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An efficient algorithm to plot flooded intertidal areas

Lihua Zhang[a,b,*], Qing Zhu[c], Li Zhang[d], Deqing Liang[a], Yixiang Tian[c]

[a] Department of Hydrography and Cartography, Dalian Naval Academy, 667, Jiefang Road, Dalian, Liaoning 116018, PR China
[b] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Science and Natural Resources Research of CAS, PR China
[c] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, PR China
[d] Department of Science Research, Dalian Naval Academy, PR China

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ABSTRACT

The efficient display of flooding in intertidal zones is crucial to coastal applications (e.g., coastal zone management and anti-flood directing systems). This paper proposes a new algorithm to plot flooded intertidal areas. Initially, a digital tide-coordinated shoreline (DTS) is traced on the basis of creating a digital intertidal zone model (DIZM) and an instantaneous water surface model (IWSM). Then unconnected depressions are obtained depending on the type of DTS. At the same time, the algorithm detects unconnected depressions by considering the influences of the changing water level, and creates an index from different water levels to corresponding depressions. Finally, unconnected depressions are effectively handled and flooded areas are plotted correctly. Experimental results demonstrate that the proposed algorithm results in a more accurate and efficient display than with traditional algorithms.

1. Introduction

An intertidal zone is located on the seashore between the high and low tide levels, and technically includes beaches and estuaries. It is known that the tidal range is between 2 and 7 m in most of the coastal areas of China. Owing to the changes of tide, the intertidal zone is flooded at high water level, while exposed at low water level, and the instantaneous shoreline is continuously changing. Moreover, the water level is sometimes raised irregularly by several meters by storm tides, and this can even result in tsunami inundation. Accurate and efficient plotting of flooded intertidal zones is crucial to coastal applications (e.g., coastal area management and anti-flood directing systems).

Considerable progress has been made in the development of methodologies for studying flooding in recent years. Geographic information systems (GIS) have become key tools in flooding computation and plotting (Chang et al., 2000; Bates et al., 2005; Rodda, 2005). Floods are classified into non-source and source floods (Liu and Liu, 2001; Ding et al., 2004; Sanyal and Lu., 2004). In a non-source flood, all points with elevations below the given water level should be included in the flooded area. The plotting of a non-source flood is simple, whereas the plotting of a source flood is difficult and challenging. The source flood needs to consider circulation conditions when the flood flushes through the surrounding lands. Since the flood may be obstructed by ring structures (i.e. unconnected depressions) or high land, it can only cover places where it flows and reaches. One of the methods used to study source floods is the seed spread algorithm (Liu and Liu, 2001; Sanyal and Lu, 2004; Bates et al., 2005; Rodda, 2005). The principle of this method is to select a representative point as a seed and to examine its contiguous cells. The cells contiguous to it and meeting the flooded conditions become seeds, and then contiguous cells to the new seeds will be examined in the same way. Based on the principle of seed point spreading, algorithms used for irregular triangular cells are developed (Ding, 2004).

* Corresponding author at: Dalian Naval Academy, Department of Hydrography and Cartography, Dalian Naval Academy, 667, Jiefang Road, Dalian, Liaoning 116018, PR China. Tel.:+86 41185856427.
E-mail address: Zlhua@163.com (L. Zhang).

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The intertidal zone flood, a type of source flood, needs to consider circulating conditions along with the alternating rise and fall of the water surface. The traditional algorithms mentioned above for plotting flooded intertidal areas have some deficiencies as follows: (1) A grid square or triangle is used as a cell to represent an area for computation and display, so the accuracy of representation is low when the cells are large. Furthermore, false depressions are sometimes formed. (2) A correct seed point must be selected initially; otherwise, an incorrect conclusion may be drawn. (3) The traditional algorithm does not consider the circulating conditions during ebbing. The water in a depression, flooded at the time of high water, does not flow out even when the current water level is lower than the elevation of the lowest overflow point on the depression boundary. (4) It needs recurrent spreading and detection for flooding and connectivity, and its complexity requires much computational time. So it is difficult to represent a flooded area with a large amount of data in a short time. Ding demonstrated that the efficiency of the traditional algorithms used in a large area flooding simulation is very low.

