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Quantification of Shoreline Change in Salaverry, Peru

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ABSTRACT

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A set of groynes and breakwaters were constructed in 1956 around the Salaverry Maritime Terminal in the northern coast of Peru to facilitate port operations. As a result, part of the longshore transport was blocked, producing undesirable impacts along the coastline. Apart from local bathymetric monitoring, a thorough shoreline change assessment has not been carried out. The aim of this study is to quantify shoreline change donwdrift of the Terminal using a combination of mapping techniques. Erosion/accretion rates were estimated using GIS, yielding an average erosion rate of 3.2m/year between 1976 and 1997, with a maximum of 7.6m/year. Despite limitations on data availability and quality, results were consistent with field observations and point measurements from aerial photographs. The potential mapping error to actual shoreline variation ratio is small and outcomes of this study can be considered statistically reliable. The integration of qualitative and quantitative data into a GIS framework is the most effective method to model erosion hazards.

ADDITIONAL INDEX WORDS: *Shoreline variation, erosion, GIS, peruvian coast, groyne, breakwater.*

INTRODUCTION

Shoreline mapping and trend quantification methods are not a homogenous practice. From simple beach profiling to the utilization of historic maps, remote sensing and state-of-the-art GIS methodologies, several factors influence the selection of techniques. Aerial photography is the most common source to map the shoreline (MOORE, 2001). It replaced the labour intensive and time-consuming traditional field surveying, although more recently available technologies like GPS or video techniques (e.g. PAJAK and LEATHERMAN, 2002; HOLAND *et al.,* 1997) have gained popularity with researchers because of advantages in time and cost.

Unfortunately, even simple data are not always available, especially in less-developed countries. Moreover, when data is accessible the quality and resolution (both temporal and spatial) are not always ideal, making the estimation of the rates of shoreline change unreliable, as they can only be as accurate as their sources (CROWELL *et al.*, 1991).

BACKGROUND

The coastal area in Peru has been occupied by ancient civilizations since the year 7000 BP. Currently, 52.3%, live within 50km of the shoreline (8.8% of the country's total area). The dynamic coastal zone is under constant pressure from increasing human development, acting simultaneously as a supply of resources, residential and recreational space, and a strategic area for commerce and communications. A thorough understanding of the complex coastal system, including the physical, ecological and human relationships, has become essential for integrated coastal planning and management.

As noted by BIRD (1985), most of the coastlines around the globe are tending to erode due to the current Holocene marine transgression. This erosion is particularly evident in low-lying sandy shores coinciding with dense population distributions such as along the northern Peruvian coast. Erosion hazards occur as a result of human actions in the coastal system; either by the modification of physical processes or by incrementing the vulnerability of the zone (e.g. building of infrastructures or dwellings). Shoreline-change data are indispensable to determining trends and potential effects of shoreline erosion or accretion on coastal communities and structures (BERGER and IAMS, 1996).

STUDY AREA

The Salaverry Maritime Terminal is located 15km south of the city of Trujillo, in the northern coast of Peru (Figure 1). The area is characterised by wide extents of moderate-energy sandy beaches (d_{50}=0.15mm). Some rocky headlands provide shelter from the predominantly S/SW swell that generates a net northward longshore transport (ENAPU, 1980).

Wave records from 1976-1977 determined the significant wave height (H_s) to be 1.5m, with a period of 13s.There was not a clear seasonal wave climate although wave heights were usually higher from May to July, reaching an annual mean maximum (H_{max}) of 2.3m, with periods up to 19.5s. South to southeasterly winds predominated, fluctuating between 2m/s in the mornings and 5m/s in the afternoons. Tides are semi-diurnal and have a mean range of 1.4m (SMECS, 1997).

A set of groynes and breakwaters were constructed in 1956 around the Terminal to provide more shelter from waves and facilitate port operations. As a result, the main breakwater blocked part of the longshore transport at an estimated rate of 1,000,000m³/year. In less than 10 years, accretion in the order of 600,000m³/year, occured in the lee of the breakwater. As a solution to this problem, the main breakwater was extended 110 meters (ENAPU, 1980).

In 1979, accumulation of sediments again reached the extent of the breakwater and sediment started to drift around and generate a shoal in the harbour entrance. An estimated 650,000m³/year of sediment began to deposit inside the protected port. After a technical study, the National Port Company (ENAPU) opted to append a new groyne to the breakwater and implement maintenance dredging to avoid deposition problems (OLIVERA, 1981).

The blockage of the littoral drift has generated undesired effects on the region. Both, accretion in the updrift and corresponding erosion downdrift of the Terminal represent high costs of maintenance and increased erosion hazards. Apart from local hydrographic and bathymetric monitoring (e.g. ENAPU, 1980; SMECS, 1997), a thorough shoreline change assessment has not been carried out. The aim of this study is to quantify and evaluate shoreline change downdrift of the Terminal in a GIS framework.

