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ADVANCES IN THE APPLICATION OF DIGITAL ELEVATION MODELS (DEMS) FOR THE EVALUATION OF COASTAL FLOODING

Artigos

ADVANCES IN THE APPLICATION OF DIGITAL ELEVATION MODELS (DEMS) FOR THE EVALUATION OF COASTAL FLOODING

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Abstract:

Abstract

Meteoceanographic forces act daily, provoking rapid changes in coastal geomorphology and impacting the human infrastructure located near the sea, principally on low-lying coasts. The current ongoing rise in sea level provoked by climate change is also a major source of concern for local and regional authorities. Geospatial models of coastal flooding are evolving rapidly, together with geomorphometric tools and their applications. These initiatives may permit the implementation of medium-and long term actions to minimize the effects of flooding, although a range of methodological considerations must be taken into account. Digital Elevation Models (DEMs) have become increasingly more accurate due to the integration of altimetric references and vertical data, as well as the increasing quality of the sensors used. For example, the application of the bathtub approach to coastal flooding assessment has been relatively successful. The choice of the flood model should include the careful selection of methods that ensure the most adequate application of the model.

Keywords: Geomorphometry, Low-Lying Coastal Areas, Coastal Surveying, Remote Sensing.

Resumo:

Resumo

AVANÇOS NA APLICAÇÃO DE MODELOS DIGITAIS DE ELEVAÇÃO (MDES) PARA AVALIAÇÃO DE INUNDAÇÕES COSTEIRAS

As forçantes meteoceanográficas agem diariamente com rápidas mudanças na geomorfologia costeira e nas construções humanas localizadas perto do mar, em especial nas áreas de baixa elevação. Atualmente, a subida do nível do mar potencialmente promovida pelas mudanças climáticas é também uma fonte de grande preocupação para os órgãos públicos de poder local e regional. Nesse sentido, os modelos geoespaciais de inundação costeira estão evoluindo juntamente com as ferramentas morfométricas e suas aplicações. Essas iniciativas permitem ações de médio e longo prazo para minimizar os efeitos das inundações. Para tanto, uma série de etapas metodológicas devem ser analisadas. Os Modelos Digitais de Elevação (MDEs) tornam-se cada vez mais precisos com relação ao emprego de referências altimétricas e de dados verticais, bem como a qualidade de aquisição dos sensores empregados. Por exemplo, o uso da abordagem bathtub tem sido aplicada na avaliação da inundação costeira com relativo sucesso. A escolha do próprio modelo de inundação deve acompanhar um esforço metodológico seletivo para sua correta aplicação.

Palavras-chave: Geomorfometria, Áreas Costeiras Baixas, Levantamento Costeiro, Sensoriamento Remoto.

Resumen:

AVANCES EN LA APLICACIÓN DE MODELOS DIGITALES DE ELEVACIÓN (MDES) PARA LA EVALUACIÓN DE INUNDACIONES COSTERAS

Los factores de cambio meteorológicos y oceanográficos actúan diariamente con rápidas variaciones en la geomorfología costera y las construcciones humanas ubicadas cerca del mar, especialmente en áreas de baja elevación. Actualmente, la subida del nivel del mar, que es potencialmente promovida por el cambio climático, también es motivo de gran preocupación para los organismos públicos del poder local y regional. Respondiendo a esa motivación, los modelos geoespaciales de inundaciones costeras están evolucionando junto con las herramientas morfométricas y sus aplicaciones. Estas iniciativas permiten acciones de mediano y largo plazo para mermar los efectos de las inundaciones. Por tanto, se deben analizar una serie de pasos metodológicos. Los Modelos Digitales de Elevación (MDE) son cada vez más precisos en cuanto al uso de referencias altimétricas y datos verticales, así que a la calidad de adquisición de los sensores empleados. Por ejemplo, el uso del enfoque de cuenca se ha aplicado para evaluar las inundaciones costeras con relativo éxito. La elección del propio modelo de inundación debe acompañar a un esfuerzo metodológico selectivo para su correcta aplicación.

Palabras clave: Geomorfometría, Zonas Costeras Bajas, Estudio Costero, Teledetección.

INTRODUCTION

Modifications of the coastline caused by climate change are one of the principal preoc-cupations of the 21st century, with direct repercussions for coastal zone management around the globe. Climate change is a major driver of land loss from rising sea levels, with an estimated economic impact of approximately US$ 60 billion per year from coastal flooding over the next few decades (HALLEGATTE et al., 2013). Nicholls et al. (2014) concluded that an increase in sea levels resulting from global warming may be inevitable, although the velocity and exact con-figuration of these changes are still unclear. Despite the inherent uncertainties associated with climate modeling, most predictions indicate a substantial rise in sea levels, and adequate tools are required to evaluate potential damage (NICHOLLS et al., 2014; KRUEL, 2016).

Coastal flooding models based on surface analysis have garnered widespread attention in the international scientific community. Increasing access to technology, such as Light Detection And Ranging (LiDAR) and Unmanned Aerial Vehicles (UAVs) with sensors, has enabled the gathering of high-resolution topographic data rapidly, and with considerable precision (EAKINS & GROTHE, 2014; NEX & REMONDINO, 2014). Over the past decade, these technologies, combined with the Global Satellite Navigation Systems (GNSS), have permitted researchers to increase significantly the number of studies that assess the impacts of sea level modifications (ANTONIOLI et al., 2017), especially on low-lying coasts, which have a reduced altimetric am-plitude (WONG et al., 2014).

The international literature covers a wide spectrum of computational tools for the georeferencing, forecasting, and evaluation of coastal flooding (LICHTER & FELSENSTEIN, 2012), whether the result of temporary transgressions of the coastline or processes on a regional or even a global scale, based on predictions of rising sea levels. In Brazil, for example, the stud-ies of Guimarães et al. (2015), Maia et al. (2016), Aguiar et al. (2018), Leal-Alves et al. (2020), and Silva et al. (2020) have demonstrated the potential of using DEMs, combined with surface hydrological modeling, for the generation of coastal flooding scenarios based on different data acquisition methods, i.e., GNSS-RTK, aerial LiDAR systems, and UAV-mounted optical sensors. It is important to note, however, that the correct use of topographic samples in hydro-logical models, on an appropriate scale and with adequate precision, requires a series of meth-odological considerations for the reliable construction of the main input: the Digital Elevation Model or DEM (POULTER & HALPIN, 2008; GESCH, 2009; CAMARASA-BELMONTE & SORIANO-GARCÍA, 2012; MURDUKHAYEVA et al., 2013; PAPROTNY & TEREFENKO, 2017).

