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# A RISK-BASED ZONING OF STORM SURGE PRONE AREA OF THE GANGES TIDAL PLAIN

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**ABSTRACT** : Flooding occurs occasionally in the Ganges Tidal Plain due to intrusion of cyclonic storm surges along the estuaries. The flood prone area has been determined by numerical simulation of tides and storm surges in 5 major estuary systems. A risk analysis based on hazard and vulnerability factors has been performed by dividing the flood prone area into 45 land units. Hazard factors are based on the simulated spatial distribution of 100-year flood depths while the vulnerability factors are based on the distribution of population densities. The land units have been grouped into low risk, moderate risk, high risk and severe risk zones whose areas are 3602, 788, 518 and 659 sq. km. respectively. Flood control embankment along the river causes increase in both surge height and intrusion distance.

**KEY WORDS :** Hazard factor, Prediction of surge, Risk analysis, Cyclone hazard, Vulnerability

## INTRODUCTION

Disaster due to occasional cyclonic storm surge floods in the coastal region is a great concern for Bangladesh. These storm surges are generated by tropical cyclones which form in the Bay of Bengal. About one-tenth of global tropical cyclones forming in different regions of the tropics occur in the Bay of Bengal (Gray, 1968; Ali, 1980). Analysis by Mooley and Mohile (1983) shows that about one-sixth of tropical cyclones born in the Bay of Bengal had landfall on the coast of Bangladesh. Tracks of severe cyclonic storm since 1960 are shown in Figure 1. More than 700,000 people have been killed by floods due to 15 cyclonic storm surges since 1960.

The Planning Commission of Government of Bangladesh requested the Bangladesh University of Engineering and Technology (BUET) and the Bangladesh Institute of Development Studies (BIDS) to prepare a master plan of cyclone shelters to provide refuge to the exposed population during storm surge floods in the coastal area and the plan was finalized in 1993. It is estimated that 2500 new shelters for 4.4 million peoples are required to meet the projected needs in the year 2002. About three-fourths of the proposed shelters are required in the Ganges Tidal Plain.

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An important issue is how to identify priority areas within the storm surge prone region when a fraction of required shelters can be constructed by an available fund. A criterion for prioritizing can be the degree of flood risk to which the population of an area is exposed. This paper discusses the results of a study by Karim and Chowdhury (1995) where storm surge flood prone region of the Ganges Tidal Plain has been divided according to a measure of risk by considering the spatial distribution of flood depth and the vulnerability of population.

## GANGES TIDAL PLAIN

The Ganges Tidal Plain covers the southern part of the south-west region of Bangladesh. It lies between the Hariabhanga river along the India-Bangladesh border in the west and the Tetulia river in the east (Barua, 1991). It is exposed to the Bay of Bengal in the south as shown by Figure 1. The length of coastline along a straight line connecting the mouths of Hariabhanga and Tetulia rivers is nearly 135 km. The area receives fresh water flows through Ganges distributaries, Gorai and Arial Khan rivers in the north. A tropical mangrove forest known as the Sundarban covers the western half of the Ganges Tidal Plain and has an area of about 6000 km$^2$.

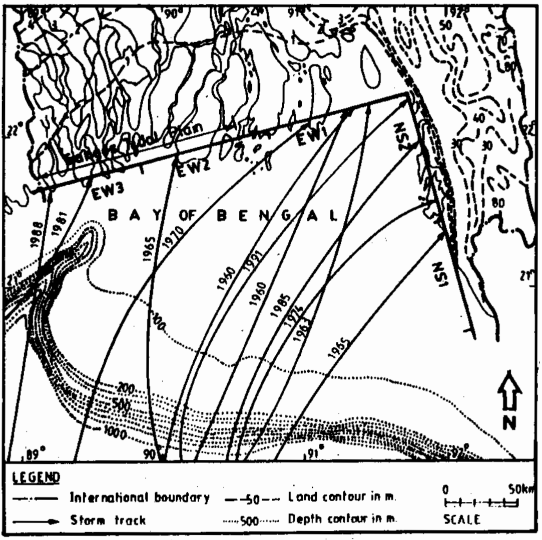

*Fig 1. Topography of Bangladesh Coastal Area and Continental Shelf and Tracks of* Severe Cyclonic Storms Since 1960