Figure 1. Location map showing the study site

METHODS

A combination of shoreline mapping techniques based on maps and aerial photography were used to quantify the shoreline variation north of the Salaverry Terminal. Data were compiled and selected based on availability and usability limitations.

Maps

Historic maps for the Salaverry area cover a time span of less than 80 years. Differences in coordinate projections and datums were found not to be a problem due to the ease of geometrical conversions using GIS. Two types of vertical datums were found. Mean Sea Level was used in maps generated from photographic aerotriangulation, and a Mean Lower Low Water tidal datum was used in coastal charts.

Two 1:25,000 maps elaborated by the Ministry of Agriculture were chosen because of their large scale and verified accuracy. The paper maps were scanned and corrected for deformations using ArcView 3.2 GIS. The shorelines were extracted using heads-up digitizing to reduce errors of interpretation, as suggested by BURROUGH and MCDONELL (1998). ArcView 3.2 with the Spatial Analysis extension was used to perform the comparison of shoreline change adapting the Grid and Graph methodology proposed by DUFFY and DICKSON (1995). This technique divides the shoreline in 100m equal intervals and estimates end-point-rate (EPR) values that are showed in a bar graph, enhancing the interpretation of very subtle shoreline variation (Figure 2).

Aerial Photography

The temporal frequency and availability of large-scale aerial photographs allowed generation of further estimates of shoreline change. Geometric corrections could not be made using softcopy photogrammetry as described by Moore (2000), because camera calibration models were unavailable and ground control could not be undertaken with sub-meter accuracies due to funding and equipment limitations.

A simpler point measurement technique developed by Stafford in 1971 (MOORE, 2000) was used instead, minimizing errors to within 0.2mm at photo scale by using the center 60% of the images (CROWELL *et al.*, 1991). Aerial photographs from 1942 (1:12,000), 1969 (1:15,000) and 2000 (1:17,000) were used to estimate the shoreline change, using the high water line (HWL) as a shoreline indicator (Table 1). Three locations along the coast: V.L Herrera, Las Delicias and the Salaverry terminal (Figure 2), were chosen due to their consistency and easy recognition of features in the three sets of photos.

Field Evaluation

Qualitative data collected in the field (visual observations and interviews) were used to assess the results obtained and identify coastal erosion risk perception and vulnerability. Data were integrated into the GIS using Hot Links that displayed it when an area of interest was clicked (Figure 3).

ANALYSIS AND DISCUSSION

Shoreline Change In The Study Area

The comparison between maps covered 6km of shoreline, 12km north of Salaverry, as shown in figure 2. Analyzed data in this area yielded an average erosion rate of 3.2m/year between 1976 and 1997, associated with the modification of the Salaverry Maritime Terminal. The erosion rates decreased to near zero values close to V.L Herrera, 13Km to the north of Salaverry. Results from aerial photography comparisons support the results (Table 1).

It can be seen that there was an apparent negative trend of erosion northwards from the Terminal, abruptly reversed in Las Delicias where accretion takes place. This reversal is attributed to the construction of a groyne with an attached seawall in 1995, after accelerated erosion caused serious damage to exposed buildings (SNMECS, 1997). Accretion occurred in the lee of the seawall gaining approximately 20m of beach at a rate of 10m/year.

The maximum rate of erosion illustrated is estimated around 7.6m/year in the northern sector of Las Delicias, adding up to a total of 160m of shoreline recession. This rate is similar to the 91m of retreat obtained using point measurements from aerial photography between 1969 and 2000. Furthermore, field observations like remains of houses offshore and dweller's testimonies confirm the presence of accelerated trends of erosion during the last 30 years (figure 3). A former road observed in the aerial photos that connected Las Delicias to Salaverry has also disappeared, in despite of various attempts of halting the erosion with the aid of sea walls and other structures (ENAPU, 1980).

Data Analysis Assessment

In the quantification of shoreline change, sources of error play an essential role in the precision and reliability of the results. Even though data were pre-filtered according to scale (>1:25,000 for maps and >1:20,000 for photos), and where accuracy was proved to be unreliable, error residuals are always present in the mapping. Data quality reports and metadata could improve the understanding of the information and hence its usability (VON MEYER *et al.*, 2000), but sources lacked description and error acknowledgement.

Two main types of error can be associated with shoreline mapping. The first one is linked to the quantifiable error from the sources. A predicted worst-case error estimate for shoreline mapping from maps or aerial photographs is within 7.5 and 8.9 m (CROWELL *et al.*, 1991). The second type relates with the uncertainty of the shoreline indicator, and it is relative to the indicator used and the environmental conditions.

Which "Shoreline"?