In this context, the present study reviews the application of geomorphometric data to the analysis of coastal flooding, evaluating its primary potentialities and limitations. Based an exten-sive review of the literature, we focus on the basic concepts of geomorphometric analysis and the generation of DEMs, the spatial resolution of altimetric data in the raster format, the im-portance of the altimetric reference datum, primarily when applied to low-lying coastal areas (with examples of how to adjust the vertical datum), the bathtub approach, and the relevance of hydrological connectivity in the elevation models applied to the assessment of coastal systems.

GEOMORPHOMETRIC ELEMENTS OF THE HYDROLOGICAL MODELING OF COASTAL AREAS

The DEM is the basic tool used for the extraction of the geomorphometric parameters (slope gradient, hillside orientation, ramp length, roughness, and vertical and horizontal curva-ture) typically employed in hydrological modeling (POULTER & HALPIN, 2008; FLORINSKY, 2012; SEENATH et al., 2016; YUNUS et al., 2016). In computational modeling, these parame-ters compose the digital surfaces, traditionally associated with the delimitation and analysis of watersheds, for the identification of flow patterns (TARBOTON, 1997; GONZALEZ & WOODS, 2002; HUNT, 2005; MENDAS, 2010; POULTER & HALPIN, 2008; PECKHAM, 2009).

Algorithms for the analysis of surface flow patterns were first introduced into hydro-graphic studies in the 1970s and 1980s. In the 1990s, these algorithms were disseminated widely in the software for Geographic Information Systems (GIS) in a number of different sets of tools for hydrological analysis. The modeling of coastal watersheds has been shown to be a versatile approach, which has contributed to the geomorphometric description of low-lying coastlines, a type of landscape that is naturally susceptible to positive oscillations in sea level (COZANNET et al., 2006; SEENATH et al., 2016; WDOWINSKI et al., 2016; PAPROTNY & TEREFENKO, 2017).

The primary datum for the extraction of geomorphometric parameters is the discrete and continuous representation of the relief in the form of a DEM. The value registered at each point/grid (discrete) or pixel/raster (continuous) is equivalent to the altitude of the terrain and the format of the records will depend on the type of sensor used to collect the data or the data conversion processes (Figure 1). Eakins & Grothe (2014) alerted that the conversion of discrete records to continuous surfaces using interpolators is an extremely delicate step in the geomor-phometric reconstruction process, given that it can cause severe distortions in the topographic information through the smoothing of the features. As a practical rule, the denser the cloud cov-er of the data points, the smaller the weight of the estimation method (EAKINS & GROTHE, 2014). It is important to note here that the conversion of records can also produce artifacts or edge effects that must be identified and corrected before other parameters can be extracted from the DEM (DANIEL, 2010; EAKINS & GROTHE, 2014; DANIELSON et al., 2016).

As the spatial resolution is an important component of surface analysis, the topological properties derived from a DEM are normally divided into categories or scalar groups. Olaya (2009) distinguished two groups of parameters: local and regional. The local group refers to all the parameters of reduced scale, with point values, such as the slope, aspect, and curvature. The regional group includes much broader parameters, which are dependent on a much larger num-ber of surface elements (cells) for an adequate representation, including the hypsometry, re-charge area, and channel segmentation.

Local parameters are geometrically-defined and flow-dependent attributes, such as the direction of the gravitational acceleration vectors, and are a common feature of surface runoff models (OLAYA, 2009; FLORINSKY, 2012). In the case of the local geomorphometric parame-ters, we highlight the slope and aspect, which have solid mathematical functions with algorithms implemented through a number of different types of GIS software (OLAYA, 2009; PIKE et al., 2009; LONGLEY et al., 2010).

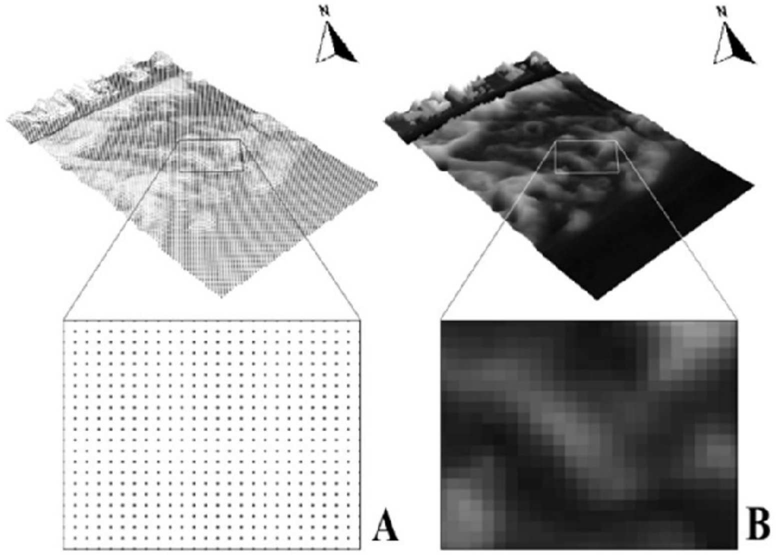

FIGURE 1
The difference between the two types of record used to compile a DEM. A) Discrete dense cloud represented by a point/grid system; B) A continuous surface model represented by a pixel/raster system.

The slope is the angle of inclination of the local surface relative to the horizontal plane, and is a determinant of flow velocity by gravity. Li et al. (2005) proposed that the slope is the primary product of the DEM because it expresses a gradient and the direction of the inclination of the surface. The aspect is the horizontal angle of the direction of the surface flow determined by gravity, which is measured clockwise and is generally expressed in azimuthal form in relation to the geographic north (FLORINSKY, 2012).

When applying a DEM approach to coastal analyses, Martínez-Graña et al. (2016) point-ed out that coastal environments with a shallow slope have a high potential for the displacement of seawater toward the continent, with the withdrawal velocity being controlled by the slope, following an extreme event (reverse-direction flow). Paprotny and Terefenko (2017) also con-cluded that long-term storms may flood more ample areas and reach higher levels in environ-ments with a medium slope, especially on low and exposed coasts. Hunt (2005) found that the synergistic association of intense precipitation episodes and high-energy coastal events may provoke hydrological processes that are twice as intense as normal.

It should also be noted that flat coastal environments associated with depositional sys-tems, such as wetlands or coastal dune field swales, tend to drain excess water relatively slowly, and usually present secondary flooding by damming the water, for up to days after the event that caused the rise in sea level. This is due not only to morphological factors, such as the inef-ficient flow of water through ephemeral channels but also to the subsurface hydrological dy-namics, which are related to fluctuations in the water table (WDOWINSKI et al., 2016; PAP-ROTNY & TEREFENKO, 2017).

