadi River：97.14×$10^3 m^3$/year (without clay)	10.4.3	
Case-2, M-3	Diversion channel,root-2	Nadi River ：48.57×$10^3 m^3$/year Diversion Chanel：48.57×$10^3 m^3$/year (without clay)	10.5.3	
Case-3,M-1	River improvement	Nadi River：96.14×$10^3 m^3$/year (without clay)	10.5.4	◎

10.5.3 Prediction Calculation of Diversion Channel-root2 (Case-2, M-3)

(1) Calculation Condition

Hereafter, the prediction calculation is carried out for variation of depth contour line in case that Diversion Channel-root2 is constructed. The calculation conditions are same as Case-1, without flood control structure in the present river channel except for the sediment discharge at the river mouth. And the present depth contour line (2014) is used as initial condition which was obtained in the reproduction calculation of the present situation.

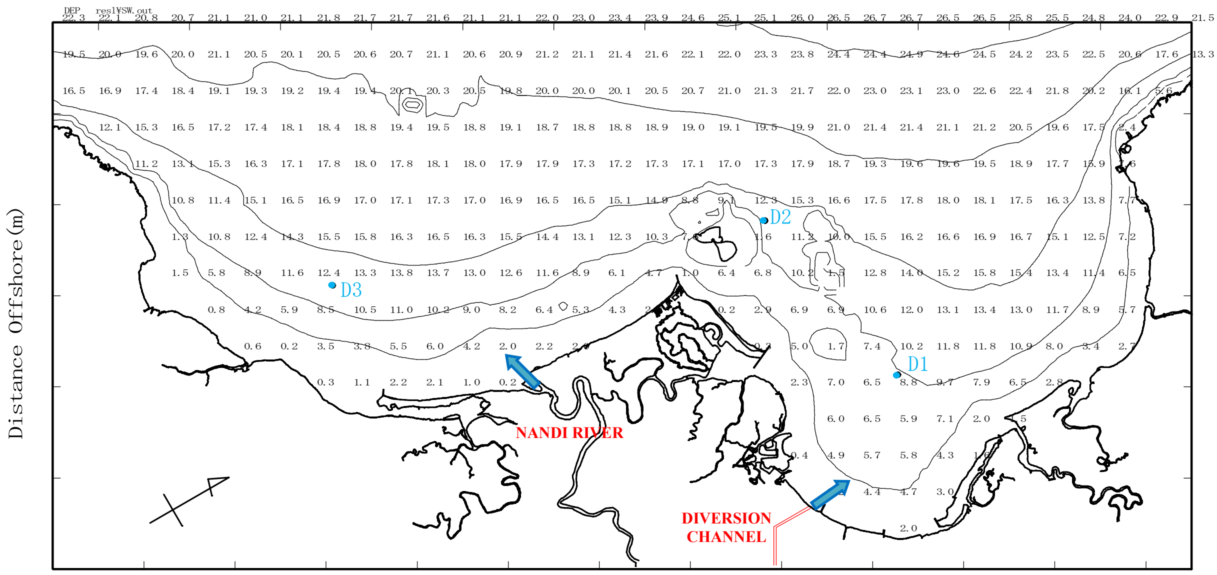
The actual sediment discharge from the diversion channel-root2 (Case-2, M-3) is depend on the structural condition of diversion point. Hereafter 50% of sediment of Nadi River is assumed to be discharged through the diversion so that the discharge difference between the diversion and main stream is to understand and the assumed discharge is safe side in the calculation, and the residual 50% is assumed to be discharged through the mouth of Nadi River (refer to the Table 10-36).

The conditions of prediction calculation are as shown in the Table 10-37, the location of the diversion in the Figure 10-71, and the distribution of sediment particles excluding clay at the mouth of Nadi River in the Table 10-38.

