Identification of Erosion Potential in an Urban River in North Australia Using GIS and Hydrodynamic Model

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Abstract: Soil erosion is a major environmental problem in urban areas due to factors such as increased level of flooding that can be attributed to greater impervious areas and lined and piped drainage system. This paper presents a case study, which identifies erosion potential areas in a coastal urban river in Australia using Geographical Information System (GIS) and two-dimensional hydrodynamic modeling techniques. The study catchment Nerang River flows through the Gold Coast City, which is a large urban centre located in southeast Queensland in North Australia. The study used Shields diagram and MIKE 21 hydrodynamic model on a 20 m grid system to identify potential erosion areas within the river for tidal flows and 10, 20, 50, 100, 200, 500 average recurrence intervals (ARIs) and probable maximum flood events. The GIS was used to spatially represent the results of the hydrodynamic modeling and then perform calculations to determine if the threshold for motion for a soil particle at each grid cell of the model bounds was exceeded. It was found that erosion potential is higher during the floods than the tidal cycles, and extent of erosion affected area increases with ARI of flood event. The findings of the study will be useful in the Nerang River management for high flow regime in relation to mass movement, bank stability, river habitat and recreational use of the river.

Keywords: *Erosion; Flooding; GIS; Hydrodynamic modeling*

1. INTRODUCTION

Riverbed erosion occurs as a result of increased flow velocity causing an increase in bed shear stress. The erosion rate depends on the force applied by the water and self-weight of the sediment particles. Boon (1998) noted that there are four main processes that contribute to riverbed erosion: (a) reduction in sediment supplies to re-nourish the depleted areas; (b) increase in riverbed slope causing an increase in the bed shear stress; (c) increase in flow velocity causing an increase in the bed shear stress; and (d) increase in discharge resulting in greater velocities within the channel.

Since runoff volume and velocity of streamflow can increase significantly in urban rivers as compared to pre-urbanised condition, the river-erosion in urban rivers may be a serious problem particularly during major floods. This paper presents a case study on erosion in a coastal urban river in southeast Queensland of Australia. The study catchment Nerang River is flowing through Gold Coast, which is one of the most rapidly growing urban areas in Australia. The study area is subject to significant tidal effect thus river erosion can occur in both downstream and upstream directions depending on the dominant flow direction. The study uses GIS, two-dimensional hydrodynamic model and Shields curve (Shields, 1936) as represented by Guo (1997) to identify erosion potential areas within the river due to tidal effect and floods of different frequencies.

The paper begins with the description of study area and data, followed by the presentation of the method and results.

2. STUDY AREA AND DATA

The Nerang River catchment having an area of 489 km^2 is used in the study. The catchment is surrounded by the McPherson Ranges on the south, the Pacific Ocean on the east, the Broadwater on the north and the Hinterland on the west. The system is comprised of numerous contributing creeks that eventually discharge into the Broadwater. The Broadwater represents the end-point of this river system, which is directly connected to the Pacific Ocean at the Southport Seaway. The Southport Seaway was constructed in 1986 to stabilize the northward progression of the Nerang River mouth.

Some 14% of the catchment area is inundated during a 1% annual exceedance probability (AEP) flood, which results in considerable over-floor flooding within the Gold Coast City, which is highly urbanised. The lower reaches of the Nerang River are protected by revetment walls to prevent riverbank erosion. Some of these walls have shown sign of failure in recent years.

The extent of the Nerang River model described here bounded by the Broadwater on the north, Burleigh Hill on the south, Pacific Ocean on the east and Pacific Highway on the west covering an area of 176 km^2, as shown in Figure 1. This part of the Nerang River is affected by tide.