The Ganges Tidal Plain is covered by a network of estuaries having inlet width of 4 to 16 km. There are five major estuary-tidal river systems and their important tidal characteristics are given in Table 1. The area is slightly above mean sea level (msl) as shown by land contours in Figure 1 and substantial part of the area is flooded during high waters of most spring tides. Flat topography and presence of wide estuaries allow the cyclonic storm surges from the Bay of Bengal to intrude far inland. As a result, areas adjacent to rivers are flooded.

**Table 1. Some tidal characteristics of river system in the Ganges Tidal Plain**

| River System | No. of branch | Average tidal range at estuary inlet (m) | | Distance of tidal limit (km) |
|---|---|---|---|---|
| | | Neap | Spring | |
| Malancha | 8 | 0.84 | 2.04 | 174 |
| Passur-Sibsa | 4 | 0.78 | 2.18 | 187 |
| Baleswar | 8 | 0.90 | 2.30 | 184 |
| Biskhali-Buriswar | 4 | 0.90 | 2.30 | 133 |
| Galachipa-Tetulia | 7 | 0.84 | 2.20 | 124 |

## SIMULATION OF STORM SURGE FLOODS

### Prediction of Surge Height at the Coast

Measured data on storm surge heights at the coast is scarce. To determine design surge heights for the Master Plan (BUET and BIDS, 1993), several analytical and empirical methods of predicting the maximum surge height were studied. These methods have been taken from Bretschneider (1966), Flierl and Robinson (1972), Das et al. (1974) and Chowdhury and Ali (1974). An approximate solution for the slope of water surface due to wind stress during cyclonic storm over a uniformly rising continental shelf, was found appropriate for the coast of Bangladesh. Details of the methodology has been discussed in Chowdhury (1994). The derived formula for the coast of Bangladesh is given below.

$$H = \frac{13 \times 10^{-6}\ LV^2}{(5 \times 10^6 + LV^2)^{0.2}} \tag{1}$$

Where H is the maximum surge height at the coast in m, V is the maximum wind speed in km/hr and L is the distance between the 200 m depth contour and the coast in km. To establish design surge heights, the coast of Bangladesh was divided into 5 segments as shown in Figure 1 where depth contours of the Bay of Bengal are also shown. Representative values of L are 140, 230, 260, 200 and 160 km for NS1 NS2, EW1, EW2 and EW3 coastal segments respectively. The coast of the Ganges Tidal Plain includes EW3 and most part of EW2.

Study by Chowdhury (1994) shows that the return period of the surge height (H) is approximately twice that of the annual maximum wind speed (V) of the cyclones those approached the coast of Bangladesh. The wind speeds, return period and interpolated peak surge-heights at the inlets of 5 estuaries are given in Table 2.

**Table 2. Estimated peak surge heights at five estuary inlets**

| Annual maximum wind speed (km/hr) | Return period of wind speed (years) | Peak surge height (m) | | | | |
|---|---|---|---|---|---|---|
| | | Malancha | Passur Sibsa | Baleswar | Biskhali Buriswar | Galachipa Tetulia |
| 195 | 10 | 3.0 | 3.1 | 3.5 | 3.6 | 3.9 |
| 233 | 25 | 4.1 | 4.2 | 4.8 | 4.9 | 5.3 |
| 261 | 50 | 5.0 | 5.2 | 5.8 | 6.0 | 6.4 |

**Computation of Surge Along the River**

Propagation of tides and storm surges along the estuaries has been simulated by a numerical hydrodynamic model developed by Chowdhury (1986). It may be mentioned that the numerical model was used successfully to simulate tidal flows in the river network of the Meghna Delta in a salt water intrusion study by Chowdhury and Haque (1990). The model is based on an implicit finite difference solution of gradually varied unsteady flow equations given below.

$$W\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} - q = o \qquad (2)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} + gA\frac{Q|Q|}{K^2} = 0 \qquad (3)$$