Table 10-36 Annual Sediment Discharge at the Mouth by Grain Size Distribution(Case 3,M-3)

	Nadi River		Diversion Channel	
Grain size (mm)	amount(m^3/year)	Rate(%)	amount(m^3/year)	Rate(%)
0.00- 0.075	37,598	38.71	37,598	38.71
0.075- 0.25	10,666	10.98	10,666	10.98
0.25- 0.425	87	0.09	87	0.09
0.425- 0.85	131	0.14	131	0.14
0.85- 2.00	58	0.06	58	0.06
2.00-19.00	29	0.03	29	0.03
total	48,570	50	48,570	50
			97,140	100

Note: Refer to Chapter 9, river bed fluctuation analysis, by 50 % of future prediction of sediment discharge



Unit of depth is m

Figure 10-71 Location of Diversion Channel (M-3)

Table 10-37 Conditions of Diversion Chanel- root2 Case (Case-2, M-3)

Item	Condition	
(1)Region for calculation	Longshore: 15000m、 DX=20m	
(2)Wave condition (wave condition is offshore)	Angle① : N241°E, Ho=2.60m, T=9.12s Angle② : N312°E, Ho=2.85m, T=8.49s Angle③ : N355°E, Ho=2.54m, T=8.95s Wave field using in N-line model is extracted form computitation nearshore wave	
(3)Term for calculation	50 years	
(4)Contour data	Initial : Current Situation(Final Conotour line by verification)	
(5)Sediment data	Data :Observed data in this investigation. Division of grain size is six .(mean grain size:0.074mm,0.137mm、0.326mm,0.601mm,1.304mm,6.164mm)	
(6)Depth of closure and Cross-shore distribution of sediment transport	Depth of closure is -7m. Cross-shore distribution of sediment transport is used calculation formula by Uda et.al(1996).	
(7)Coefficuent of sediment transport formula	K1=0.77、K2=1.62K1 (K1:Komar(1970), K2:Ozasa・Brampton(1980))	
(8)Boundary conditions	Longshore	South end: Q1=Q2, Norhh end: QN=0
	river mouth outflow sediment	NANDI River : 48,570m3/year (without Clay) Diversiion Channel : 48,570m^3/year (without Clay)
(9)Nourishment beach method	Distance alongshore:	none
	depth:	none

* Item (1)、(2)、(5)、(6)、(7) is same as verification.

Table 10-38 Grain Distribution at Nadi Bay (NL13) and Nadi River Mouth(SP13-17)

(unit: %) : without Clay

NL13	Depth (m)								
Grain size (mm)	1.0	0.0	-1.0	-2.0	-3.0	-4.0	-5.0	-6.0	-7.0
0.005 - 0.075	2.03	2.03	1.99	1.95	19.10	36.24	53.39	53.39	53.39
0.075 - 0.250	8.46	8.46	35.58	62.69	56.54	50.41	44.27	44.27	44.27
0.250 - 0.425	5.37	5.37	18.79	32.22	22.05	11.87	1.69	1.69	1.69
0.425 - 0.85	22.21	22.21	12.28	2.33	1.64	0.94	0.25	0.25	0.25
0.85 - 2.00	41.13	41.13	20.91	0.68	0.55	0.42	0.30	0.30	0.30
2.00 - 19.00	20.80	20.80	10.46	0.13	0.12	0.11	0.11	0.11	0.11
total	100	100	100	100	100	100	100	100	100

SP13-17	Depth (m)								
Grain size (mm)	1.0	0.0	-1.0	-2.0	-3.0	-4.0	-5.0	-6.0	-7.0
0.005 - 0.075	2.03	2.03	14.94	15.07	28.96	42.85	56.74	70.62	84.51
0.075 - 0.250	8.46	8.46	67.25	38.37	32.18	25.99	19.81	13.63	7.44
0.250 - 0.425	5.37	5.37	16.35	29.76	24.83	19.91	14.98	10.06	5.14
0.425 - 0.85	22.21	22.21	0.74	9.15	7.64	6.13	4.63	3.11	1.60
0.85 - 2.00	41.13	41.13	0.25	5.05	4.21	3.38	2.54	1.71	0.88
2.00 - 19.00	20.80	20.80	0.47	2.61	2.18	1.74	1.30	0.87	0.44
total	100	100	100	100	100	100	100	100	100

(2) Calculation Results

The Figure 10-72 shows the prediction calculation in case that the Diversion Channel-root2 is constructed. The upper part of the figure shows the contour line changes (m), and the lowest part shows the variation of depth contour line compared with present topography in 50 years, after implementation of the Diversion Channel.