THE SPATIAL RESOLUTION OF DEMS IN COASTAL FLOODING MODELS

The resolution of altimetric data is highly dependent on technology and the acquisition methods, as well as the data processing, in particular, the conversion of records using determin-istic or probabilistic interpolators, which generate continuous surfaces (EAKINS & GROTHE, 2014). As discussed by Antonioli et al. (2017), the use of high-resolution 3D topography has been increasing significantly in recent years, which has enhanced the capacity of coastal studies, which are now able to determine the retraction of the coastline in much greater detail in compar-ison with the Sea Level Rise (SLR) scenario.

Twenty years ago, the spatial resolution of the data was only 30 meters, but in the pre-sent day, the ample availability of the global-scale DEMs produced by the National Aeronautics and Space Administration (NASA) through the Shuttle Radar Topography Mission, or SRTM (PIKE et al., 2009) provide researchers and a small number of decision-makers around the globe with DEMs that have a resolution of 1 meter or less. Most of these data are obtained by aerial survey using LiDAR systems linked to GNSS receivers in Real-Time Kinematic mode (RTK), for ground support. In the past few years, the use of UAVs with Structure-from-Motion (SfM) photogrammetric processing has also increased considerably (WESTOBY et al., 2012; CLAPUYUT et al., 2016; JAMES et al., 2017).

Spatial resolution is the measure of the smallest angular or linear division between two objects (JENSEN, 2014), and its definition will depend on the type of record used in the DEM. In the case of pulse-type data acquisition, as used in the LiDAR system, the initial spatial resolu-tion is determined by the combination of the laser projection features in the field, while the sample density is represented by the number of points collected per unit area (grid) and the in-terpolation method used to generate the continuous surface (HENGL & EVANS, 2009; JEN-SEN, 2014). In the case of DEMs obtained by aerial photogrammetry, by contrast, the resolution is determined by parameters such as the instantaneous field of view (IFOV) and the height of the flight. In the raster format, spatial resolution is normally expressed in meters, according to the length and width of the raster on the ground (PIKE et al., 2009), which is also known as the Ground Sample Distance, or GSD (Figure 2).

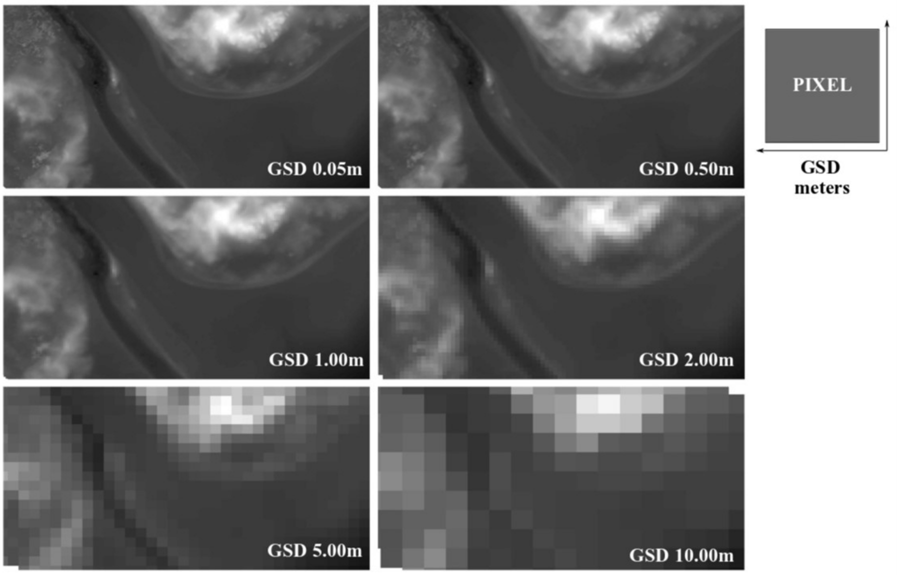

FIGURE 2
Digital elevation models with different spatial resolutions.

As discussed above, the geomorphometric parameters such as the slope and orientation (aspect) are functions related directly to the spatial resolution of the DEM, which defines the level of detail of the surface of the matrix (LI et al., 2005; HENGL & EVANS, 2009) and con-sequently influences the estimated behavior of the hydrological displacement (POULTER & HALPIN, 2008; MENDAS, 2010; POPPENGA & WORSTELL, 2015; YUNUS et al., 2016). Given this, low-resolution digital models, with cell-pixel dimensions greater than 10 m x 10 m, provide matrices with highly generalized features, which are inadequate for the distinction of targets within the limited interior area of the pixel (EAKINS & GROTHE, 2014).

This means that the resolution has a direct impact on the quality of all the DEM products. With regard to the relationship between the spatial resolution of the DEM and the slope, Hengl & Evans (2009) pointed out that if the GSD is sufficiently refined, with a resolution of a few cen-timeters, it will be possible to detect variations in slope even on surfaces of reduced altimetric amplitude, such as a depositional coastal plain (Figure 3). At the opposite extreme, as the spatial resolution becomes coarser, the slope will become more homogeneous.

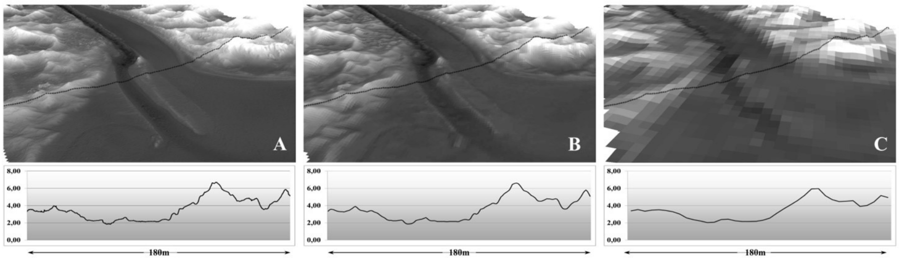

FIGURE 3
Examples of the DEMs of a depositional coastal plain at different spatial resolutions. A) The centime-ter resolution (GSD 0.05 m) results in a topographic profile with the greatest detail of the terrain inflections; B) By decreasing the resolution (GSD 1.0 m) the topographic profile presents a major degree of smoothing; C) The topographic profile generated using a much a coarser resolution (GSD 5.0 m) presents a high degree of homoge-neity in the forms.

Jensen (2014) established one general, but practical rule to determine the resolution re-quired for an analysis, i.e., that the GSD image should be at least half the size of the target to be identified, in its smallest dimension. However, Hengl & Evans (2009) encouraged the use of mathematical applications for the more adequate determination of the cell-pixel size of the DEM, taking the density of inflections of the terrain into account for the digital representation, that is, the more heterogeneous the morphology of the landscape to be reconstructed, the greater the sampling effort should be.