A tide-coordinated shoreline is the linear intersection between the coastal land and a desired water level (Li et al., 2002). It is the tide-coordinated shoreline that forms the boundary of the flooded areas (Zhang et al., 2007). Although the instantaneous water level is changing, the shoreline is always the boundary of the flooded areas. So long as a digital tide-coordinated shoreline (DTS) can be obtained and utilized reasonably, the flooding situation can be computed and displayed. By considering these issues, this paper proposes an algorithm based on DTS to plot the flooded intertidal areas.

2. Algorithm for plotting flooded intertidal zones based on DTS

2.1. Basic theory of the algorithm

The basic theory of the proposed algorithm is described as follows. (1) Because seawater covers the land that is lower than the current water level, flooded areas will be formed. Two models should be created for plotting flooded areas. One is a digital intertidal zone model (DIZM), and the other is an instantaneous water surface model (IWSM). The DIZM is generally stable, while IWSM is continuously changing. (2) Theoretically, the shoreline can be acquired from a subtraction of the DIZM from the IWSM, where the nodes with differential values of zero represent the shoreline (Li et al., 2002). Usually, a DTS is formed by a part or all of the nodes. (3) Because the traced DTSs are the boundaries of flooded areas, they can be used to represent the flooded extent in a reasonable way. (4) A key issue in a source flood is the handling of unconnected depressions. The unconnected depressions will be found based on characteristics of the DTSs. Depressions, which are not flooded at the highest water level, are always displayed by the terrain DIZM, whereas other depressions, which are flooded at the highest water level, should always keep the flood extent of the time when the water level is equal to the elevation of the lowest overflow point on the depression boundary. An index of different water levels with unconnected depressions should be created in the tidal ranges. (5) The instantaneous water level is computed, and unconnected depressions are searched for based on the current water level, then flooded areas are displayed instantly.

2.2. Creation of models

An intertidal zone is an intersection area of sea and land, so data from various data sources need to be integrated in order to create a DIZM (Zhang et al., 2005). DIZM, one kind of digital elevation model, can be represented by $Z_{DIZM} = f(x,y)$. However, there may be some discrepancies in the projections, scale, and horizontal and vertical data. Accordingly, the first step in representing changes in the intertidal zone is conversion to a common datum and the integration of the various data into a uniform reference frame. The authors adopted the WGS84 coordinate system, Gauss projection and a seamless vertical datum (Zhang et al., 2005) based on the theoretical lowest tide level (TLWL). This study uses measurements from TLWL upwards, elevations positive, depths negative, for consistency with landward effects. The DIZM, after data integration, is shown in Fig. 1.

In order to represent the changes in the flooded areas, it is necessary to compute IWSM expressed by $Z_{IWZM} = f(x,y,t)$. The exact calculation of Z_{IWZM} should take sea surface topography and hydrodynamics into account. A "Water Plane" method (an approximate method, which can be used to stand for the IWSM) has proved to be practical and efficient in flooding simulation (Liu and Liu, 2001; Ding et al., 2004; Sanyal and Lu, 2004). IWSM, simplified to $Z_{IWZM} = f(t)$ in the study, is only dependent on time t, and is independent of planar position. The harmonic method is usually employed to forecast changes of coastal water level (Bao et al., 2003; Cox et al., 2002; Hess, 2002).

As the tide rises, the instantaneous shoreline will change, and seawater will inundate the areas that are

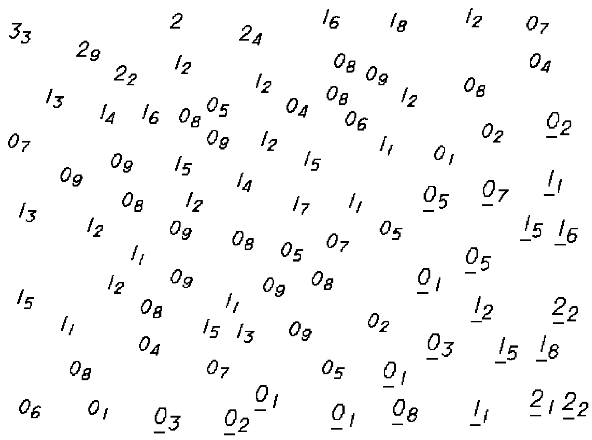

Fig. 1. Digital intertidal zone model (DIZM). Units as "Meters above TLW".

lower than the instantaneous water level. Plotting of the flooded intertidal zone sometimes is a result of IWSM covering DIZM, and intersection lines of Z_{DIZM} and Z_{IWZM} form DTSs.