The Figure 10-73 shows superposition of depth contour lines of the Case 1(without structure), and Case 2(M-3, Diversion Channel) in after 50 years in order to visible of variation. From the figure it is observed that the variation of sediment discharge from the river have changed remarkably the topography of around each mouth, and the topography apart from the mouth has no significant change.

Judging from the above results, the drift sand in this seashore is mainly composed of sediment discharge supplied from the river and transport distance of drift sand is short as well as the wave height is low so that the influence of sediment discharge is limited only to the change in near the mouth of diversion.

And due to low wave, the fine particles of mainly silt are likely to sediment in sea bottom deeper than 1m from seashore line.

The characteristics of depth contour line change by construction of the Diversion Channel are summarized below:

i) The drift sand will transport continuously toward present direction in future.

ii) The sediment discharge will divert same as river flow to the Nadi Bay by the construction of Diversion Channel so that the sediment discharge from Nadi River main stream will decrease which will cause decease of expansion of the river mouth terrace to offshore compared with Case 1, without structures.

iii) On the other hand, the depth contour line near the mouth of diversion will expand to offshore corresponding to the increase of sediment discharge, of which tendency is remarkable in the deeper contour line of -2m.

iv) In the both side of seashores of Cape of Denarau, the recession of sea shore line (erosion of depth 0m) have no difference compared with Case 1, without structures, therefore no difference of erosion by the construction of the Diversion Channel is observed.