In the specific case of coastal flood models, Yunus et al. (2016) and Paprotny & Terefenko (2017) concluded that the geomorphometric generalization of the features will result in severe limitations of the assessment, producing major errors of estimation, which depreciate the approaches that are highly dependent on the topographic component. Given this, DEMs with either a very coarse resolution or with severe information losses due to a strong smoothing in the register conversion stage (Eakins and Grothe, 2014) are not adequate to assess sea-level rise, given that small differences in elevation may have different impacts on the affected areas (GFDRR, 2015).

For surveys of coastal areas with a small altimetric range using LiDAR systems, Paprotny & Terefenko (2017) showed that a dataset with a mean density of 4 points/m² (rural areas) or 12 points/m², in the case of urban areas, resulted in a maximum cell-pixel spatial resolution of 1 meter after the conversion of the records. Digital Elevation Models with a resolution of 1 meter were applied to the analysis of coastal flood scenarios by Camarasa-Belmonte & Soriano-Garcia (2012); Murdukhayeva et al. (2013); Rotzoll & Fletcher (2013); Leon et al. (2014), Wadey et al. (2015), Poppenga & Worstell (2015; 2016), and Antonioli et al. (2017).

Despite their intrinsic value, DEMs with a high spatial resolution present a number of drawbacks, in particular, a substantial increase in processing time. Fine resolution surface mod-eling (centimetric GSD) requires an enormous computational capacity. In the case of flood models, assessments based on high-resolution DEMs are normally restricted to detailed studies of relatively small areas, with the cartographic products typically being constructed on a scale of at least 1:5000 (HENGL & EVANS, 2009), while the mapping of larger areas usually involves a coarser resolution that tends to lead to a higher level of uncertainty (SEENATH et al., 2016, YUNUS et al., 2016). As Hengl & Evans (2009) and Longley et al. (2010) pointed out, the choice of a given spatial resolution implies certain costs, associated not only with the acquisition of the data, but also for the application of the model itself. Considerations on the potentialities and limitations of high resolution DEMs are summarized in Table 1.

TABLE 1
Summary of some potentialities and limitations of the use of high-resolution DEMs for the study of coastal flooding.

Use of high-resolution DEMs in the study of coastal flooding		
Potential	**Limitations**	**Reference**
Reliable, continuous spatial representation of coastal morphology.	Increased computational costs, that is, a higher spatial resolution requires a much greater processing capacity (hardware)	Hengl & Evans (2009); Longley *et al.* (2010).
High spatial resolution permits the detailed detection of secondary variables (e.g., slope), even within small topographic areas, which is not feasible with low-resolution DEMs, which homogenize the features.	A high resolution can generate complex surfaces, especially in urban surveys. This may require additional post-processing (classification, filtering and mosaicking) to avoid false obstructions to the hydrological flow.	Webster *et al.* (2004); Wadey *et al.* (2015); Poppenga & Worstell (2015); Yunus *et al.* (2016); Paprotny & Terefenko (2017).
Possibility of associating the Digital Elevation Model with external vertical references, such as a tidal datum or orthometric height.	This requires a tidal station and appropriate series of data, in the case of a tidal datum, and very precise GNSS instrumentation for accurate georeferencing (to ensure adequate orthometric adjustments).	Gesch (2009); Leon *et al.* (2014); Schimid *et al.* (2014); Kruel, 2016; Martínez-Graña *et al.* (2016).
Continuous improvement of remote sensing platforms (in particular, LiDAR and UAV systems) for the acquisition of DSM data.	The high cost of high-resolution orbital DEMs, while the use of UAVs is limited to low altitudes and the imaging of small areas.	Casella *et al.* (2014); Vianna & Calliari (2015); Simões *et al.* (2019); Leal-Alves *et al.* (2020).

However, Gesch (2009) stated that it is not enough to simply obtain a high-resolution model, but that it also is necessary that both the horizontal and the vertical resolutions are ap-propriate for the type of evaluation being undertaken. The spatial characteristics of the DEM may lead to under- or over-estimates in the coastal flooding assessment, especially when the conditions of surface displacement are established by friction. Gesch (2009) also pointed out that, in some cases, the uncertainty associated with the geomorphometric model may exceed the predicted SLR value itself. Leon et al. (2014) recommended incorporating the uncertainty of the DEM in the assessment of coastal flood models.

Poppenga & Worstell (2016) expressed the same concern, noting that a high-resolution elevation dataset does not necessarily produce a reliable surface flow model. Other methodolog-ical considerations are also necessary, including the adjustment of the vertical reference for coastal areas (GESCH, 2009; SCHIMID et al., 2014; KRUEL, 2016) and the rules of hydrologi-cal connectivity (POULTER & HALPIN, 2008; MENDAS, 2010; EAKINS & GROTHE, 2014; POPPENGA & WORSTELL, 2015; YUNUS et al., 2016).

VERTICAL REFERENCE AND METHODS FOR THE DETERMINATION OF LOCAL SEA LEVELS

Longley et al. (2010) emphasized that the understanding of the altitude of a given coastal area and its metric relationship with the relative sea level, is fundamental for predicting the effects of climate change. A number of authors (BUSH et al., 1999, 2001; ROTZOLL & FLETCHER, 2013; MURDUKHAYEVA et al., 2013; HOOVER et al., 2016; MARTÍNEZ-GRAÑA et al., 2016; WDOWINSKI et al., 2016) have also pointed out that the altitude is the most important feature of the assessment of coastal flooding, and when DEMs are applied to hydrological modeling, it is necessary to correlate the altimetric accuracy obtained during the collection of the the topographic data with the local sea reference level (GESCH, 2009).

Studies of the topography of coastal areas typically adopt a vertical datum based on local tide measurements or tide datum. This tidal reference verifies the difference in height between successive high and low tides and, depending on the geographic location, these oscillations may vary from a few centimeters, in the case of microtidal regimes, to a number of meters, in macrotidal areas (MARTÍNEZ-GRAÑA et al., 2016). As the tide datum consists of a vertical reference that establishes the boundary of an area subject to tidal fluctuations (GHILANI & WOLF, 2011), the understanding of local patterns is crucial to many types of coastal management activity (KRUEL, 2016).

The mean higher high water (MHHW) line is one of the most widely-used tide datum parameters in risk assessment, being used as the extreme vertical reference in the studies of Murdukhayeva et al. (2013), Rotzoll & Fletcher (2013), Eakins & Grothe (2014), Schimid et al. (2014), Hoover et al. (2016), Kruel et al. (2016), and Yunus et al. (2016). However, Ghilani & Wolf (2011) and Eakins & Grothe (2014) found that, worldwide, other references are also used, including the mean high water (MHW), mean low water (MLW), and the mean lower low water, or MLLW (Figure 4).