Where x is the distance along river (m), t is the time (s), W is the water surface width (m), h is the elevation of water surface with respect to a common datum (m), Q is the volume of water flow per unit time along the river ($m^3/s$), q is the volume of lateral water inflow per unit time per unit length of the river ($m^3/s/m$), K is the conveyance of flow section ($m^3/s$) and is equal to $CAR^{1/2}$, R is the hydraulic radius of flow section (m), A is the cross sectional area of water flow ($m^2$), C is the Chezy roughness coefficient ($m^{1/2}/s$) and g is the acceleration due to gravity ($m^2/s$). The widths of rivers in the Ganges Tidal Plain are so large compared to depth that the cross-sections can be represented as equivalent rectangular sections in the model. The smallest width-depth ratio in the modelled rivers was 28:1. The rectangular river section is provided with horizontal floodplains on both banks and then sloping land surfaces. Identification of important channels for representation in the model was done with the help of 1:500000 scale Landsat imageries taken on March 1988 at Space Research and Remote sensing Organization. River cross-section data were extracted from bathymetric charts collected from Bangladesh Inland Water Transport Authority. Data on some river cross-sections were obtained from the report of Sir William Halcrow & Partners Ltd. (1993). Data on land elevation at 1 km square grid have been collected from the data base of Master Plan Organization (presently known as the Water Resources Planning Organization).

The momentum of water in the flooded land remains insignificant if the water depth is not substantial. Then the flooded area can be treated as storage section. With the increase in flood depth, part of the flooded area begins to act as conveying section. So the effective conveyance area, required for computing discharge and hydraulic radius, has been determined by a methodology after McDowell and O'Connor (1977) as given below.

$$A = A_r + A_f \, (Y_f / Y_r)^{0.5} \tag{4}$$

Where $A_r$ and $A_f$ are areas for river section and flooded section respectively and $Y_r$ and $Y_f$ are water depths in river and floodplain respectively.

**Determination of Flooded Area**

Estimation of flooded area required simulation of tides and storm surges in the 5 major river systems. Numerical model based on Eqs. (2) and (3) gives h and Q at grid points along the river. Discretization of 5 river systems have been shown in Figure 2 and it includes 31 river brances and 15 junctions covering 1478 km of river length. Details of the simulation have been discussed in the report by Karim and Chowdhury (1995). Solution of Eqs. (2) and (3) requires specification of boundary conditions. The discharges were specified at inland model boundaries located at distances beyond the tidal limits given in Table 1. The water level hydrograph was specified as boundary condition at an estuary inlet. Calibration and verification of the model were made against observed spring tides.

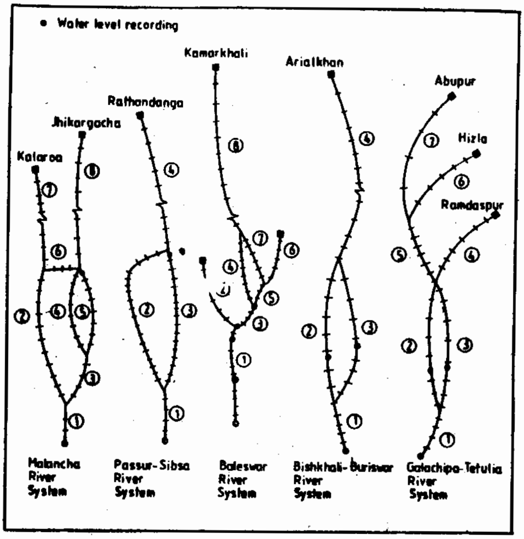

*Fig 2. Schematization of Five River Systems in the Ganges Tidal Plain*

Prediction of flooded area was made for the extreme condition where peak surge reached the coast at the time of spring tide high water. In this case the vertical displacement of water level is highest. In fact such extreme condition occurred during the cyclone of April 1991 when approximately 138000 people were killed. The water level boundary condition at an estuary inlet was approximated by superposing a sinusoidal semi-diurnal tidal hydrograph and a triangular storm surge hydrograph. The triangular surge hydrograph is consistent with the computed surges in the two-dimenstional hydrodynamic model studies of storm surges in the Bay of Bengal by Ahsan and Chowdhury (1986), Kampsax and others (1992). The boundary condition at the estuary inlet can be expressed mathematically as given below.

$$h_b = Z_0 - 0.5\,S\,\mathrm{Cos}\,(2\pi t/T) + 2H\,(r + (1 - 2r)\,t/T) \qquad (5)$$

$r = 0$ for $0 \le t \le 0.5T$;

$r = 1$ for $0.5T < t \le T$.