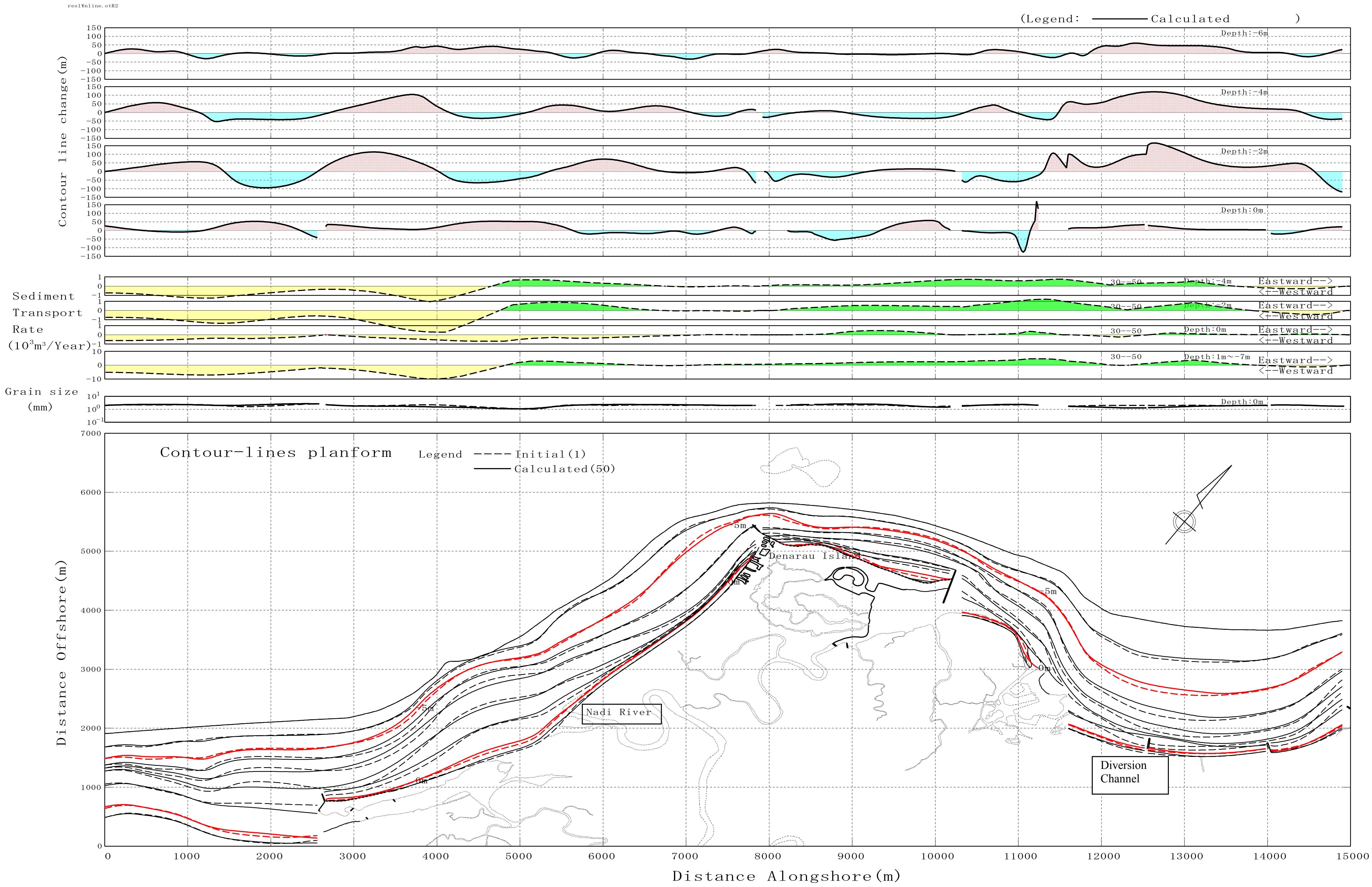


Figure 10-72 Comparison of Depth Contour Line between Present Condition (Case 1) and Construction of Diversion (Case 2) after 50 years

