Concepts and representation of beach nourishments by spatio-temporal ontologies.

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Abstract

This study addresses concepts and representation of beach nourishment by two spatial ontologies and one spatio-temporal ontology. We extend a spatial ontology based on crisp objects to one with fuzzy objects, to which temporal aspects are added. The fuzzy ontologies are described using semantic membership functions. The three ontologies are applied to a case study on beach nourishments at the Isle of Ameland. Resulting amounts differed from 58600 to 78600 m^3. Quality issues are discussed. We conclude that the three ontologies can be implemented and applied, each having its own characteristic qualities.

1. Introduction

Landscape units are frequently vague in spatial extent (Fisher et al. 2003). The reason is that both context and definitions are poorly defined, often delineated by conceptual ideas, than by actual extents in space. An example that we study in this paper concerns broad sandy beaches and extensive dune ridges, dominating the Dutch coastal zone. This region exhibits a highly dynamic character. It is subject to continuous processes as beach erosion and sedimentation, which influence its morphology. This in turn has an economic impact on beach management and public security. Beach nourishment is carried out if safety of the land is at risk. Here the problems are defined as: (1) how to localize and quantify beach areas that require nourishment, and (2) how to assist the decision maker to manage the process of nourishment in time. To be able to address these questions, we use geographic information of different sources. We use an ontology-driven approach to integrate the different data sources.

An ontology can be defined as an explicit specification of a conceptualization, which gives the definitions of classes, relations, functions and other objects (Gruber 1993) (Guarino 1995). An ontological approach guides the conceptualization of the beach areas, their attributes and relationships. Ontologies for beach nourishment support knowledge sharing within various government organizations (Jeansoulin and Wilson 2002). They help to understand the role of the quality of the data sources and also the required qualities for the decision maker, the so-called fitness for use (Hunter 2001, Vasseur et al. subm). For analyzing and understanding a dynamic geographical problem, a spatio-temporal ontology, i.e. an ontology representing space and time, is essential (Claramunt 1997, Frank subm). Hence, the ontology is to be extended with temporal issues, such as processes and events.

In the past, ontologies have proven to be useful for handling real world objects within a geographical information system (Jeansoulin and Wilson, 2002; Vlag et al. subm., Vasseur et al. subm.). As such, different approaches of handling such objects can be dealt with, and data quality issues can be addressed.

The aim of this paper is to conceptualize and represent beach nourishment by using a spatio-temporal ontology. Essential quality elements are discussed. To do so, we describe three methods for the conceptualization of the beach nourishment process. First, crisp objects represent the identification of the beach areas suitable for nourishment. Second, the beach areas are represented and modeled by fuzzy sets. Third, we incorporate temporal uncertainty by fuzzification of timeseries representing the processes and events within the application.

2. Methodology

2.1 Ameland casestudy

The study area is located at the northwestern part of Ameland, a coastal barrier island on the fringe between the Wadden Sea and the North Sea (figure 1). Geomorphological processes such as erosion, transport and sedimentation of sandy materials are causing major changes the coast of Ameland, in particular at the northwestern part of the island, which is a geomorphologically highly active area. Sand nourishments have to be carried out to counteract beach erosion. To calculate the required volume of sand, the expected erosion, the recurrence interval and the sand reserve have to be determined. Either beach nourishments or underwater sand nourishments are applied for sand nourishments (Roelse, 2002). In this study we focus on beach nourishments, as their effects on the maintenance of the coastline are better known.

Beach objects required for nourishment are to be localized, of which the borders are subject to complex coastal dynamics. Identification of beach objects should include both the attributes, and events and processes working on them.

2.2 Dataset

The dataset for the Ameland case study consists of multi-temporal digital elevation models and satellite imagery. Each digital elevation model of Ameland is derived from the JARKUS data from the DONAR database (Eleveld 1999). The

DONAR database contains annual beach and foredune profiles derived from stereometric analysis of aerial photographs for the dry part of the coastal transect. The underwater part of the profile is measured with echosoundings from ships with automatic position-finding systems. The transects are 200 to 250 m apart and elevation is measured at 5 m intervals along a cross-shore line. From the point data, we interpolated the profiles towards a 30 m × 30 m grid. Satellite images are derived from Landsat5-TM and Landsat7-ETM+ satellites. Landsat images contain pixels corresponding to 30 m × 30 m ground surface.