Where $h_b$ is the elevation of water level at the estuary inlet (m), $Z_0$ is the height of mean tide level above msl at the estuary inlet (m), T is the period of semi-diurnal tide (s), S is the range of spring tide (m) and H is given by Eq.(1). Values of S are given in Table 1 while those of H in Table2.

Predicted intrusion distances of 0.2m surge residual in 5 river systems for different return periods are given in Table 3. It is seen that the intrusion distances of surges are not larger in rivers having higher values of H compared to those in rivers having lower H. For example, the largest intrusion distance of 62 km occurs in the Baleswar river where H is 5.8m for 100 years return period while the intrusion distance is 51 km in the Galachipa-Tetulia river which has the highest H of 6.4 m. The intrusion distances in 5 rivers systems vary from 44 to 55 km for H of 20 years return period while 50 to 62 km for H of 100 years return period. Based on information on past storm surge floods, approximate surge intrusion distances have been reported in BUET and BIDS (1993) and they vary from 38 to 58 km. The predicted intrusion distances do not differ much from the historical information.

Model predicted flooded areas for each river system are also included in Table 3. The predicted total flooded areas are 5265, 5464 and 5567 sq. km. for H of 20, 50 and 100 years return periods respectively. It is observed that the magnitude of flooded area is relatively insensitive to large variation in H. The flooded area increases by less than 16% when the return period of H is increased from 20 years to 100 years. The 100 - year H is nearly 60% higher than the 20-year H. Insensitiveness of the flooded area implies that the possible error in the boundary condition in Eq. (5) has minor influence upon the predicted magnitude of flooded area.

**Table 3. Model computed storm surge intrusion distance and flooded areas**

| River | Peak surge height (H) at estuary inlet (m) | Return period of peak surge height (years) | Intrusion distance of 0.2m surge residual (km) | Flooded area (km$^2$) |
|---|---|---|---|---|
| Malancha | 3.0 | 20 | 55 | 980 |
| | 4.1 | 50 | 58 | 1021 |
| | 5.0 | 100 | 61 | 1039 |
| Passur Sibsa | 3.1 | 20 | 52 | 1250 |
| | 4.2 | 50 | 56 | 1285 |
| | 5.2 | 100 | 60 | 1308 |
| Baleswar | 3.5 | 20 | 53 | 1140 |
| | 4.8 | 50 | 58 | 1192 |
| | 5.8 | 100 | 62 | 1213 |
| Biskhali-Buriswar | 3.6 | 20 | 44 | 1020 |
| | 4.9 | 50 | 46 | 1058 |
| | 6.0 | 100 | 50 | 1079 |
| Biskhali-Buriswar | 3.9 | 20 | 46 | 875 |
| | 5.3 | 50 | 48 | 907 |
| | 6.4 | 100 | 51 | 928 |

Model computed water surface profiles along the Baleswar river for H of 20, 50 and 100 years return periods are shown in Figure 3 where profiles of river bank level and spring tide high water are also shown. It is seen that the storm surge dampens quite rapidly. This is mainly because of the effect of vast storage of flood water on the land.