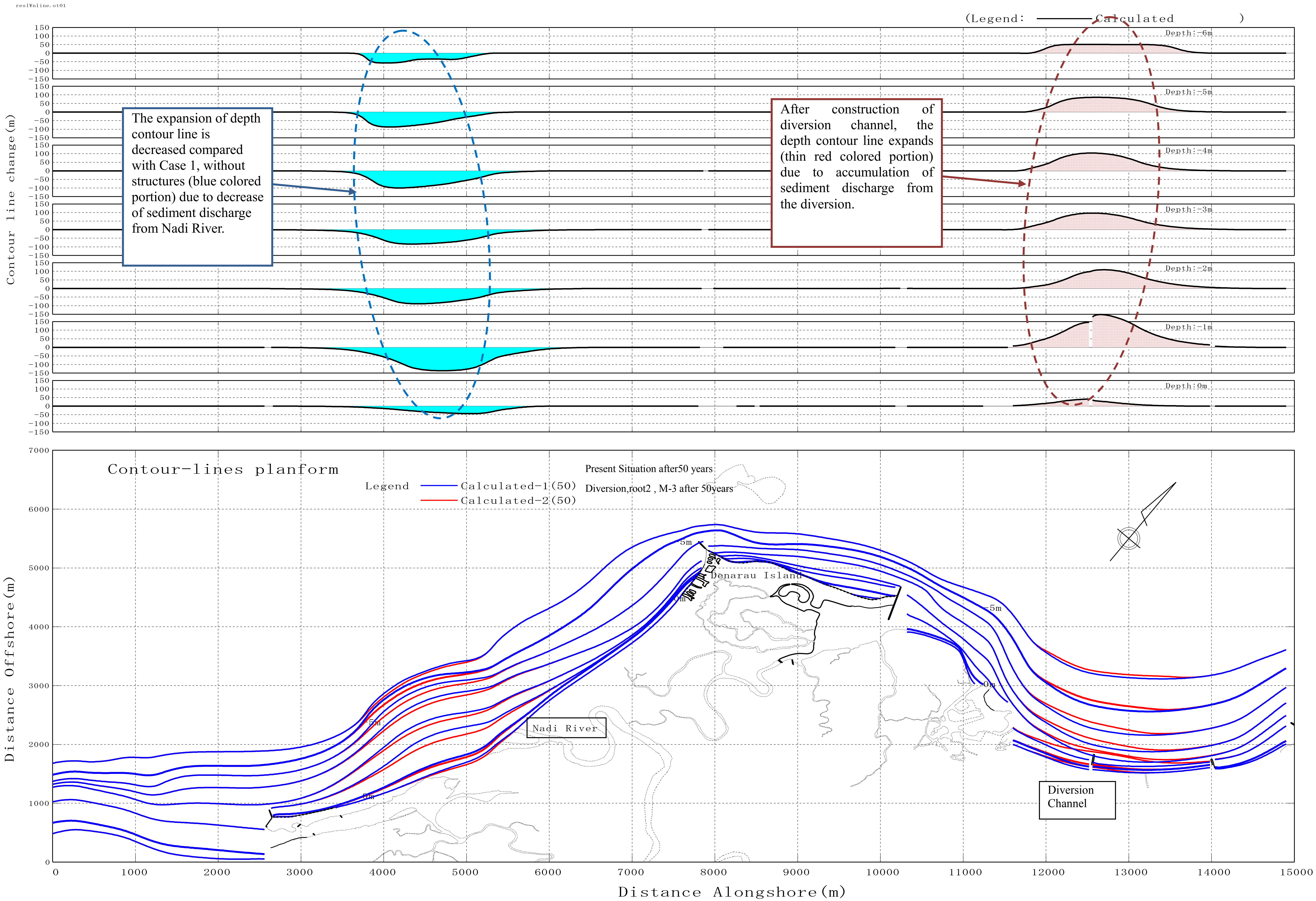


Figure 10-73 Comparison of Prediction of Depth Contour Line between Present Situation (Case 1) and Diversion Construction (Case 2) after 50 years

10.5.4 Prediction Calculation of River Improvement (Case-3, M-1)

(1) Calculation Conditions

Hereafter, the prediction calculation is carried out for variation of depth contour line in case that the River Improvement is constructed. The calculation conditions are same as Case-1, without flood control structure in the present river channel except for the sediment discharge at the river mouth. And the present depth contour line (2014) is used as initial condition which was obtained in the reproduction calculation of the present situation.

The annual sediment discharge by particle size at the mouth of Nadi River is shown in the Table 10-39. The conditions of prediction calculation of River Improvement (Case-3, M-1) are as shown in the Table 10-40.

Table 10-39 Annual Sediment Discharge at the Mouth and Grain Size Distribution (Case M-1)

Grain size (mm)	amount(m^3/year)	Rate(%)
0.00- 0.075	74,874	77.88
0.075- 0.25	20,795	21.63
0.25- 0.425	125	0.13
0.425- 0.85	192	0.20
0.85- 2.00	106	0.11
2.00-19.00	48	0.05
total	96,140	100

Note: Refer to Chapter 9, river bed fluctuation analysis, by future prediction of sediment discharge

Table 10-40 Conditions of River Improvement Case (Case M-1)

Item	Condition		
(1)Region for calculation	Longshore: 15000m、 DX=20m		
(2)Wave condition (wave condition is offshore)	Angle① : N241°E, Ho=2.60m, T=9.12s Angle② : N312°E, Ho=2.85m, T=8.49s Angle③ : N355°E, Ho=2.54m, T=8.95s Wave field using in N-line model is extracted form computitation nearshore wave		
(3)Term for calculation	50 years		
(4)Contour data	Initial : Current Situation(Final Conotour line by verification)		
(5)Sediment data	Data :Observed data in this investigation. Division of grain size is six .(mean grain size:0.074mm,0.137mm、0.326mm,0.601mm,1.304mm,6.164mm)		
(6)Depth of closure and Cross-shore distribution of sediment transport	Depth of closure is -7m. Cross-shore distribution of sediment transport is used calculation formula by Uda et.al(1996).		
(7)Coefficuent of sediment transport formula	K1=0.77、K2=1.62K1 (K1:Komar(1970), K2:Ozasa・Brampton(1980))		
(8)Boundary conditions	Longshore	South end: Q1=Q2,	Norhh end: QN=0
	river mouth outflow sediment	NANDI River	: 96,140m3/year (without Clay)
(9)Nourishment beach method	Distance alongshore:	none	
	depth:	none	

* Item (1)、(2)、(5)、(6)、(7) is same as verification.

(2) Calculation Results

The Figure 10-73 shows the prediction calculation in case of the River Improvement -root2 is constructed. The upper part of the figure shows the contour line changes (m), and the lowest part shows the variation of depth contour line compared with present topography in 50 years after implementation of the River Improvement. The Figure 10-74 shows superposition of depth contour lines of the Case 1(without structure), and Case 3(M-1, River Improvement) in after 50 years in order to visible of variation.