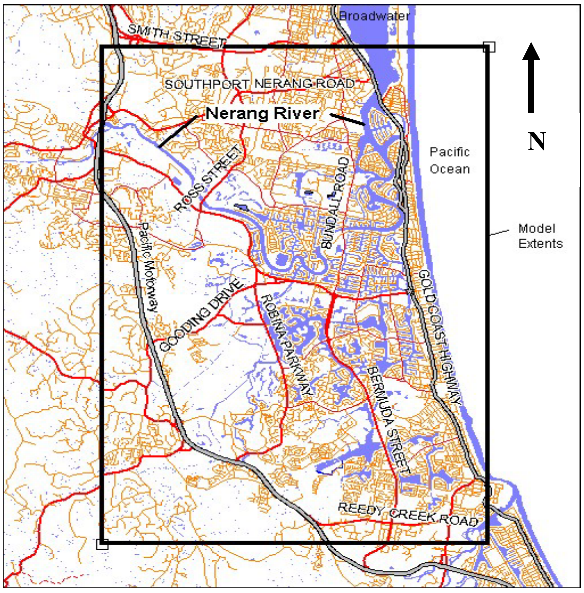


Figure 1. The extent of the model area

The sediment in the lower reaches of the Nerang River is of ocean origin and the riverbed is generally made up of non-cohesive sand material. The important properties that govern the hydrodynamics of non-cohesive sediments are particle size, shape and specific gravity (USACE, 1995), of which particle size is the most important in sediment transport modeling. Particle size analysis was conducted on sediment samples collected from 9 different locations within the Nerang River. Particle distribution curves on semi-logarithmic graphs were plotted for each sample, from which the 16th, 50th and 84th percentile particle sizes were interpolated and the geometric mean particle size and standard deviation were determined (the values were found to be 0.29 mm and 1.3 mm respectively). The geometric mean particle size of 1.3 mm indicates 'well sorted and uniform' bed material according to Diplas and Southerland (1988). No specific information was available on particle shape and density of the bed material. It was assumed that the bed material is of 'quartz type' and a specific gravity of 2.65 was adopted.

The hydraulic slope of the river was determined from minimum bed levels at two locations within the river located 17.5 km apart giving a slope of 0.00013114 m/m.

3. METHOD

Shields diagram of sediment transport

At the interface between the fluid and the riverbed, a moving fluid applies a shear force to the exposed surface of the sediment particles on the riverbed. This force induces 'bed shear stress' which can be determined from the following equation:

$$\tau_0 = \gamma RS \tag{1}$$

where τ_0 = bed shear stress
γ = specific weight of water
R = hydraulic radius
S = bed slope.

In terms of bed velocity, shear stress can be expressed as:

$$\tau_0 = \gamma (Vn)^{3/2} S^{1/4} \tag{2}$$

where V = bed velocity
n = Manning's coefficient.

Shields (1936) introduced critical shear stress, which refers to the stress required to initiate movement of a sediment particle. Incipient motion is the term commonly used to denote the beginning of sediment motion. Shields (1936) developed a relationship between dimensionless shear stress (known as Shields parameter τ^*) and particle Reynolds number R_* to present his research on sediment transport. These terms can be defined as below.

$$\tau_* = \frac{\tau_0}{\gamma (SG - 1) gD} \tag{3}$$

where SG = specific gravity of the sediment mixture
g = acceleration due to gravity
D = mean particle size.

$$R_* = (\tau_0 / \rho)^{1/2} D / \upsilon \tag{4}$$

where ρ = density of water
ν = kinematic viscosity of water.

Shields (1936) conducted a series of experiments with sediment of selected densities to establish the criterion for incipient sediment motion as shown in Figure 2. The thick line in this figure is the critical condition for incipient motion to occur;

for Shields parameter τ* greater than this line, sediment motion occurs.

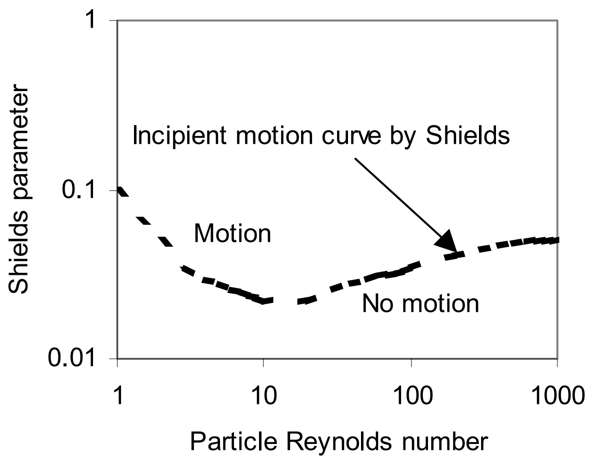


Figure 2. Incipient motion diagram (Shields, 1936)

Guo (1997) developed a formula for the Shields curve as given below, which was adopted in this study to represent the threshold motion of a particle:

$$Y = 0.009148X^{-1} + 0.05449(1 - e^{0.5661z}) \quad (5)$$

where Y = Shield's entrainment function (Y-axis in Figure 2)
X = Particle Reynolds Number (X-axis in Figure 2).
$Z = X^{0.5224}$

Flood modeling

A hydrological model was developed for the study area for the Gold Coast City Council by Gutteridge Haskins and Davey Pty. Ltd. (GHD, 1999). This model was subsequently updated by the Council and was used in this study.