The beach objects are structured in compartments within a higher conceptual level, based on perceivable regions on the beach. Compartments are the regions between two transects.

2.3 Beach nourishment

According to Dutch policy regulations, beach nourishment is carried out (1) if safety of the interior is at risk, (2) to safeguard dune objects, (3) to stimulate and manage beach recreation, or (4) to reduce the loss of nature areas (Roelse 2002). Reference is made to the basal coastline, being the coastline position on 1-1-1990 as well as to the beach volume at basal coastline, being the standard for preservation of the coastline. Beach nourishments are carried out when the actual coastline is below the basal coastline. The actual beach volume can be calculated by multiplying the beach area with the surface area using the altitude between the upper boundary (the dune-feet) and the lower boundary (the mean low water line).

Next, it is possible to calculate structural erosion, by plotting the actual beach volumes against the beach volume at basal coastline. A negative trendline indicates erosion, whereas a positive trendline represents sedimentation.

Two constraints apply when deciding upon nourishment (A) or no nourishment (O) for a coast compartment. The first constraint (C_1) is that a coast compartment shows structural erosion, the second constraint (C_2) is that the volume for beach nourishment should exceed 0.2 Mm^3. Constraint C_2 is a soft constraint, as nourishment may be carried out, depending on local and regional policies (Roelse 2002).

2.4 Modeling a beach nourishment process.

Beach nourishment will be described in three different ways. First, a crisp approach considers sharp boundaries between different beach objects. Second, a fuzzy approach describes departments as memberships of three parameters. Third, membership functions are included for modeling temporal processes.

2.4.1. Creating a spatio-temporal ontology

The ontological approach handles the underlying data management problem as an integration of both data and semantics, within a common reasoning framework (Jeansoulin and Wilson 2002). The ontological approach clarifies the structure of knowledge, and leads to coherent knowledge base. An ontology exists of objects, their attributes and relationships (that may be time dependent), events, processes and states. Ontologies may enable knowledge sharing and reuse for different domains or time intervals.

For our application, the spatio-temporal problem can be defined as: 1) how to localize and quantify beach areas that require nourishment, and (2) how to assist the decision maker to manage the process of nourishment in time. Ontological features for the Ameland case study, as objects, attributes, relationships, state and events, are summarized in table 1.

2.4.2. Crisp compartmental method

Identification of areas that require beach nourishment depends upon terrain altitude (height around zero), vegetation index (non-vegetated zones) and wetness index (dry zones). Altitudes between –1 and 2 m at Dutch standard sea-level (NAP) are considered as beach areas. Such areas are derived from digital elevation models (DEMs). Similarly, non-vegetated and dry zones are derived from Landsat TM imagery. Non-vegetated zones are selected as areas with negative NDVI values; dry zones are selected as areas with a wetness index lower than zero. The delimitation of the object beach should satisfy the constraints for altitude, non-vegetated and dry zones (Vasseur et al., submitted).

Identification of beach areas that require beach nourishment requires compartments (*C*) to distinguish zones with sedimentation from those with erosion. These compartments are perpendicular to the coast, 100-200 m wide, and fixed in time. Compartment width is a fixed limit (*CL.geo*), whereas its length is the distance between the beach-sea boundary (*BS.geo*) and the beach-dune boundary (*BD.geo*). Both boundaries are dynamic in time (*BS.geo*(*t*), *BD.geo*(*t*)), due to erosion and sedimentation processes. For the crisp compartmental approach, these boundaries are assumed to be sharp.