From the figure it is observed that the difference of the depth contour line in the both prediction cases is very small so that the River Improvement will not affect so much the present seashore condition. The reason is that the sediment discharge after River Improvement is 96.14 x 10^3 m^3/year and that of present is 97.14 x 10^3 m^3/year of which deference is only 1 %.

The characteristics of depth contour line change by construction of the River Improvement are summarized below:

i) The drift sand will transport continuously toward present direction in future.

ii) The sediment discharge by the River Improvement will not change so much with the present situation Case 1, without structures, so that the influence to the seashore is nil.

iii) In the both side of seashores of Cape of Denarau, the recession of sea shore line (erosion of depth 0m) have no difference compared with Case 1, without structures, therefore no difference of erosion by the construction of the River Improvement is observed.

In conclusion, the influence of the River Improvement will be almost nil, to the present condition, Case 1 without structures.

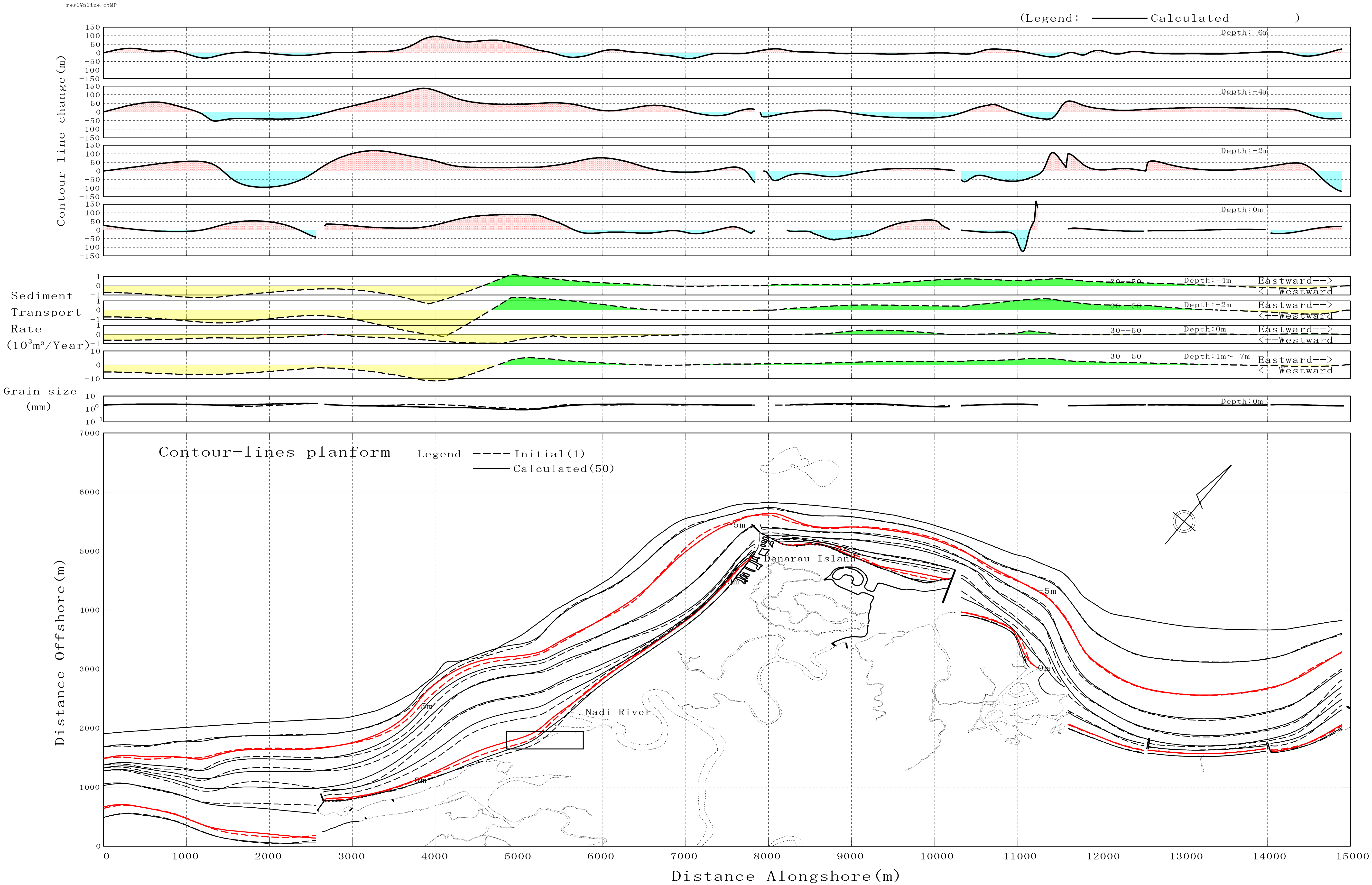


Figure 10-74 Comparison of Depth Contour Line between Present Condition (Case 1) and River Improvement (Case 3) after 50 years