This study utilized a calibrated two-dimensional hydrodynamic model of the Nerang River system, represented on a 20 m grid, to produce peak velocity results that are converted to a spatial GIS format for interrogation. This study used MapInfo and Vertical Mapper as GIS tools. The GIS system performed functional analysis of the grids to allow identification of erosion potential areas within the river system.

Two-dimensional hydrodynamic modeling was undertaken using Mike 21 software (DHI, 2000). The Snowy Mountain Engineering Corporation (SMEC) developed and calibrated this model for the Council for 100-year ARI flood event (SMEC, 2001). The model determines: (a) flux in the x and y direction; and (b) water level for each grid point at each time step. This allows for the extraction of water levels, discharges and velocity in x- and y-direction and resultant. The flood events simulated in the study include 10, 20, 50, 100, 200, 500 years ARIs and probable maximum flood (PMF). The PMF is the flood that has an AEP of 1 in 10^6 (I.E.Aust., 1998). Peak velocities and water depths were extracted from each of the above flood events. The velocities extracted for each grid point represent a depth-averaged velocity for the 400 m^2 represented by each grid point.

Tidal modeling

The Gold Coast City Council developed a two-dimensional Mike 21 model of the Nerang River tidal system, which was calibrated against recorded tide readings sourced from the Queensland Department of Transport. This calibrated tidal model formed the basis for the tidal analysis of this paper.

For the tidal simulation, the peak velocities were extracted from the model covering both the rise and fall of the tide. The simulation velocities represented the peak velocity over the 96-hour period (recorded at 20 minute intervals) for which the flood simulations were run. The Coomera River Tidal Study (Kinhill, 1991) recorded velocities at numerous locations within the Coomera River, which identified the bed velocity to range between 62 and 100 percent of the average velocity. Empirical relationships derived by the United States Bureau of Reclamation (USBR) suggest a ratio of 75 percent of the depth average velocity to be representative of the bed velocity. In determining the appropriate bed velocity in this erosion study, a value of 75% of the extracted depth averaged peak velocity was used for the determination of bed shear stresses.

Computation of erosion potential

The extracted hydrodynamic modelling results were imported to the GIS system, which allows functional manipulation of spatial data. The bed shear stress at each grid point (using Equation 2) within the modelled area for the selected flood events and tidal simulations were estimated. The bed shear stress values were used to determine the Shields' parameters (Equation 3) and particle Reynold's number (Equation 4) for each grid point for the selected flood events and tidal simulations.

The particle Reynolds number derived for each individual grid point was entered into the Guo's equation (Equation 5) to determine the critical value of the Shields parameter for each grid point. The critical value of Shields' parameter is the value at which motion of particles is initiated, i.e. particles are subject to motion if the Shields parameter exceeds the critical value.

Erosion potential areas for the purposes of this study were defined as those areas where the Shields parameter plotted against the particle Reynolds number is above the threshold for motion curve defined by Guo's formulae. These areas were determined from a comparison between the Shields parameter determined for each grid point of each simulation and the critical Shields parameter.

4. RESULTS

Figure 3 illustrates the locations within the Nerang River system that are likely to experience bed erosion resulting from the tide movement, which shows that the erosion potential area is in the order of 3% of the total river area. The affected locations are:

- Within the Broadwater
- Adjacent to Paradise Waters
- Southern End of Chevron Island
- Adjacent to Evandale Council Chambers
- Within the Nerang River between Via Roma Bridge and Florida Gardens Canal
- Within Florida Gardens Canal
- Within Little Tallebudgera Creek
- Within the Nerang River immediately upstream of the intersection of Boobegan Creek.

It is to be noted here that this investigation does not differentiate between incoming and outgoing tides; therefore, the locations identified above may not experience significant scouring and may not demonstrate a net loss of sediment due to the repetition of tidal cycles, but it indicates that there is enough energy in the river at these locations to move sediment particles. The results indicate that the Nerang River is subject to particle movement during tidal cycles and therefore may not be in a state of equilibrium. The lower reaches of the river searches for a balance in an attempt for equilibrium. This will indicate a shifting of sandbanks within the lower reaches possibly causing impacts for marine vessels. The majority of the lower reaches of the river are retained (revetment walls) and therefore minimal bank erosion/bank failure would be expected during tidal conditions.