2.3. Acquisition of DTS

2.3.1. Approach to generating a DTS

A differential value between Z_{IWZM} and Z_{DIZM} is computed to acquire a DTS.

$$dZ = Z_{IWSM} - Z_{DIZM} \quad (1)$$

A traced contour with a value of 0 is a DTS, and an area with $dZ>0$ is potentially a flooded area. Gridding contouring is used to trace the DTS when Z_{DIZM} is represented by regular grid data. In this study, because Z_{DIZM} is delineated with a triangulated irregular network (TIN), the DTS is obtained by triangulation contouring. The principle of tracing a DTS is similar to that of a contour, and the traced contour can be smoothed further. Fig. 2 shows the TIN and smoothed DTSs in the study area.

2.3.2. Direction and classification of DTS

If the area to the left of a DTS is shallower ($dZ<0$) and to the right is deeper ($dZ>0$) along the tracing direction, the direction is positive; otherwise it is negative. As shown in Fig. 2, the directions indicated by arrowheads are positive. There are three types of DTS: Type I is a closed curve, the inside of which is at a lower elevation than the curve ($dZ>0$), i.e., a boundary of a depression without an outlet, e.g., c_1 and c_2 in Fig. 2; Type II is a closed curve where the inside area is a highland ($dZ<0$), e.g., c_3 in Fig. 2 is a boundary of an island or a submerged rock; Type III is unclosed because of the limit of the local study area, e.g., c_4, c_5 in Fig. 2, they are intersection lines of land and sea.

2.3.3. Handling of DTS

A traced DTS should be recorded along its positive direction, which can be determined by the values of two vertexes of a side in a triangle. If the value of the left vertex is larger than that of the right, the direction is positive. Contrarily, when the direction is negative, it is necessary to reverse equal value nodes. To their left is dry land ($dZ<0$) and to their right is a potentially flooded area ($dZ<0$) after DTSs are processed.

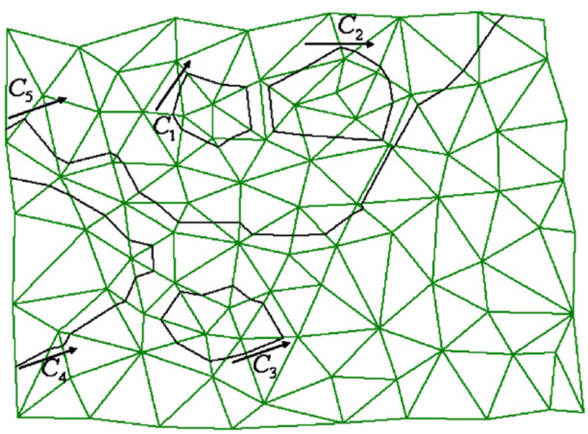

Fig. 2. TIN and directions of DTSs. Vertexes of a closed contour are clockwise around depressions and anticlockwise around peaks.

2.4. Representation of flooded areas based on DTS

2.4.1. Formation of flooded area

Theoretically, areas with $dZ>0$ can be flooded ones, and traced DTSs are their boundaries. In the flooded areas, the DIZM is invisible. The depth-buffer method, which compares surface depths at each pixel position on the projection plane, is commonly used to detect the visible surface. When a graphic engine (e.g. OpenGL) is used to render the scene, it is easy to display the flooded areas by the depth-buffer method. However, the special and difficult problem is how to deal with the inside areas of the Type I DTS (i.e., a boundary of an unconnected depression) in a source flood. In the flooding computation with alternating rise and fall of the water surface, unconnected depressions are further categorized into two types. Type Ia is a depression, which is not flooded at the highest water level ($Z_{\max}$). Type Ib is a depression, which is flooded at the highest water level. The terrain of the DIZM should always be displayed inside a Type Ia depression, whereas the inside of a Type Ib depression should always keep the flood extent of the time when the water level is equal to the elevation of the lowest overflow/inflow point on the depression boundary. So long as all unconnected depressions are found, the flooded areas can be displayed in a reasonable way.