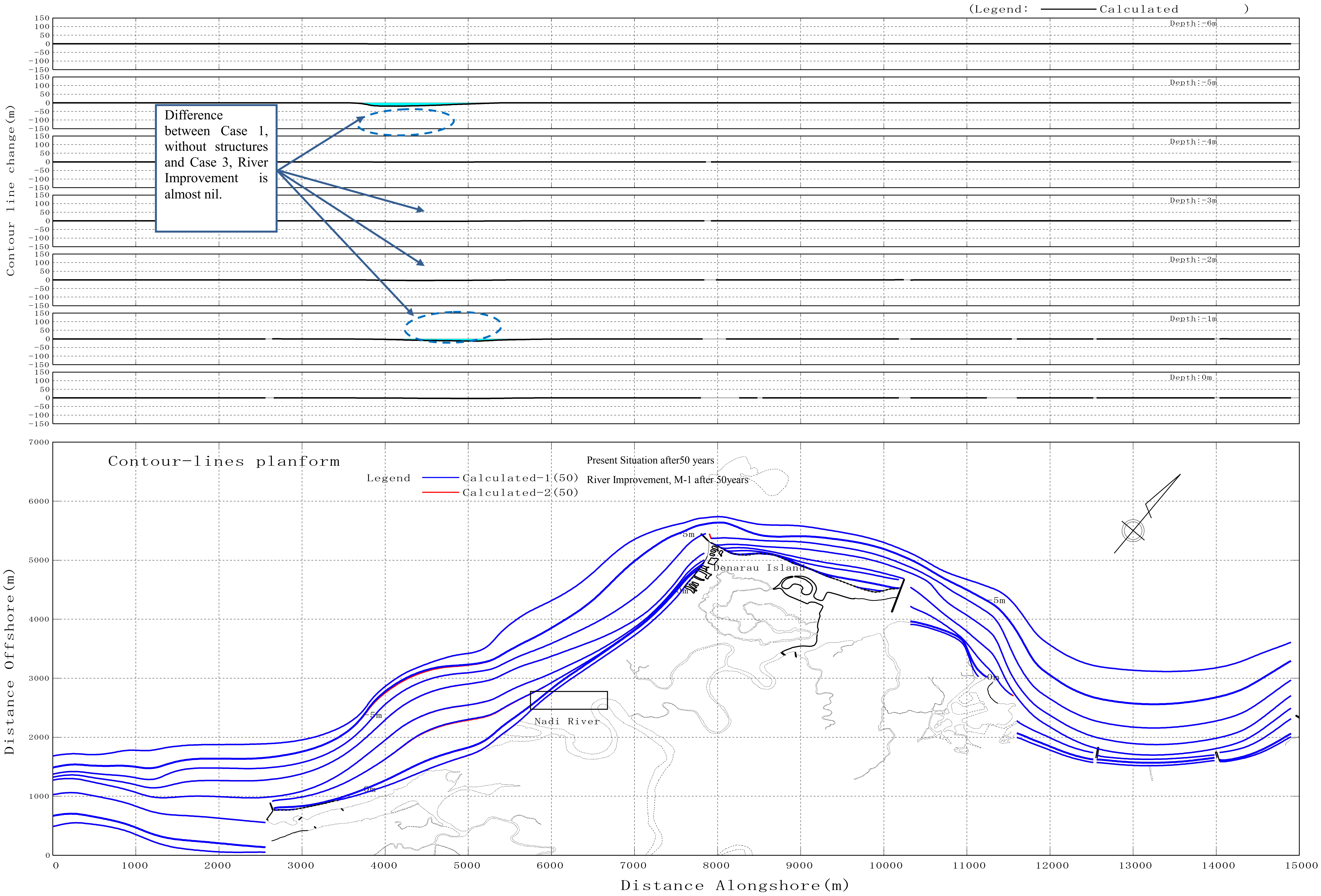


Figure 10-75 Comparison of Prediction of Depth Contour Line between Present Situation (Case 1) and River Improvement (Case 3) after 50 years

10.6 Evaluation of Influence of Flood Control Structures and Issue in Future

10.6.1 Evaluation of Influence of Flood Control Structures

In the previous section, the variation of sea shore topography was calculated from present to 50 years after in the case of River Improvement (Case-3, M-1). In the conclusion, the terrace at the mouth of Nadi River will expand according to elapsing of years; however the difference to the Case 1, without structures is almost nil. The reason is that the sediment discharge from Nadi River is decreased by 1 % in annual average in the River Improvement.

As described above, the influence of the River Improvement (Case 3, M-1) to the seashore topography is almost same as that of Case 1, without structures, so that the mitigation works for the River Improvement is not necessary.

10.6.2 Issues in Future

The mitigation work for decrease of influence to the seashore required by the River Improvement is not necessary, however the issues at present will continue after completion of the River Improvement.

(1) Dredging of Rive Mouth

The dredging of 165.1 x $10^3 m^3$ was implemented at Nadi River, from river mouth, 0 km to 7km from 2008 to 2012. In future the maintenance work of dredging is likely to be required in the tidal reach where the sedimentation occurs in normal river flow

(2) Sand Bar at River Mouth

As to the sand bar at river mouth, due to accumulation of fine particles and acting of low wave with height less than 1.0m, the river mouth terrace (accumulated under sea surface) will mainly expand and the sand bar over sea surface will be not likely to develop and clog the river mouth. This is confirmed by observation that there is no formulation of sand bars which clog the river mouth at present and in the past