The interpretation of the tide datum may imply some degree of arbitrariness, and in many cases, represents not only the geomorphological and oceanographic characteristics of the coast, but it also reflects local socioeconomic activities (Ghilani & Wolf 2011). In a study of the assessment of flooding caused by SLR and storm tides in Boston (Massachusetts, USA), Kruel (2016) identified the use of five vertical data, each one attending specific sectors of the local community. This can become a problem for coastal management and civil defense based on risk charts, given that it is important to use flood thresholds based on the tide datum (WDOWINSKI et al., 2016).

FIGURE 4
Diagram of the tide datum.

Schimid et al. (2014) emphasized that many flooding models use orthometric data as a reference, that is, vertical references adjusted to geodesic systems, which are not tide data per se, and thus represent a zero value that is not equivalent to any actual tide level for the location. This may represent an important source of error, depending on the reference used for the adjustment of the geoid model, especially if the study area has a large tidal amplitude. In an attempt to minimize problems of this type, Gesch (2009) demonstrated that topographical surveys using LiDAR systems based on ellipsoidal references have significantly improved the vertical accuracy of the topographic data, although the cartographic products derived from this tool should incorporate the difference in height between the local mean sea level and the vertical datum zero adopted for the analysis.

Concerns over the lack of vertical consistency among the different data used in coastal research in the United States led to the National Oceanic and Atmospheric Administration (NOAA) producing an adjustment tool called VDatum. This software was designed to convert geospatial data among a range of altimetric references used in the United States, whether derived from tides, or orthometric (geoid) or geometric (ellipsoidal) sources. This software, including the version for use in internet browsers, is available at https://vdatum.noaa.gov/.

One other limitation associated with the tide datum is the accessibility of the tide-measuring instruments. Most ports and waterways use tide gauges, but the availability of the data depends on the distribution network (SILVA et al., 2004; SCHIMID et al., 2014). Many of these tide gauges are also installed in sheltered locations that are influenced intensely by rivers, such as deltas and estuaries, making inferences impossible for adjacent areas that are exposed directly to meteoceanographic forces, as shown by Goulart (2014) in the case of Cassino Beach in Rio Grande do Sul state, southern Brazil.

Although a tide table (based on astronomical parameters) provides the predicted tide at a given latitude, it does not substitute the historical records from a tide gauge, which will normally be linked directly to the reference body of water. Martínez-Graña et al. (2016) showed that the lack of tide data or even a discontinuity in a time series may be a severe limitation for the estimation of the local sea-level rise, generating a high level of uncertainty due to the temporal and spatial inaccuracy of the vertical reference. However, in the absence of local tide data or where the tide datum is incompatible, there are other ways of estimating the vertical reference level of the coastline.

Boak & Turner (2005) demonstrated that topographic leveling based on high-frequency beach profiles measurements georeferenced in a planialtimetric framework can provide reliable data on the short-term behavior of the water line. The principal limitations of this method are related to its reduced temporal representativeness, which restricts the sample to the morphodynamic behavior of the beach system for any given period. Topographic surveys, regardless of the data collection mode, may represent only the seasonal or daily characteristics of the local sea level due to the high level of variability of the transport rates and the typical sedimentation patterns of the beach environment (Figure 5).

The identification and georeferencing of tidal fluctuations can also be achieved using temporal series of high-resolution aerophotogrammetric images (MARTÍNEZ-GRAÑA et al., 2016). This technique is widely used for the delimitation of coastlines (Boak and Turner 2005), and requires both horizontal and vertical records, but it can be a robust method for the spatial analysis of tides when using geometric correction, which reduces the inherent distortions of the images that represent the morphology of the terrestrial surface and provides an image bank co-register, which ensures the spatial matching of the mosaic series.

It is possible to estimate the reference tide level of a beach using a series of video images. A seafront camera system enables the high-frequency monitoring of beach dynamics, but only during the daylight hours, due to spectral sensor limitations (BOAK & TURNER, 2005; GOULART, 2014). A video image database can provide statistics on the long-term patterns of the high-frequency changes in the system (BOAK & TURNER, 2005). Goulart (2014) employed this method using an ARGUS video monitoring system, with the application of the orthorectification technique, which consists of the use of a set of equations and ground control points for the conversion of the oblique images into plane mosaics of the vertical view. This permits the horizontal position of the water line to be estimated using digital image processing algorithms.

FIGURE 5
Different approaches for the collection of coastal data. A) Aerophotogrammetric survey using a UAV; B) Geodetic survey using GNSS equipment.

The reduction in the level of the ellipsoidal datum through the calculation of the geoid undulation is another technique used frequently in flood analysis (WEBSTER et al., 2004; LEON et al., 2014) in particular when topo-bathymetric data are integrated (DANIELSON et al., 2016; SEENATH et al., 2016). Ellipsoidal systems consider the Earth's surface to be a geometrically perfect ellipsoid with constant gravimetric potential and rotation around its polar axis, whereas geodetic systems represent the terrestrial surface with its irregularities in the form of non-uniform heights. The irregularity of the geoid representation is due to the variation in the distribution of the density and mass of the planet, in addition to its rotation, which results in a non-homogeneous distribution of the terrestrial gravitational field.

As it is not possible to measure the geoid directly using a pure positioning system, inferences are made from the ellipsoid (MONICO, 2008). Using the gravimetric data in the form of a geoidal undulation (N), it is possible to determine the height difference between the ellipsoidal data collection system and the geodetic reference system, thus obtaining the orthometric height (H) from equation 1, following Monico (2008) and IBGE (2016):

$$H=h-N \qquad \text{[equation 1]}$$

where h is the ellipsoidal height and N is the geoid undulation, both for a given surface point.

The vertical adjustment provided by the geoid undulation is fundamental to the adoption of orthometric heights in coastal research, especially in studies that focus on the hydrological dynamics of the continent-ocean interface. Due to the gravimetric reference, there is a zero approximation of the geodetic vertical datum with the Global Mean Sea Level (GMSL). While a direct relationship between the zero height of the geoid surface and mean sea level is usually assumed for a coastline, it is important to note that the geoid may differ from the mean level because of gravimetric variations around the globe (FERNANDES, 2007). Concerns on this imprecision, as highlighted above, are justified, given that, in many cases, the vertical error may exceed the sea elevation predicted by projected scenarios of sea-level rise (GESCH, 2009).