2.4.2. Decision of an unconnected depression

Because the Type I DTS is the boundary of the unconnected depression, all unconnected depressions can be determined depending on the characteristics of the traced DTS.

Differentiation of closed and unclosed DTS depends on whether there is superposition of their starting and end points. However, all of the Type I and Type II DTS are closed. They need be further differentiated by whether their nodes are clockwise or anti-clockwise. The DTS can be analyzed using the following method: with the geographic coordinates of nodes of a closed DTS being (x_1,y_1), $(x_2,y_2)\ldots(x_n,y_n)$, the polygon area consisting of n nodes is depicted by the formula

$$S = \frac{1}{2}\sum_{i=1}^{n}(x_i - x_{i+1})(y_i + y_{i+1}) \quad (2)$$

If $S>0$, the DTS is of Type I (e.g., c_1 and c_2 in Fig. 2), or else Type II (e.g., c_3 in Fig. 2). If all the Type I DTSs are found in the area, all unconnected depressions are obtained.

2.5. Consideration for high water level

2.5.1. The influence of high water level on unconnected depressions

Actually, the alternating rise and fall of the water surface is continuous. In order to display the phenomena, the continuous changes should be discretized using a series of flooding scenes. The inside of depressions not flooded at the highest water level (Z_{max}) should always be displayed by the terrain of DIZM. During the change from the highest water level to the lowest one, if a new depression appears, the depression is recoded, and its display will be kept at the lower water level. The current water level and the elevation of the lowest overflow point on the depression boundary are compared when the water level changes from the lowest to the highest. If the current water level is lower than the elevation of the lowest overflow point on the depression boundary, the flood areas are the same as when the water level was equal to the elevation of the lowest overflow point. Otherwise, the depression is connected to external water; thus it is no longer a distinct, disconnected depression.

2.5.2. Identification of a new depression

As the water level falls, unconnected depressions appear continuously. The appearing depressions are of two forms: a depression computed with the current water level being located inside an old depression, where the elevation of the lowest overflow point on the depression boundary is higher than the current water level (e.g., *B* in Fig. 3(b) is located inside a previous depression *A*). The other case is when the depression is located outside an old depression (e.g., *C* in Fig. 3(b)). Actually, the former is a type of depression within an old one, and its extent will not change as the water level falls. It will always keep the extent of its initial formation, so it is not a truly new depression. The latter, being located outside an old depression, is a truly new depression. A new depression is displayed, and will keep the extent of the time when the water level was equal to the elevation of the lowest overflow point on the depression boundary. The method of differentiating a new depression is: if any node of a new Type I DTS is located outside an old Type I DTS, then the inside of the new DTS is a new depression; otherwise, the area is not a new depression.

2.5.3. Creation of an index table for water levels to depressions

Depressions at various water levels are different. An index table for water levels to depressions is pre-created to avoid real-time computation. The highest value Z_{max} and the lowest value Z_{min} of water level are computed using Z_{IWSM}. Suppose a water level resolution d is needed for continuous scene simulation (e.g., 0.1 m), N represented by formula (3) is called the grade number of the water level.

$$N = Floor\left(\frac{Z_{max} - Z_{min}}{d}\right) \quad (3)$$

Based on the value of d, water level Z_i, which has different grades i ($i = 0, 1, \ldots, N$), is computed with the formula

$$Z_i = Z_{max} - i \times d \quad (4)$$

The unconnected depressions at different Z_i are computed, and an index from grade of water level to depressions is created. All computations can be completed prior to the continuous display.