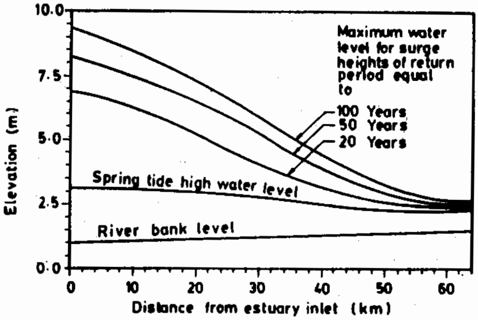

*Fig 3. Computed Maximum Water Level Profiles Along the Baleswar River System*

## RISK ANALYSIS

### Risk Index

A method of risk assessment has been used by Mott MacDonald and Others (1993) to prepare comprehensive disaster management programme under the Ministry of Relief of the Government of Bangladesh. This approach has been followed here. It is a Risk Index (RI) for a unit of land based on a Hazard Factor (HF) and a Vulnerability Factor (VF) as expressed below.

$$RI = HF \times VF \tag{6a}$$

$$HF = \frac{\text{HI of the land unit} \times 10}{\text{highest HI among all land units}} \tag{6b}$$

$$VF = \frac{\text{DP of the land unit} \times 10}{\text{highest DP among all land units}} \tag{6c}$$

Where HI is the hazard index and DP is the density of population.

As per method in Mott MacDonald and Others (1993), a scale is to be devised for the HI in eq. (6b). This approach is somewhat different from that suggested in a manual prepared under the auspices of the UNDRO (1991). In that manual, the hazard factor is a probabilistic function of magnitude of the phenomena causing the hazard over time. However absence of time series data on flooded area did not permit a probability analysis. To devise a scale for HI, three critical values for flood depths have been selected here and they are 0.6, 1.0 and 3.5 m. The basis is as follows. The height of plinth level above the ground is usually 0.6 m in school buildings, community centres and public buildings. As per BUET and BIDS (1993), there is a possibility of loss of lives when the depth of storm surge flood exceeds 1.0 m. The minimum height of stilts for shelters proposed by BUET and BIDS (1993) is 3.5 m.

The relative measure of hazard to population is represented here by an integer value for HI and it is a function of critical flood depths. Three alternative scales for HI have been investigated by Karim and Chowdhury (1995). (1) HI increases linearly, (2) the rate of increase in HI is linear and (3) HI increases geometrically. It is observed that the linear scale for HI produces a map of RIs which is consistent with the severely affected areas identified in BUET and BIDS (1993) based on historical records of damage. So the scale for HI selected here is as follows.

$0 < d \leq 0.6m$ : $HI = 1$

$0.6m < d \leq 1.0m$ : $HI = 2$

$1.0m < d \leq 3.5m$ : $HI = 3$

$3.5m < d$ : $HI = 4$

Where d = h-G, G is the elevation of ground surface in m and h is obtained from numerical simulation based on Eqs. (2) and (3).

## DELINEATION OF LAND UNITS

The flood prone area is to be divided into land units so that HIs can be determined for them. For practical advantages, a land unit should not cross an administrative boundary. The Thana is an important geographical boundary in the Local Government administration system in Bangladesh. The Thana has been subdivided into land units such that the spatial range of variation of flood depth in a land unit fits into one of the depth ranges of the HI scale. This delineation has been done by overlaying the contours of 0.6, 1.0 and 3.5 m flood depths on a map showing Thana boundaries. These depth contours are based on the result of numerical model simulation corresponding to the peak surge heights of 100 years return period at estuary inlets. A total of 45 land units have been delineated as shown in Figure 4 and listed in Table 4. It may be mentioned that the number of Thanas in the flood prone area is 15. The density of population among land units varies from 58 to 719 persons per sq. km. Data on population density from 1991 census have been used and they have been obtained from the Bangladesh Bureau of Statistics (1993).