On the basis of the beach volume it is decided if either sedimentation or erosion occurs within a compartment. For *np* pixels each of size *ps* the beach volume within a compartment (*C.vol*(*t*)) is calculated as:

$$C.vol(t) = ps \times \sum_{i=1}^{np} e(i,t) \qquad (1)$$

where $e(i,t)$ is the elevation of pixel i at time t. A compartment will be indicated for nourishment, when the beach volume in a compartment shows structural erosion.

2.4.3. Fuzzy compartmental method

In the fuzzy compartmental method, description of the beach objects will be fuzzy. Beach objects suitable for beach nourishment can be described by a membership of dry, non-vegetated beaches (Van de Vlag et al., subm.). A compartment is bound by two static compartment limit (*CL.geo*) and by two vague boundaries: the sea-beach boundary (*BS.geo*(*t*)) and the beach-dune boundary (*BD.geo*(*t*)). These boundaries are illustrated in figure 2.

The sand volume within the fuzzy compartmental method can be calculated, using:

$$C.vol(t) = ps \times \sum_{i=1}^{np} m(i,t) \times e(i,t) \tag{2}$$

where $m(i,t)$, membership value of location (i) in compartment C at time t. It is calculated as

$$m(i,t) = \min\{mb(i,t), md(i,t), mv(i,t)\} \tag{3}$$

where $mb(i,t)$ is the membership function of the beach object, $md(i,t)$ that of dry object and $mv(i,t)$ that of a non-vegetated object in which pixel i occurs at time t. Membership functions are compiled as triangular functions. The $mb(i,t)$ equals 1 if altitude ranges from 0 to 1 m amsl, it increases linearly from 0 to 1 between –1.1 to 0 m amsl and decrease linearly from 1 to 0 between 1 and 3 m amsl, and it equals 0 elsewhere. The $md(i,t)$ equals 1 if wetness index is less than -3, and decrease linearly from 1 to 0 for the wetness index moving from -3 to 3 m amsl, and it equals 0 elsewhere. Finally, the $mv(i,t)$ equals 1 if the ndvi value is less than -0.05, it equals 0 if the ndvi is larger than 0.05 and it decrease linearly from 1 to 0 in between. Note, that data are collected at one instance in time.

2.4.4. A temporal fuzzy compartmental method

Including temporal uncertainty into the beach nourishment processes we consider daily fluctuations for the wetness index, monthly fluctuations for the vegetation index and yearly fluctuations for altitude. To do so, temporal membership functions are introduced, which have the highest values when the most reliable data can be collected. For vegetation, the $nv(t)$ equals 1 between 1 June and 1 August, it equals 0.5 between 1 November until 1 March, and it is linear in between (figure 3). Similarly $nd(t)$ equals 1 during flood time and equals 0.5 during low tide, and further follows a sine form, i.e. $nd(t) = 0.75+0.25\cdot\cos(2\pi\cdot t/12.5)$, with t expressed in hours in relation to high tide (figure 3). Finally, the function $nb(t)$ is included to describe the actual digital elevation model.

2.4 Quality Elements and Quality Matrix

2.4.1. Quality Elements

Several organizations of standardization (ISO 2003, FGDC2000, CEN/TC-287 1994/1995) and scientific literature (Guptill and Morrison 1995, Joos 2003) suggest quality elements in the sense of ‘fitness for use’. More precisely, the recognized external quantitative data quality elements that measure fitness for use concern the following parameters: completeness, logical consistency, and accuracy (Fisher 2003). In our approach to describe three methods for beach nourishments, we encounter the following ISO quality elements and subelements as most essential (ISO 2003):

- *Positional accuracy*
  Relative or internal: closeness of the relative positions of features in a dataset to their respective relative positions accepted as or being true.
  Gridded data position: closeness of gridded data position values to values accepted as or being true.
- *Temporal accuracy*
  Accuracy of a time measurement: correctness of the temporal references of an item (reporting of error in time measurement).
- *Thematic accuracy*
  Accuracy of quantitative attributes: and the correctness of non-quantitative attributes and of the classifications of features and their relationships.
  Classification correctness: comparison of the classes assigned to features or their attributes to a universe of discourse (e.g. ground truth or reference dataset).