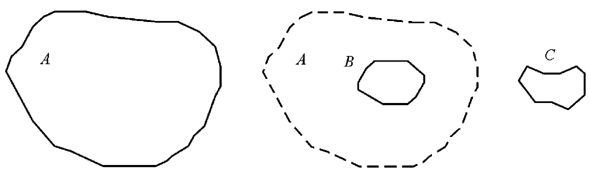

Fig. 3. Decision for a new depression. (a) Depression at a previous higher water level Z_1. (b) Depressions at a later lower water level Z_2. *B*, being located inside an old depression *A*, is not a truly new depression. Even though water level changes from Z_1 to Z_2, the extent of the old depression *A* is unchangeable. *C*, being located outside an old depression *A*, is a new depression.

2.6. Plotting at different water levels

2.6.1. Query of unconnected depressions

On the basis of Z_{IWSM}, water level Z at any time can be computed during the continuous display. Then, the grade of water level is computed using the formula

$$i = Floor\left(\frac{Z_{max} - Z}{d}\right) \quad (5)$$

Unconnected depressions can be queried from the index table based on the grade of water level. In the real-time plotting, DIZM is always displayed inside of the Type I depressions, and IWSM is always rendered inside the Type II depressions.

2.6.2. Display of the depression

Because the highest water level Z_{max} is lower than the elevation of the lowest inflow point on the depression boundary, the Type I depressions are not flooded at any time, and their insides are always displayed as terrain. So a hole polygon is formed according to the boundary of the Type I depression. The terrain and current water level are compared inside of the hole polygon; then flooded areas are computed.

Although a Type II depression is an unconnected depression, it is flooded when the current water level is higher than the elevation of the lowest overflow point on the depression boundary.

Because the extent of the depression covered by water is possibly a hole or concave polygon, it should be decomposed into some convex polygons. The OpenGL class GLUtesselator is used to render scenes in this study.

3. Model evaluations

3.1. Accuracy

A group of data was used to test the accuracy of the proposed algorithm. Fig. 4(a) is a sketch map of flooded areas based on the traditional seed spread algorithm, and Fig. 4(b) is a result of the proposed algorithm based on DTS (the shaded areas, shown in Fig. 4, represent flooded areas). A triangle, used for computation and display in the traditional algorithm, is selected as a minimum cell. If the mean height value of the three vertexes in a triangle is lower than the current water level, the whole triangle

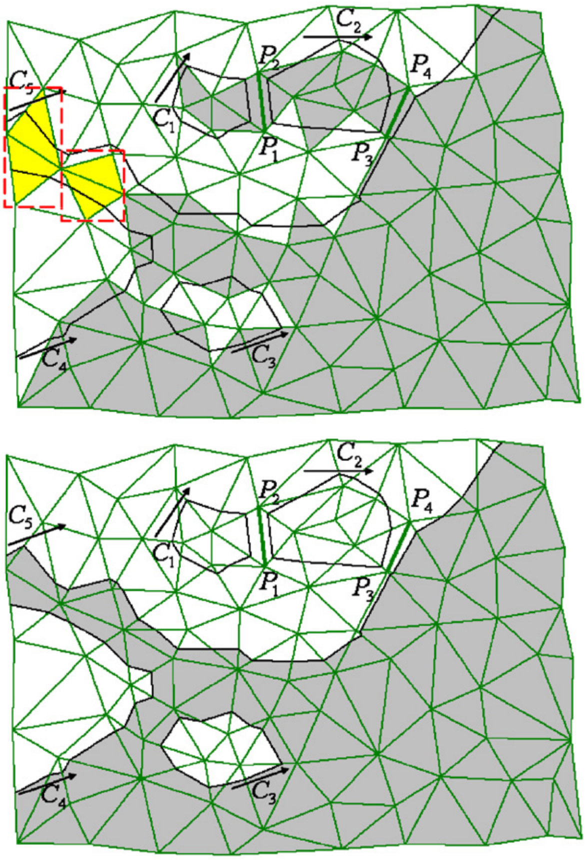

Fig. 4. Comparison of flooded areas based on different algorithms. (a) Result of traditional seed spread algorithm. (b) Result of proposed algorithm based on DTS.