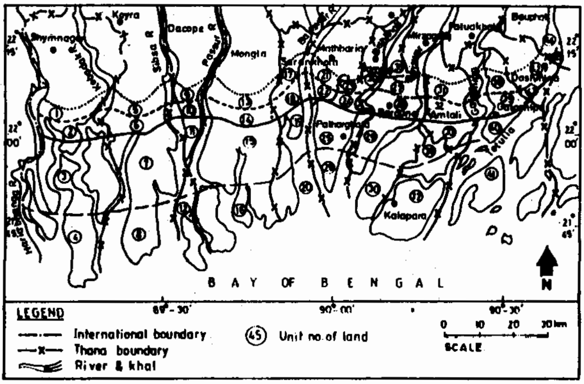

*Fig 4. Land Units in the Storm Surge Flood Prone Area in the Ganges Tidal Plain*

## RISK ZONES

RIs have been computed for all land units using Eqs. (6a-c). They are listed in Table 4. Priority areas for construction of shelters can be selected from this table. For example, land units 30 and 37 should get the highest priority. It is seen that the RI varies from 4.5 to 50.0 among 45 land units. The flood prone area can be divided into four risk zones by selecting four equal intervals of RI as given below.

Low Risk Zone : $0 < RI \leq 12.5$;
Moderate Risk Zone : $12.5 < RI \leq 25.0$;
High Risk Zone : $25.0 < RI \leq 37.5$;
Severe Risk Zone : $37.5 < RI \leq 50.0$

**Table 4. Risk Index Values of land units of the Flood Prone Area**

| Thana | Land Unit | Risk Index | Thana | Land Unit | Risk Index | Thana | Land Unit | Risk Index |
|---|---|---|---|---|---|---|---|---|
| Shymnagar | 1 | 5.5 | | 16 | 10.0 | | 31 | 12.5 |
| | 2 | 9.5 | | 17 | 7.8 | Amtali | 32 | 23.0 |
| | 3 | 9.0 | Sarankhola | 18 | 10.0 | | 33 | 33.0 |
| | 4 | 10.0 | | 19 | 11.3 | Bamna | 34 | 22.8 |
| | 5 | 4.5 | | 20 | 12.0 | Betagi | 35 | 23.0 |
| Koyra | 6 | 7.0 | Mathbaria | 21 | 25.0 | Kalapara | 36 | 39.0 |
| | 7 | 9.0 | | 22 | 46.0 | | 37 | 50.0 |
| | 8 | 10.0 | | 23 | 15.0 | | 38 | 11.3 |
| | 9 | 6.3 | Patharghata | 24 | 26.0 | | 39 | 15.5 |
| Dacope | 10 | 9.0 | | 25 | 31.5 | Galachipa | 40 | 22.5 |
| | 11 | 12.0 | | 26 | 34.0 | | 41 | 26.0 |
| | 12 | 11.0 | | 27 | 18.8 | Dasmina | 42 | 10.0 |
| | 13 | 4.5 | Barguna | 28 | 34.5 | | 43 | 19.0 |
| Mongla | 14 | 8.0 | | 29 | 43.5 | Bauphal | 44 | 20.0 |
| | 15 | 9.8 | | 30 | 50.0 | | 45 | 39.0 |

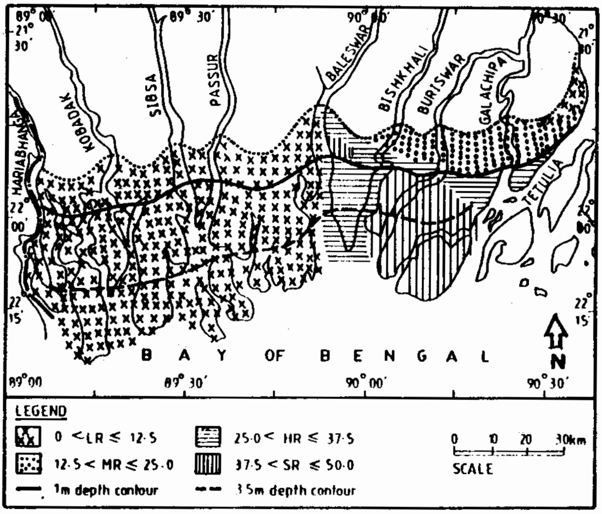

*Fig 5. Risk Index Map of Storm Surge Flood Prone Area in the Ganges Tidal Plain (LR : Low Risk; MR : Moderate Risk; HR : High Risk; SR: Severe Risk).*

Figure 5 displays various risk zones of the flood prone area in the Ganges Tidal Plain. Number of land units, areas and population of different risk zones are given in Table 5. It is seen from Figure 5 that entire western half of flood prone area has low risk. This is because it is covered by forest (Sundarban) which has very thin population. The forest area in the low risk zone is approximately 3230 sq. km. while the total area in the low risk zone in the Ganges Tidal Plain is 3602 sq. km. as shown by Table 5. The population of the forest area in the low risk zone is approximately 333500. It is seen from Figure 5 that a small area adjacent to the Baleswar river but quite inland from the sea is in the severe risk zone. This is because the area has the highest population density.