The shoreline is the actual limit of the confluence between land, sea, atmosphere and biological/cultural boundaries (CARTER, 1988). It is constantly influenced by processes that determine the dynamic beach evolution. Defining a static and 2-dimensional position of this feature is restrictive and has generated controversy among coastal researchers.

A reasonable shoreline indicator or proxy must be practical, repeatable, consistent and reliable (PAJAK and LEATHERMAN, 2002). This means that users must be able to identify and

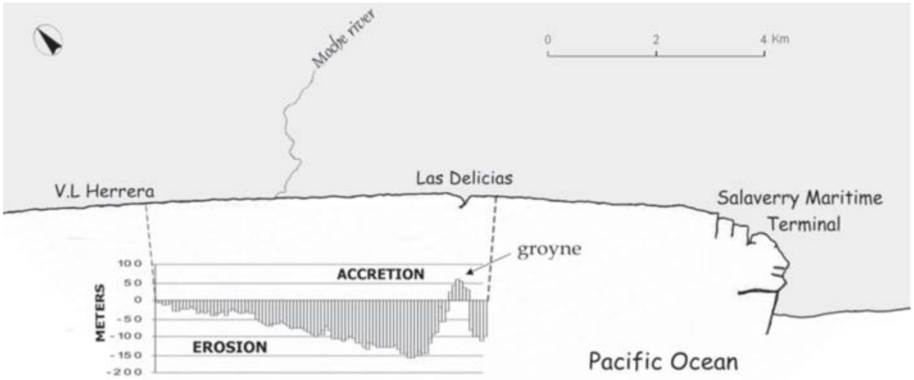

Figure 2. Grid and graph analysis showing rates of change (1976 1997). The area of accretion is due to the groyne built in Las Delicias beach in an attempt to reduce the accelerated erosion associated with the enlargement of the Salaverry maritime terminal's groyne in 1981.

discriminate it precisely without complications, using any technique at any moment of time. In reality, such an indicator cannot be easily defined. The High Water Line (HWL) is considered the best shoreline indicator by many, but not all, researchers (PAJAK and LEATHERMAN, 2002).

This study used HWL as the shoreline indicator extracted from the aerial photography. The advantage of using the HWL as a shoreline proxy is that it was easily photo interpreted (tonal variation). A problem related with this tidal datum is that its position can be highly variable, particularly on gentle-slope sandy beaches. The variation of the HWL is usually in the order of tens of meters; mainly affected by variation of tides, seasonal and cyclic beach changes (e.g. storm/swell profiles, ENSO), storm events, wind and wave setup, and runup (PAJAK and LEATHERMAN, 2002).

Reducing the errors of MHW variation is possible by using images showing swell conditions, particularly between spring and neap tides, and avoiding post-storm data. The HWL position range for these specific conditions is within 10m (PAJAK and LEATHERMAN, 2002). When possible, it is recommended that dune bluff or cliff edges be used as indicators to assure a more stable, and hence reliable long-term position of the shoreline.

Estimating shoreline change

As MOORE (2000) suggests, the selection of techniques to quantify shoreline change is a significant challenge. Factor affecting this decision include the level of accuracy required, the type of output desired, method of ground control collection and the availability of funding/equipment.

The temporal resolution of data was the greatest problem in the accurate analysis of data. To establish a consistent trend of shoreline variation, a long record of more than several decades of shoreline positions is needed (DOUGLAS *et al.*, 1998). In addition, knowledge of metadata and storm events will assure the most accurate and representative calculations (GALGANO *et al.*, 1998), as errors and anomalies could be quantified and incorporated in the analysis.

In this case, trends were defined using the simple EPR technique. This method is straightforward to use but do not produce suitable results, as data between the endpoints is not considered (CROWELL *et al.*, 1997). The modifications of the Salaverry Terminal in different moments of time introduce further variability in the shoreline behavior that are difficult to model. Not only more sets of data are needed, but also other non-linear statistical techniques like polynomial best fits should be regarded (CROWELL *et al.*, 1997).

Even though sources and techniques used were not of the highest quality and errors could be acknowledged but not precisely quantified, the results obtained can still be considered statistically acceptable (CROWELL *et al*., 1997). Total mapping errors are assumed to be ±7.5 meters, plus ±10m due to the variation of MHW. The ratio between potential errors and actual shoreline change (mean change of 76m in 21 years) is still low. In cases like the one in Salaverry where the shoreline variation is large, erosion rates will be highly reliable even where data sources and analysis is restricted.

GIS and Spatial databases

GIS facilitates the process of compilation, storage, analysis and retrieval of large spatial databases, cross-referencing several types of information (BURROUGH and MCDONNELL, 1998). In the present study, maps were geometrical corrected and digitized using GIS software. Source errors could be identified, improving the filtering and selection of datasets, and consequently the quality of results.