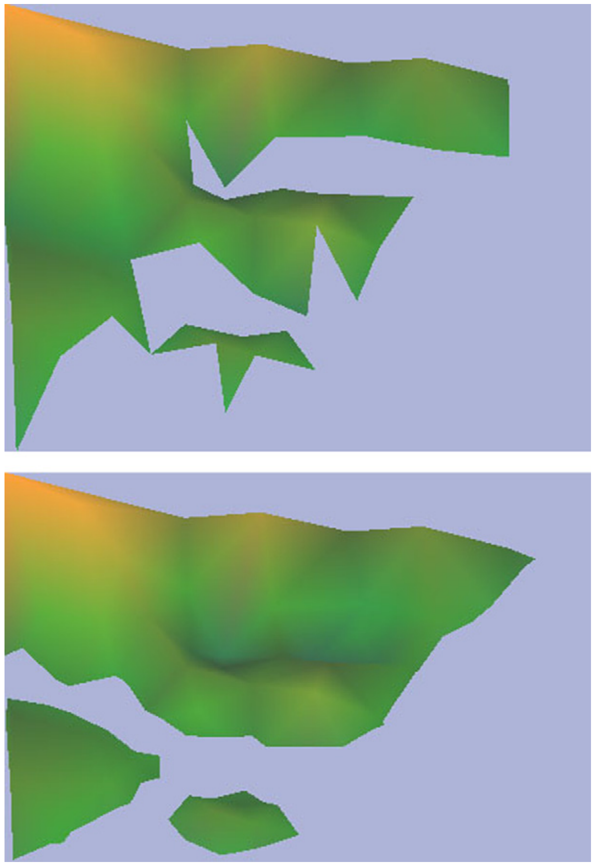

Fig. 5. Comparison of three-dimensional displays of flooded areas based on different algorithms. (a) Result of traditional seed spread algorithm. (b) Result of proposed algorithm based on DTS.

should be incorporated into the flooded area. However, in the proposed DTS algorithm, a DTS is traced on the basis of vertex values of a triangle, and flooded or dry parts are further computed in the triangle; thus, the computation is more accurate. As shown in Fig. 4(a), the boundaries of flooded areas are indented. Fig. 4(b) shows a smoother boundary than that in Fig. 4(a). The representation by the proposed algorithm is more suitable for the actual case.

Furthermore, the proposed algorithm has obvious advantages over the traditional algorithm in detailed representation. As shown in Fig. 4, vertexes p_1, p_2, p_3 and p_4 are higher than the current water level ($Z_{IWSM} = 1$ and Z_{DISM} of vertexes are shown in Fig. 1), two low lands are divided into two unconnected depressions by line segments p_1p_2 and p_3p_4. However, as shown in Fig. 4(a), correct depressions are not formed using the traditional seed spread algorithm, and low lands are connected with an outside water body. Moreover, the traditional algorithm forms two false depressions as shown in Fig. 4(a) (the shaded areas in the two dashed frames, although the mean value of the vertexes in the triangles is lower than the current water level, the triangles are not adjacent to triangles in other shadow areas. So, they are not incorporated into the flooded areas). As shown in Fig. 4(b), two unconnected depressions, labeled C_1 and C_2, based on the proposed DTS algorithm, are displayed correctly, and two false depressions are not formed.

In order to compare the results of different algorithms further, the model, using a three-dimensional graphics mode, is shown in Fig. 5. Fig. 5(a) shows the result of the traditional seed spread algorithm while Fig. 5(b) exhibits the result of the proposed algorithm based on DTS. The proposed algorithm results in a more accurate display than the traditional algorithm.

3.2. *Effect of a seed point*

Another group of data was tested to show the result of using different seed points. Figs. 6 (a) and (b) show different results derived from seed points P_1 and P_2, respectively. Fig. 7 shows the result derived from the proposed algorithm based on DTS. In fact, the areas *A* and *B* (as shown in Fig. 7) are connected, but they are displayed as unconnected areas due to the limited ranges of the study area. Only one area is flooded using the traditional algorithm wherever a single seed point is selected; the correct result cannot be obtained from a