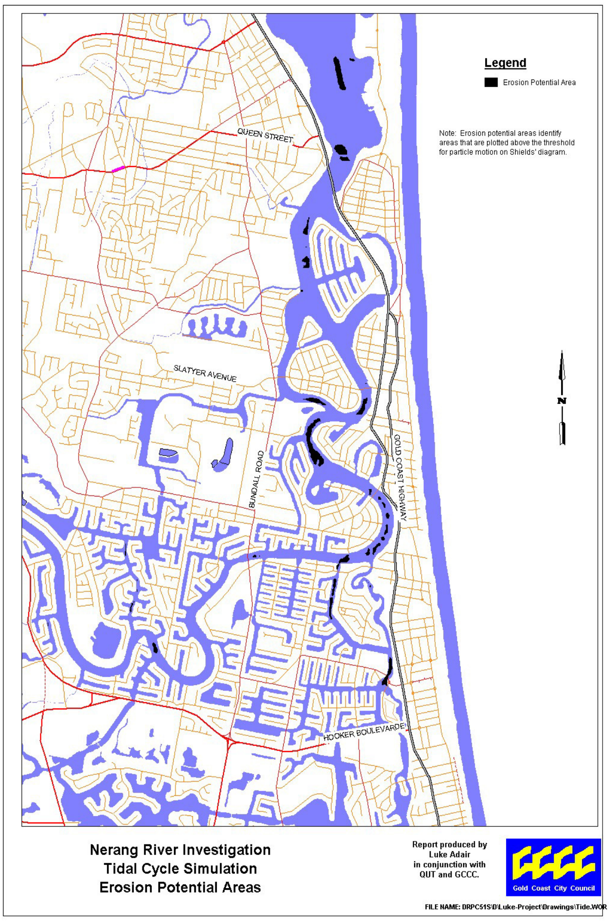
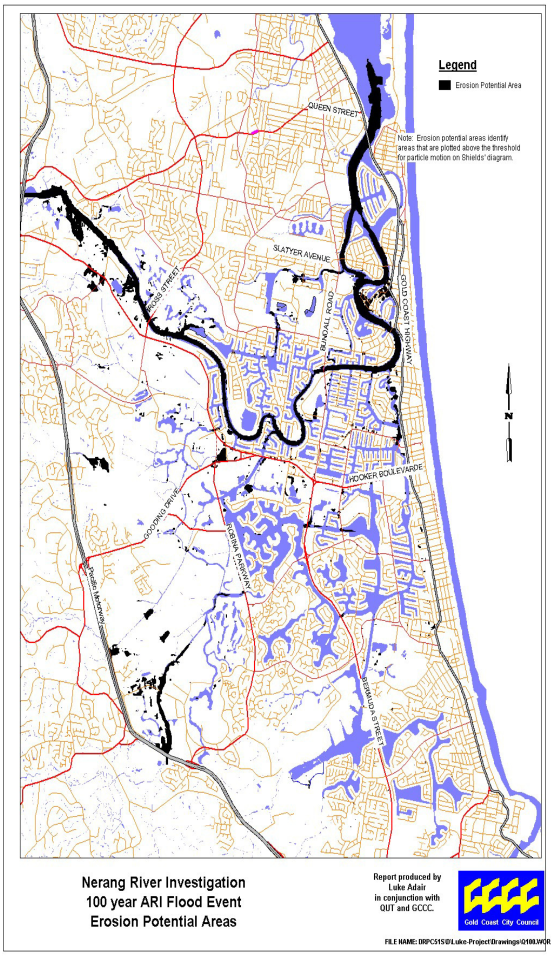


Figure 3. Tidal cycle erosion potential areas (Erosion potential areas are marked in black color)

Unlike tidal movement, the direction of flow during a flood event is in one direction, from upstream to downstream. The peak velocities were found to be greater for flood events than that of tidal movement. Figure 4 demonstrates the 100-year ARI erosion potential areas, which shows that the erosion potential area in this case is much greater than that of tidal cycles.

Considering the plots of all the selected ARIs, the erosion potential areas within the main river were estimated to be in the order of 80%, 85%, 90%, 95%, 98% and 100% for ARIs of 10, 20, 50, 100, 200 and 500 years. The erosion potential for PMF is extremely high as illustrated in Figure 5. It was found that the erosion potential area increases with the ARI of flood event, which is as expected. It is to be noted that the particle sizes used for these calculations were sourced within the river and not from river overbanks.