THE BATHTUB APPROACH AND HYDROLOGICAL CONNECTIVITY RULES

The bathtub model (LEON et al,. 2014; SCHMID et al., 2014), or bathtub approach (POULTER &HALPIN, 2008; NOAA 2017), is a globally popular concept for the assessment of coastal flooding (YUNUS et al., 2016; ANTONIOLI et al., 2017). The bathtub is a geospatial approach that uses digital elevation models to simulate water flow, and depends on the quality of the topographic input data (POULTER & HALPIN, 2008, SEENATH et al., 2016, YUNUS et al., 2016).

The bathtub approach is used primarily for the assessment of the flooding potential of coastal areas (flood inundation vulnerability) or is associated with demographic data and infor-mation on infrastructure to determine the flood inundation risk. The calculations of the bathtub approach can be implemented in GIS software (POPPENGA & WORSTELL, 2015, SEENATH et al., 2016, YUNUS et al., 2016, NOAA 2017, PAPROTNY & TEREFENKO, 2017), which facilitates integration with other georeferenced databases, or even in matrix calculation software.

The name of this approach alludes to the process of filling a bathtub (PAPROTNY & TEREFENKO, 2017), given that the procedure generates information progressively on the depth and extension of the flooding as the water fills the geomorphometric structure of the drainage basin. In the modern conception of this approach, it is assumed that the body of water will in-clude all the land located at altitudes below the projected water level, given that there is a direct connection with the source of the flood or with the flooded cells. The bathtub approach is wide-ly used in the assessment models of climate change impacts related to sea-level rise (SEYATH et al., 2016, YUNUS et al., 2016, ANTONIOLI et al., 2017, PAPROTNY & TEREFENKO, 2017).

Despite its ample use, the bathtub approach has a number of limitations and demands certain precautions for its application. Both Schimid et al. (2014) and Paprotny & Terefenko (2017) alert that many of the applications of the bathtub approach are static, and do not consider the flow direction, thus assuming that the flood effects are instantaneous. Poppenga & Worstell (2015) emphasized that the absence of hydrological connectivity in the elevation model may lead to the exclusion of some potentially flood-prone interior areas, which is critical for the reli-able assessment of the risks associated with coastal dynamics. However, only the most tradition-al bathtub models are based exclusively on the intersection of the topographic information with the water surface (the height of the water slide) generating what is commonly known as simple bathtub or zero-way model (POUTER & HALPIN, 2008; MASTERSON et al., 2014; YUNUS et al., 2016) (Figure 6).

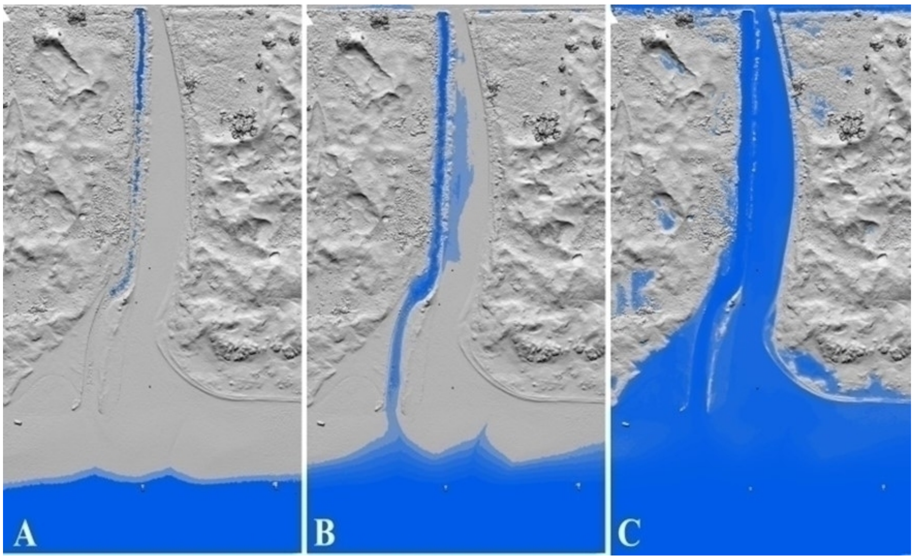

FIGURE 6
Example of a simple bathtub model obtained using GIS software for different SLR values applied to a coastal DEM. A) 10 centimeter SLR simulation; B) 50 centimeter SLR simulation; C) 1 meter SLR simulation.

The simple bathtub modeling of flooding is generally used in low-resolution digital sur-face models, which implies a series of restrictions for the analysis of coastal flooding (YUNUS et al., 2016). This approach also tends to neglect the direction of the flow due to the zero-way rule, given that the simpler design of this procedure does not predict displacement between cells, but rather a uniform distribution of the water depth among the cells that are lower than the refer-ence level, with the lower units being filled or drowned simultaneously (POULTER & HALPIN, 2008).

In recent years, however, a number of authors have introduced a more complex ap-proach to the flood models based on the bathtub approach, which makes them more versatile. This approach is usually referred to as a modified bathtub (MURDUKHAYEVA et al., 2013; YUNUS et al., 2016; KRUEL et al., 2016; NOAA, 2017). Poulter and Halpin (2008) empha-sized that the appropriate application of the bathtub approach depends on two basic aspects of the surface analysis. The first of these aspects refers to the adjacent displacement or, in hydro-logical terms, the insertion of the surface flow, which is associated with the scale of the data (the detail of the morphological features) and the spreading rule (cell connectivity and runoff coeffi-cient) adopted in the study, which had rarely been employed in coastal flood models, but were widespread in studies of the drainage systems of hydrographic basins.

The employment of water displacement algorithms with multiple directions is well estab-lished in raster surface modeling, in particular within the scope of hydrographic basin analysis (TARBOTON, 1997; GONZALEZ & WOODS, 2002; POULTER & HALPIN, 2008; MENDAS, 2010). According to Longley et al. (2010), when a digital surface imposes friction on the flow (displacement cost between cells) that is, when the displacement velocity is not uniform, the overflow will tend to reach a greater extension in more susceptible topographies, such as those at a low elevation or with a smoother slope (lower cost of displacement). The water displace-ment function is commonly known as a spread, and consists of the total friction calculated for each of the possible paths established by the rules of displacement (LONGLEY et al., 2010). Essentially, a displacement rule is selected for the hydrological model in which the flow priori-tizes the path with the least friction, from a given set of possible paths. The rules used most fre-quently include the zero-way, the four-way and the eight-way.

The zero-way rule, which was presented above, is applied in the simple bathtub ap-proach, in which there is no hydrological connectivity among the cells (no displacement). This single condition rule states that the cell will be flooded instantaneously if its elevation is lower than the projected sea level (YUNUS et al., 2016). By contrast, the four-way and eight-way rules establish paths connecting adjacent cells (Figure 7). The four-way rule is based on the con-nection of the cells located in the four cardinal positions, evaluating paths in four possible direc-tions. The eight-way rule, adds the four diagonal axes, permitting the evaluation of eight possi-ble path directions.