2.4.2. Quality Matrix

The matrix of quality represented in table 2, can be used to characterize a state but also characterize a process and event. The relevant cases within the beach nourishment are depicted in the matrix, linking an attribute of quality to some ontology features.

3. Results

3.1 Comparison of the approaches

The methodology of a crisp-, fuzzy- and temporal fuzzy approach results in figure 4. Here, the beachplain of the Ameland is depicted, whereby the beachplain is the beach area, that is dry and non-vegetated. The fuzzy- and fuzzy temporal approach (figure 4 middle and right) differ from each other, as the slope of the membership function is corrected according to the temporal (un)certainty of the vegetation- and wetness index. At high tide, the certainty that a beach is wet or dry is high, while at low tide this temporal certainty is low. The same for the vegetation; in summer the certainty about vegetation is high, while during growing season this certainty is lower. The capturing date of the landsat image is 7 November 1995, at 9h30, just after low tide. This corresponds with a low temporal certainty for vegetation and wetness. The slope of the membership functions for vegetation is corrected for this temporal uncertainty, and is less steep, resulting in the image of a fuzzy beachplain as shown in figure 4 right.

After trendline calculation, there are only two regions that are indicated as areas with structural erosion. Only the lower left region is of interest, as actual beach nourishment are actively carried out in that area (Van de Vlag et al., subm). The calculation for beach volumes, using the compartmental method (see figure 5), are represented in table 3. Obvious is that the fuzzy approaches indicate lower volumes, as thematic uncertainty, as well as temporal uncertainty is accounted for. The volumes as show in table 3 are lower than the criteria for nourishment, and beach nourishment in 1995 will not be carried out.

3.2 Quality Elements

Table 4 describes the quality of the objects in a general fashion that apply to the case study. Different membership functions occur, whereas spatial and temporal precision apply to a lmited set of objects. We note that the three different procedures lead to different quality assessments. The crisp compartment method results in statements on objects that have a precision accuracy. The fuzzy compartment methods describes both the positional and the thematic accuracy. Thematic accuracy is described by membership functions, that were included from the semantic import model. Finally, the temporal fuzzy compartment method includes statements on positional, thematic and temporal aspects. Note that the temporal membership functions occur that were also based on a semantic import model.

4. Discussion

The selection of quality elements essential for the study area is done by using previous studies (Cheng 2001, Van de Vlag et al. subm, Vasseur et al. subm). From the perspective of beach nourishments, the accuracy to describe the relevant objects is the most important one, assuming that data gathering and data reliability is not a real issue. Positional elements concerns the elevation, and a choice for boundaries of objects. Positional accuracy is determined by the DEM, in particular by its grid resolution. Temporal accuracy is determined by seasonal factors for vegetation, for the wetness index by tidal fluctuations, and for elevation by both erosion/sedimentation processes and by incidental changes. Seasonal factors may be difficult to relate to vegetation, as many factors come into view. Also the relation between tidal effects and wetness may be influenced by other factors as well (vegetation, weather). Finally, processes on sedimentation and erosion are not always fully understood and applicable to large areas of land. Also, events such as severe drought and large storms may interfere. Thematic accuracy concerns determination of a classification using quantitative figures. This may be subjective and influenced by spatial variation.

Causes of uncertainty in objects to determine their suitability for beach nourishment, lies in natural variation of the parameters which describe the object. That, together with the reason that both context and definitions are poorly defined and is often delineated by conceptual ideas, leads to the conclusion that objects need to be treated as vague objects, with membership functions representing its thematic and temporal uncertainty. In this study, we show that temporal uncertainty is part of thematic uncertainty and their interrelationship is joined inextricable. This is expressed by using the temporal (un)certainty and correct the slopes of the membership functions for thematic uncertainty.

Hence, a realistic a geospatial model to fully describe natural phenomena may be complicated. Relationships between ontological features as objects, attributes, states, events and processes will occur at multiple conceptual levels. Quality elements for each of these features will contribute to the overall quality of the model and its final product. Therefore, to retain a manageable model, a structure using hierarchy may obtain a better relief for describing its ontological features, as well as its quality elements.