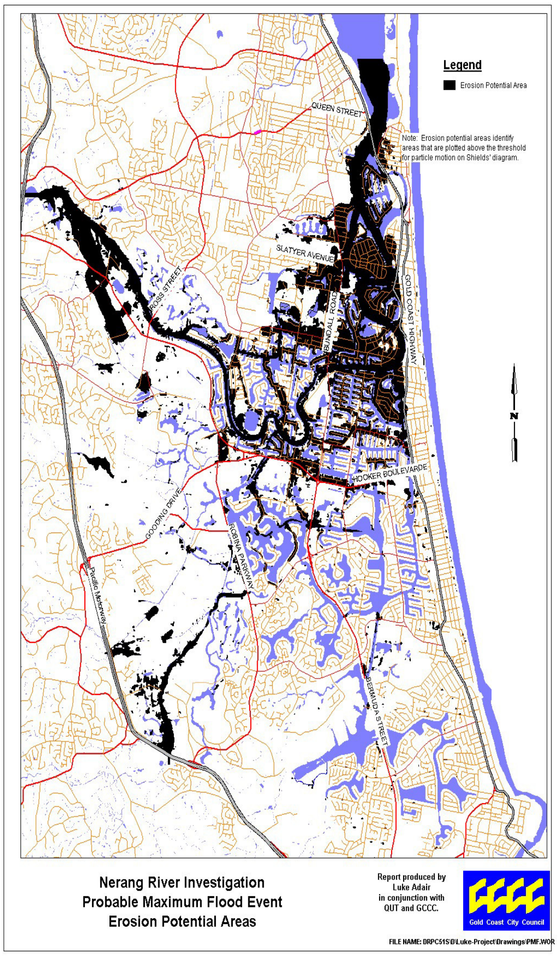


Figure 4. 100-year ARI flood erosion potential areas (Erosion potential areas are marked in black color)

Figure 5. Erosion potential for PMF (Erosion potential areas are marked in black color)

The results of this investigation indicate that a major flood event will result in significant bed erosion in the Nerang River. If the affected area is located in the close proximity of the riverbank, the existing revetment walls may be badly affected. The increased level of bed material in river water is likely to have an adverse impact on marine life and aquatic plants. During a high flood (greater than 100-year ARI), the erosion rate will be significantly higher, that may lead to significant bank failure and shift of sand banks, which is likely to affect aquatic flora and fauna and recreational use of the river.

5. CONCLUSIONS

A method for determining erosion potential areas in the Nerang River Gold Coast has been developed incorporating results from two-dimensional hydrodynamic modeling and GIS. The method covers flood events ranging from 10-year to PMF and tidal cycles. The following conclusions can be made from this case study:

- The Nerang River system in Gold Coast Australia is subject to bed erosion during tidal cycles, but the affected area is relatively smaller, in the order of about 3% of the total river area.
- The flood events show far greater erosion potential than the tidal cycles. In the case of 10-year flood, the erosion potential area is close to 80% of the river area. For 100-year flood, this is close to 95%. The erosion potential area increases with ARIs of flood events.

- The erosion potential for PMF is extremely high.
- The findings of the study will be useful in the Nerang River management during high flow regime in relation to mass movement, bank stability, river habitat and recreational use of the river.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Boon, S., DNR River Facts - What Causes Stream Bed Erosion. Department of Natural Resources Queensland, Water and Catchment Management Unit, June 1998.

DHI, Danish Hydraulic Institute, Mike 21 modelling software, 2000.

Diplas, P., and Sutherland, A., Sampling Techniques for Gravel Sized Sediments. American Society of Civil Engineers, Journal of Hydraulic Engineering, 114: 481-501, 1988.

GHD, Nerang River Hydrological Model. Prepared by Gutteridge Haskins and Davey Pty Ltd for the Gold Coast City Council, December 1999.

Guo, J., The Albert Shields Story Discussion. American Society of Civil Engineers Journal of Hydraulic Engineering, page 666, July 1997.

I.E. Aust., Australian Rainfall and Runoff – A Guide to Flood Estimation. Institution of Engineers, Australia, 1998.

Kinhill Cameron McNamara, Coomera River Tidal Studies, prepared for Albert Shire Council, 1991.

Shields, A., Anwendung der Aechichkeits-mechanik und der turbuleng forschung aufdir Geschiebewegung' Mitt Preussische. Versuchsanstalt fur Wasserbau and Schiffbau, Berlin, 1936.

SMEC. Nerang River Hydraulic Modeling Study - Final Report. Prepared for the Gold Coast City Council, May 2001.

United States Army Corp of Engineers (USACE). Engineering Design Sedimentation Investigations of Rivers and Reservoirs. Manual No. 1110-2-4000, 1995.