As Longley et al. (2010) pointed out, in hydrological models based primarily on DEMs, the adoption of either the four- or the eight-way rule resolves the topological problem of the hydrological connectivity. These models predict coastal flooding if two conditions are met:

As Longley et al. (2010) pointed out, in hydrological models based primarily on DEMs, the adoption of either the four- or the eight-way rule resolves the topological problem of the hydrological connectivity. These models predict coastal flooding if two conditions are met:

- the elevation of the cell is below the projected sea level;
- the cell is connected to the flood source or to another cell that is already flooded.

In the latter case, the water may flow into any of the neighboring cells, according to the displacement rule (four-way or eight-way) moving in the direction of the lowest friction, accord-ing to the slope (YUNUS et al., 2016). Poulter & Halpin (2008) considered the choice of a con-nectivity rule to be decisive to the delimitation of the flooded area, although the geomorphomet-ric model would still be the most important component of the evaluation. These authors pointed out that, while the four-way rule may underestimate the flow connections because it presents only four possible paths, the introduction of the diagonal paths may overestimate connectivity in the eight-way rule. In both cases, however, the higher connectivity tends to enrich the micro-features of the relief obtained by high-resolution DEM. Yunus et al. (2016) demonstrated that the bathtub approaches which employ the zero-way rule tend to maximize the extension of the flood, given that all the terrains lower than the projected sea level would be flooded, without exception, that is, without the definition of the costs of displacement or connectivity.

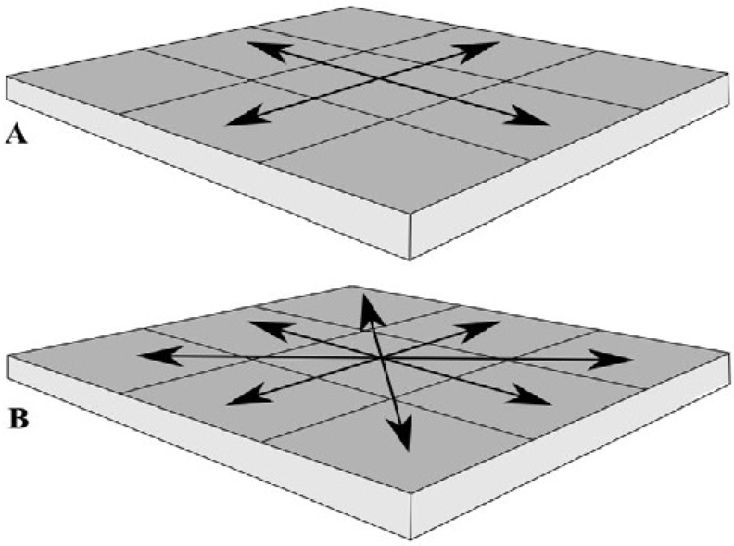

FIGURE 7
Diagram of a matrix demonstrating the two displacement rules (optimal path): A) The four-way rule; B) The eight-way rule.

The second aspect identified by Poulter & Halpin (2008) refers to the adequate distinction of the different types of digital elevation models. The DEM usually refers to a digital representation of the earth's surface, but if it contains data on the height of targets that are above the ground, it is considered to be a Digital Surface Model (DSM), while the Digital Terrain Mod-el (DTM) is a surface model that includes only the ground elevation, with minimal interference from other objects (Figure 8).

Paradoxically, the high resolution of the DEMs, provided by the modern tools of topo-graphic data acquisition and processing, bring new concerns with regard to the hydrological connectivity in the flood models. In the 1990s and up to the the mid-2000s, the topographical resolution of no more than 30 m was not a concern for the representation of the micro relief in geomorphometric models (POPPENGA & WORSTELL, 2016).

The statistical smoothing provided by the interpolation methods (POULTER & HALPIN, 2008) or even the surface cloud of points that overlap features in the presence of drainage channels (POPPENGA & WORSTELL, 2016) may have a decisive impact on the quality of the assessment of flood models because they interfere in the displacement rules of the cells. In coastal flooding models, the data associated with features of high verticality may cover depres-sions and natural drainage channels which provide connectivity, but may not be represented in the surface model.

In a study of hydro-connectivity, Poppenga & Worstell (2016) concluded that the eleva-tion data obtained with LiDAR systems (and by extension, sensors coupled to UAVs) present a new challenge for hydrological modeling, given that they are based on obtaining elevations through a surface cloud of points that has a very high sample density, which includes all kinds of elevated features. In urban areas, infrastructure such as buildings, bridges, and artificial drainage systems will be georeferenced from the ground elevation, to which the respective height is added. Rural areas are not different, given that tall reference points such as trees and transmission towers have the same limitation for the definition of the elevation of features that are above ground level.

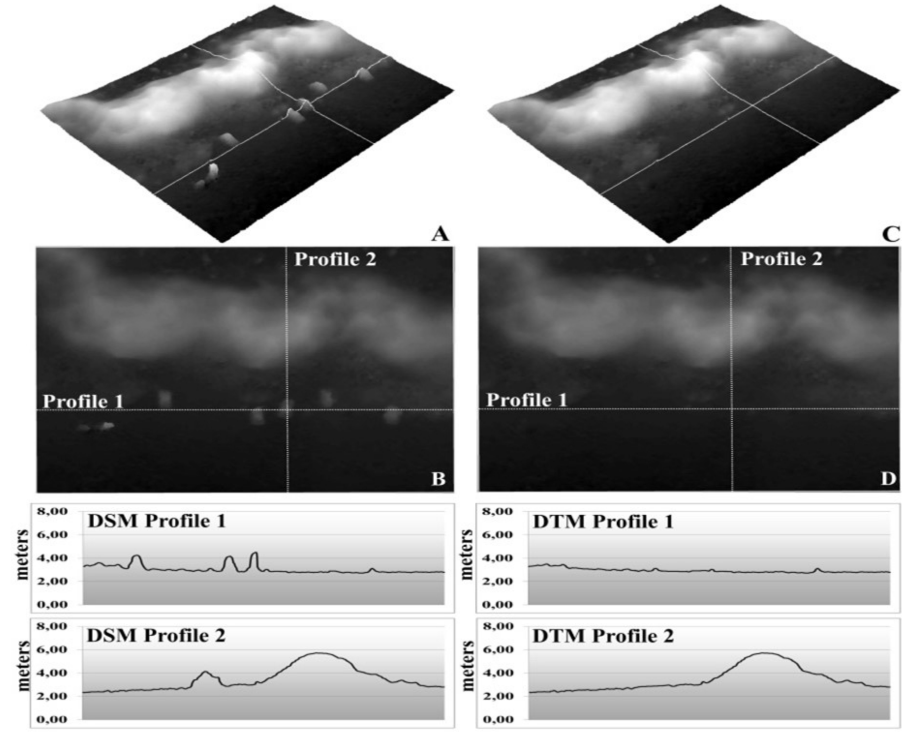

FIGURE 8
Profiles showing the geomorphometric difference between DSMs and DTMs. A and B) The topo-graphic transition between beach and dune - profiles 1 and 2 highlight the presence of artifacts, that is, cars parked at the seafront (DSM); C and D) The same study area, but with the artifacts omitted by the dense cloud classification method (DTM).