The different types of data used in the analysis, including quantitative and qualitative observations, were integrated and simultaneously examined in different spatial scales and discrete moments of time. GIS was an ideal framework to quantify and present shoreline variation rates, although some inherent limitations in multidimensional analysis, especially with temporal analysis as noted by BARLETT (2000), have to be taken into account in further investigations.

High-quality and standardized spatial databases covering longer time spans and geographical extents are needed to improve the prediction capability of coastal systems (KOMAR, 1998) and sharing of information. Transforming this knowledge into appropriate forms and scales propitiates the sharing of information between coastal users (CAPOBIANCO *et al.*, 1999), giving way to better management practices.

The need for a proactive and more integrated approach to the planning of coastal zones is imperative and GIS plays an essential role facilitating this task.

CONCLUSIONS

The use of hard structures to control coastal processes and stabilize the shoreline produced undesirable impacts along the Salaverry coastline. Increased erosion rates on the downdrift side of the Salaverry Maritime Terminal were identified and quantified using mapping techniques.

Despite limitations on data availability and quality, results were consistent with field observations. The potential mapping error to actual shoreline variation ratio is small and outcomes of this study can be considered statistically acceptable and reliable.

A GIS framework is considered to best suit the modelling of erosion hazards. Error reduction is greatly improved by integrating several types of qualitative and quantitative data into one system. In addition, information is shared more efficiently as interpretation is simplified and communication between users facilitated.

Table 1. *Shoreline change (MHW datum) using point measurements from aerial photography*

Years compared	Salaverry	Las Delicias	V.L. Herrera
1942 - 1969	76.5m	-25m	-9m
1969 - 2000	50m	-90.5m	1m

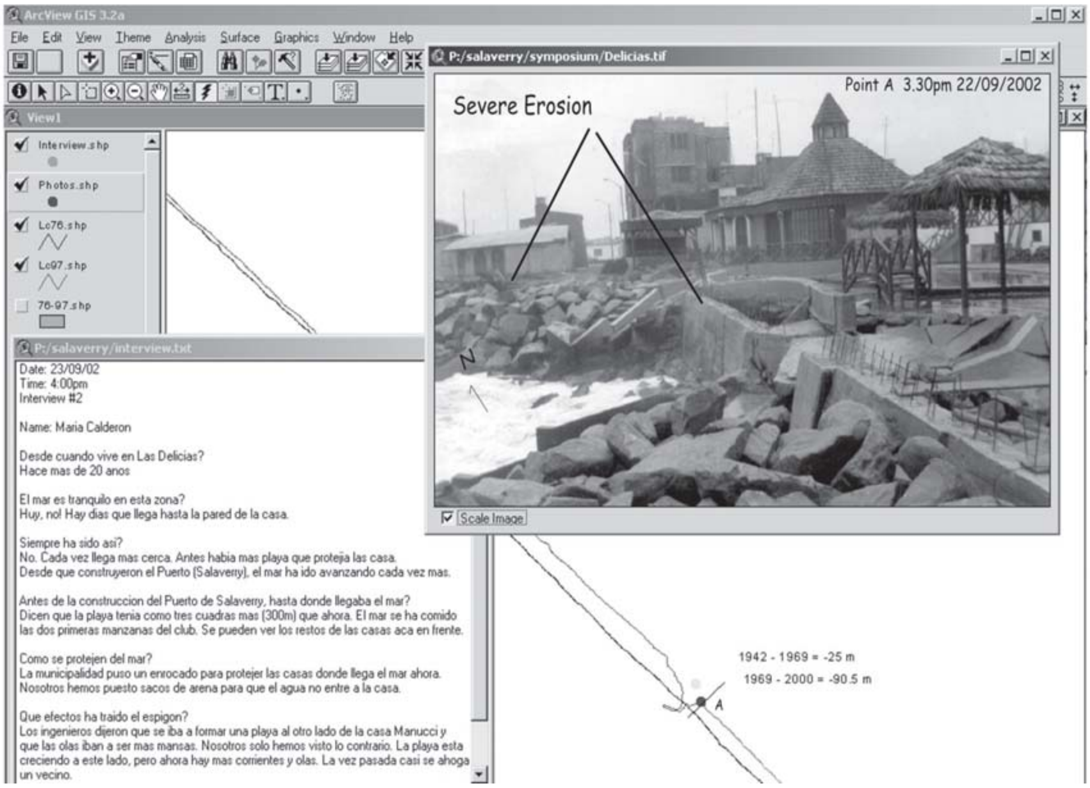

Figure 3. GIS framework integrating qualitative and quantitative data.

Special importance must be regarded to the conception of high-quality spatial databases covering longer spatial and temporal extents. These are needed to improve the effectiveness and accuracy of similar approaches to quantify shoreline variation and focus integrated management policies where required.

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