The height of sea bed around the river mouth is estimated visually as EL+0.8m at highest and EL-1.0m at lowest, and L.A.T. (Lowest Astronomical Tide) is -1.05m. Since the riverbed lower than L.A.T is lower than lowest height of river terrace, and the sea surface is always higher than L.A.T.so that the zone less than L.A.T. is to be dead zone for effective river flow section. In dredging of river channel, if the zone with less height than L.A.T. is excavated, the zone will not contribute the enlargement of effective flow area. Therefore dredging is to be planned the zone more than L.A.T. -1.05m.

10.6.3 Monitoring Plan

The terrace at river mouth is estimated to expand further by sediment discharge from Nadi River according to the prediction analysis of the contour line change model.

According to the development of river mouth terrace, the depth of water will be more shallow and uniform so that there are some possibilities of enlargement and shape change of river mouth delta, and in some cases river course change when the large amount of sediment is discharged in big flood. Such kind of river mouth change may influence to the flow conditions of floods. However the change is affected by flow condition, partial erosion and sedimentation, so that the prediction of such is difficult.

Therefore it is effective that the monitoring of change of shape and water depth and so on at river mouth is implemented periodically. The monitoring plan is as shown in the Table 10-41. And based on the monitoring, appropriate maintenance works such as dredging and so on, are to be implemented from time to time.

Table 10-41 Monitoring Plan at River Mouth

Item	Method	Timing	Frequency
1)Change of topography	- Aerial photogrammetry (periodical)	- After rainy season	- every 5years
	- Aerial photogrammetry (temporally)	- After big flood (temporally)	- occasionally
2)Change of cross section	- Longitudinal and cross section survey (periodically)	- After rainy season	- every 5years
	- Longitudinal and cross section survey (temporally)	- After big flood (temporally)	- occasionally