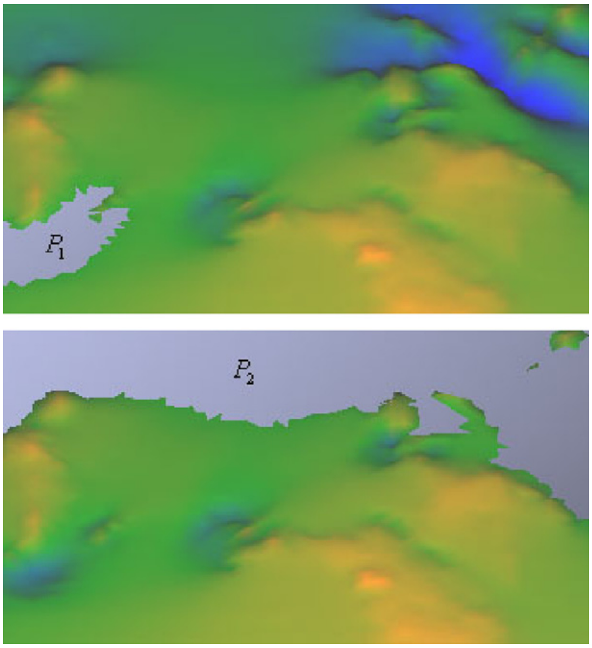

Fig. 6. Different results derived from seed points in traditional algorithm. (a) A selected seed point in the left-bottom of an area. (b) A selected seed point in the top of an area.

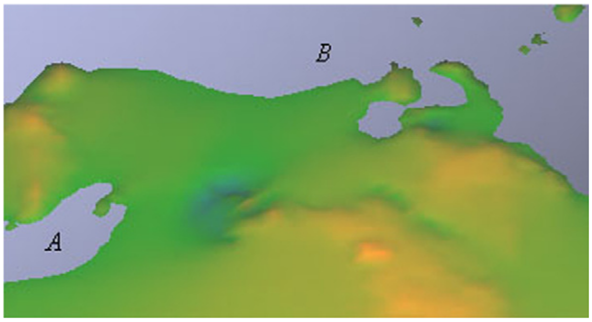

Fig. 7. Result derived from proposed algorithm based on DTS.

single selected seed point. However, the proposed algorithm can obtain the correct results.

3.3. Effects of high water level

Fig. 8 shows a series of scenes that do not consider high water level (a, b, c are the scenes of water levels Z_{max}, $(Z_{max}+Z_{min})/2$, Z_{min}, respectively). Fig. 9 also shows that the scenes of corresponding water levels consider the influences of the high water level's effects. Depressions, flooded at Z_{max} (as shown in Fig. 8(a)), are not covered by water at lower water levels (as shown in Figs. 8(b) and (c)). If the influence of high water is considered, depressions, flooded at Z_{max} (as shown in Fig. 9(a)), are also covered by water at the other water levels (as shown in Figs. 9(b) and (c)). Actually, the water surface is rising and falling, and high water affects flooded areas directly, so

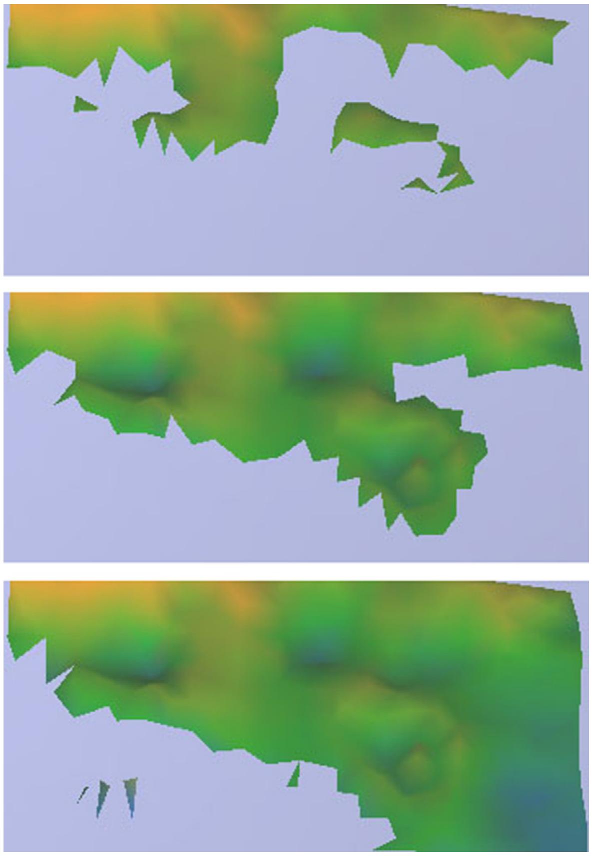

Fig. 8. Result of traditional seed spread algorithm not considering effect of high water. (a) Result at water level Z_{max}. (b) Result at water level $(Z_{max}+Z_{min})/2$. (c) Result at water level Z_{min}.

plotting of flooded areas with the proposed algorithm that considers prior high water levels is more accurate.