Population is the only element at risk in above analysis. More comprehensive risk analysis can be done by considering damages to other elements which depends on the distribution of land-use such as village, agricultural land, rural growth centre, infrastructure etc. Future studies can consider these aspects which would be useful in planning disaster preparedness programme and hazard reduction measures.

**Table 5. Number of land units, areas and population of risk zones**

| Zones | No. of land units | Area ($km^2$) | Population |
|---|---|---|---|
| Low Risk | 23* | 3602* | 452,200* |
| Moderate Risk | 10 | 788 | 303,900 |
| High Risk | 6 | 518 | 168,000 |
| Severe Risk | 6 | 659 | 262,200 |

[* Includes forest area of approximately 3230 sq. km. having population 333,500]

## HYDRAULIC IMPACTS OF EMBANKMENT

Flooding of adjacent land can be prevented by constructing embankment parallel to the river bank. Construction of embankment reduces the storage area for flood water and confines the flow to the river. As a result, the propagation characteristics of storm surges along the river would change. A computer experiment has been performed to assess the hydraulic impacts of embankments located along both sides of the river bank. Set back distances and the side slopes were specified as per criteria given in Kampsax and Others (1992). The height of embankment was specified such that the storm surge did not overtop it.

A comparison of predicted surge residuals at specified locations along the Baleswar is given in Table 6. It indicates that the intrusion distance increases substantially in embanked condition compared to that in the unembanked condition.The height of storm surge also

**Table 6. Comparison of simulated surge heights at different locations along the Baleswar river for 'with' and 'without' embankment situations.**

| Peak surge height at estuary inlet (m) | Surge residuals in m at a distance of | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 30km | | 40km | | 50km | | 60km | |
| | NE | WE | NE | WE | NE | WE | NE | WE |
| 3.5 | 1.31 | 2.25 | 0.63 | 1.75 | 0.25 | 1.13 | 0.10 | 0.81 |
| 4.8 | 2.28 | 3.00 | 1.15 | 2.50 | 0.52 | 1.82 | 0.18 | 1.00 |
| 5.8 | 3.00 | 4.18 | 1.75 | 3.15 | 0.87 | 2.30 | 0.28 | 1.20 |

[ NE : No embankment; WE : with embankment] increases considerably. For example, at 50 km inland, the increase in surge height is 250% when the peak surge height at the estuary inlet is 4.8 m. These results indicate that higher and longer embankment would be required to offset the increases in surge height and intrusion distance.

If the embankment fails during the storm surge then the damage would be much higher compared to that in the without embankment situation. This is because the failure of embankment would create a hydraulic condition similar to that of the dam-break wave. So construction of embankment may increase the risk of greater catastrophy. The study by BUET and BIDS (1993) observed that there were loss of lives and extensive damages as embankment failed. The report of Kampsax and Others (1992) records that, for protection of human lives, a coastal embankment that was breached during cyclonic condition was worse than no coastal embankment.

## CONCLUSIONS

The storm surge flood prone areas in the Ganges Tidal Plain as simulated by a numerical hydrodynamic model, are 5265, 5464 and 5567 sq. km. when the peak surge heights at estuary inlets are of 20, 50 and 100 years return periods respectively. The risk index which reflects flood risk to population, varies from 4.5 to 50.0 among 45 land units. The areas of low risk, moderate risk, high risk and severe risk zones are 3602, 788, 518 and 659 sq. km. respectively. Constructions of embankment along a river to prevent storm surge flooding is likely to cause substantial amplification of the surge height in the river as well as increase in the intrusion distance.

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