Schimid et al. (2014) and Poppenga & Worstell (2016) emphasized that paludal envi-ronments and coastal plains are more susceptible to imprecisions when analyzed by DSMs be-cause protruding features result in an addition to the elevation values that are far above the real values, due to the low geomorphometric amplitude of these landscapes. Yunus et al. (2016) showed that these additions to the elevation are intrinsic to the DSMs and result in a less exten-sive estimate of coastal floods. It is important to note that this effect is due not only to the verti-cal increment promoted by the features, but also to the blocking of channels and the masking of the depressions located underneath them. The presence of artifacts (EAKINS & GROTHE, 2014), together with other geometric discrepancies, such as border effects (Danielson et al. 2016), further add to these typical features of the DSM.

In this context, Poulter & Halpin (2008) considered that, to obtain a reliable representa-tion of the floodplain, it would be necessary, in some cases, to correct the hydrological connec-tivity of the DSM, which would permit a greater displacement of the water through the removal of the impoundments (maximum friction value). Furthermore, Poppenga & Worstell (2016) pre-sented semi-automated methods that validate the hydro-connectivity of the surface models, es-pecially where the features of the surface drainage are essential. These corrective techniques were expected to the approximation of the surface (DSM) and terrain models (DTM), thus re-ducing the uncertainties associated with the false friction promoted by the increase in elevation increase and the obstruction of the flow channels.

One other alternative pointed out, presented by by Yunus et al. (2016), is the use of mixed models with records being collected both on the ground (e.g., using GNSS-RTK) and from the air (e.g., LiDAR systems). In most cases, the validation of the vertical accuracy of sur-face models is already based on this approach, through the use of Ground Control Points, or GCPs (NEX & REMONDINO, 2014), but with a relatively small number of ground samples relative to the total survey area (LEON et al., 2014). The objective is not only to obtain high precision control points, but also the construction of combined geomorphometric models using DTMs and DSMs according to the requirements of the hydrological modeling.

In this case, the channel topography, depressions, and pathways would be mapped with ground-based tools, which would avoid the classification of features that represent potential impoundments of the surface runoff. In areas of exposed ground or with minimal vertical inter-ference, the records would be collected with an aerial platform, supported by GCPs for the ad-justment of the model and checkpoints for its validation. In this case, as Poulter & Halpin (2008) pointed out, it would be important to consider the financial costs of including redundant data in the project, as well as the computational costs of applying this approach to a large survey area.

CONCLUSION

Based on a comprehensive set of climate modeling data and methods, the projections proposed by the IPCC indicate a marked rise in sea level over the course of the 21st century. This trend raises a number of questions on the vulnerability of coastal zones around the world. In addition to the sea-level rise, the intensification of storms is also anticipated as a result of climate change, acting synergistically on the alteration of the coastline. From this perspective, a number of studies have attempted to identify thresholds or flood quotas in urbanized coastal areas in order to provide input for eventual adaptation planning.

Parallel to this, the international scientific literature has given increasing prominence to the use of geotechnology in the scope of coastal studies, given that the methods and equipment used for geomatics have been decisive for the acquisition and analysis of data, especially for the topographic quantification of coastal plains. Unfortunately, however, the high costs associated with the equipment, field surveys, and subsequent processing represent a major obstacle, espe-cially for public administrators, who are the most interested parties here.

Coastal flood assessment by surface analysis has proven to be a versatile and relatively simple tool to use, given that it is based on consolidated topological and computational tech-niques. The principal obstacles include the difficulty of obtaining adequate data for a given scale, resolution, and precision. The review of the specialized journals showed that the application of this approach in coastal studies has been increasing in recent years, and that up to a little over a decade ago, surface analyses was associated primarily with the study of hydro-graphic basins.

We believe that the inceasing application of surface analysis to the assessment of coastal flooding scenarios, especially the bathtub approach, is due primarily to the responsiveness of the method, which many authors have found to be effective and reliable for the assessment of the impacts of the rise in sea level on low-lying coasts. We also believe that the increasing ro-bustness of the models and the projections presented by the IPCC, as well as their adoption in national plans on climate change, have contributed to the growth in this field of research and the ongoing refinement of existing methods.

We have emphasized the bathtub approach here because it is relatively versatile when run in GIS or numerical computing software, but we aware of the existence of a range of other computational options (the DIVA model, SMC Sistema de Modelado Costero [Coastal Modeling System], and LISFLOOD-FP) that provide similar results and are described in full in the interna-tional literature. To circumvent a number of the obstacles inherent to surface modeling, a num-ber of scientists have dedicated their researcher to broadening and correcting the bathtub ap-proach, including an increase in the complexity of the model to better simulate typical features of the hydrological patterns of coastal areas.

A number of recent studies have highlighted the need to integrate of other data, such as the water table, isostatic adjustments, and detailed descriptions of land use and occupation, with the latter being used primarily in assessments that include the socioeconomic aspects of the im-pact of coastal flooding. The effective implementation and integration of all of these elements is facilitated and enhanced by the use of GIS software. However, data integration may also add significant computational costs, which should be considered carefully before adding new layers of information.

One of the limitations of the bathtub approach is that it is not adequate for the modeling of shallow waves, as provided by other modeling systems (the Simulating WAves Nearshore [SWAN] model, for example), even when topo-bathymetric data are integrated. Similarly, mor-phodynamic processes and sedimentary flows cannot be predicted by surface analysis. Alt-hough the approach now includes the roughness of the terrain and water displacement direc-tions, based on the analysis of optimal flow paths, the method still uses waves height and sea-level projections as predetermined, fixed input.

One final question that should be emphasized here is the need for care in the selection of the topographic data for analysis. Surface analysis is highly dependent on the Digital Elevation Model (DEM) that supports it, and accurate data acquisition, proper adjustment in relation to the vertical reference datum, appropriate interpolation to the sample set, and the configuration of the hydroconductivity are decisive elements for the adequate application of the procedure. In addition to the inherent imprecision of the elevation values, the reliability of coastal flood mod-els depends on the validation of the topographic product, and the evaluation of the uncertainties involved.

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