3.4. Efficiency

The test environment was as follows: the CPU—P4 at 2.4 GHz, 512 MB of memory, and Windows XP Professional operating system (Table 1).

Experimental results demonstrate that the proposed algorithm can result in an accurate and efficient display for which the observed inundation extent is available and the free surface remains approximately horizontal. A key issue in flooding plotting is the computation and display of scenes in real-time, and the time interval between before-and-after frames must not be too great. Traditional seed spread algorithms need to compute flooding and connectivity iteratively, and the time for computing flooded areas is unsuitable for plotting the flooding of a large area (Ding et al., 2004). The proposed algorithm based on DTS avoids iterative computation, and most of the computation can be completed prior to continuous display, so the efficiency of the real-time display obviously improves, and can meet the requirements of plotting the flooded intertidal zones. Although the proposed method traces DTS based on TIN in this paper, it can be extended to DIZM represented by regular grids.

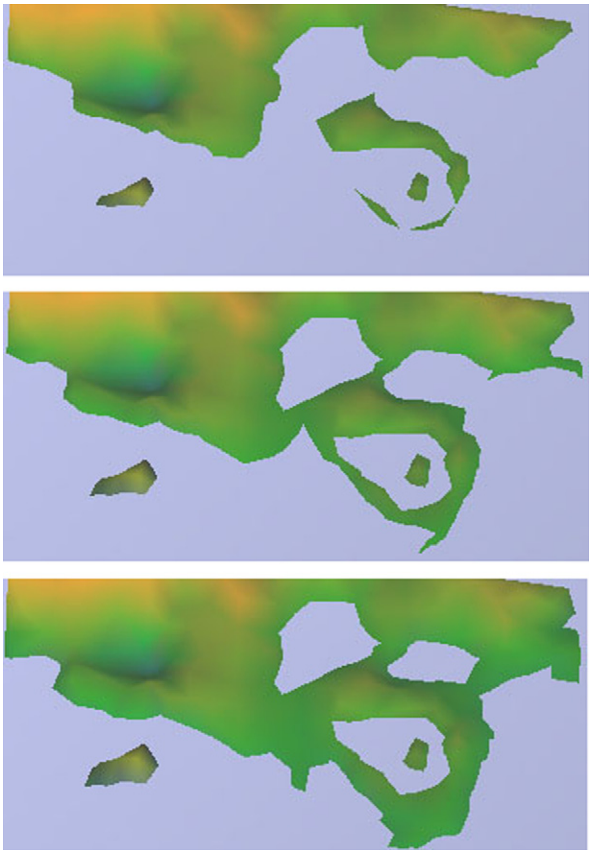

Fig. 9. Results of proposed algorithm considering high water's effect. (a) Result at water level Z_{max}. (b) Result at water level $(Z_{max}+Z_{min})/2$. (c) Result at water level Z_{min}.

Table 1
CPU time for three-dimensional representation with source flood simulation based on different data.

Number of triangles	Number of unconnected depressions	CPU time of traditional seed spread algorithm (s)	CPU time of the proposed algorithm based on DTS (s)
4716	6	0.8	0.026
7001	6	1.8	0.035
12,623	6	5.9	0.060
23,902	6	23.8	0.142
33,190	13	103.9	0.176
45,697	29	231.6	0.253
1,24,816	6	662.2	0.592
2,23,772	6	2130.5	1.077

The proposed algorithm, as a graphical tool to plot flooded areas, is fast and efficient; moreover, it is more accurate than traditional algorithms in dealing with source floods. Certainly, more accurate plotting of flooded intertidal zones should take sea surface topography and hydrodynamics into account, which will be performed in our future research.

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