5. Conclusions

This study identified three methods for describing beach objects suitable for beach nourishments. The crisp method is relatively simple and easy to understand and implement, but may fall short when a realistic description of objects is required, and hence may lead to erroneous decisions. The fuzzy approach is an extension that is more realistic, as the described objects are closer to the way that they occur in decision procedures and to the use in ontologies. However, important temporal aspects are only included in the next extension, the temporal fuzzy compartmental method.

The case study focused on beach nourishment at the Isle of Ameland. It has shown that the three methods can be implemented and applied to determine the required amount. The three approaches resulted in different amounts of beach nourishment volumes, ranging from 51600 to 78600m^3. Issues of quality are discussed. Further steps are identified to quantitatively valuate different quality aspects, such as positional, temporal and thematic accuracy.

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Table 1: Ontological features as objects, attributes, relationships, states and events for the Ameland application.

Elements	Description
Objects	
C.id	Compartment
CL.id	Compartment limit
BD.id	Beach - Dune boundary
BS.id	Beach - Sea boundary
Attributes	
C.vol	Compartment Volume
C.vol90	Compartment Volume (basal)
CL.geo	Compartment limit (geometry)
BD.geo	Beach - Dune boundary (geometry)
BD.ndvi	Beach - Dune boundary (ndvi)
BD.z	Beach - Dune boundary (altitude)
BS.geo	Beach - Sea boundary (geometry)
BS.wi	Beach - Sea boundary (wetness index)
BS.z	Beach - Sea boundary (altitude)
C.se	Compartment (structural erosion)
Relationships	
RC/CL	Relation Compartment/Compartment Limit
RC/BD	Relation Compartment/Beach Dune Boundary
RC/BS	Relation Compartment/Beach Sea Boundary
RC/C.se	Relation Compartment/Compartment (struc. erosion)
Processes	
C.vol/t	Graph of Compartment volume against time
TL.id	Trendline
TL.trend	Trend

Table 2. The matrix indicates columnwise the characteristics of the application and rowwise the elements of quality of interest for the application. NR = not relevant.

	Quality Elements		
Ontological Features	*Positional accuracy*	*Thematic accuracy*	*Temporal Accuracy*
Object	√		
Attributes ~ thematic		√	
Attributes ~ temporal		√	√
Relation	NR	NR	NR
Process	√	√	√
Event	√	√	√

Table 3. Beach nourishment volumes using the crisp compartmental (CC), the fuzzy compartmental (FC) and the temporal fuzzy compartmental (TFC) approach.

	CC	FC	TFC
Volume (m^3)	$78.6 \bullet 10^3$	$58.7 \bullet 10^3$	$51.6 \bullet 10^3$

Table 4. Quality elements for the ontological features. Abbreviations: CC = classification correctness, QAA = quantitative attribute accuracy, NR = not relevant.

	Positional Accuracy		Thematic Accuracy		Temporal accuracy
	Relative	Gridded	CC	QAA	
Elements					
C.id	48.6 m	30.3 m			< 1 year
CL.id	NR	30.3 m			< 1 year
BD.id	48.6 m	30.3 m			< 1 year
BS.id	48.6 m	30.3 m			< 1 year
Attributes					
C.vol	48.6 m	30.3 m	mv(i,t)		nb(t)
C.vol90	48.6 m	30.3 m	mv(i,t)		nb(t)
CL.geo	NR	30.3 m			
BD.geo	48.6 m	30.3 m	mv(i,t)		
BD.ndvi	48.6 m	30.3 m		NR	nv(t)
BD.z	NR	30.3 m		+/- 0.28 m	
BS.geo	48.6 m	30.3 m	mv(i,t)		
BS.wi	48.6 m	30.3 m		NR	nd(t)
BS.z	NR	30.3 m		+/- 0.28 m	
C.se	48.6 m	30.3 m	mv(i,t)		nd(t)
Processes					
C.vol/t					< 10 year
TL.id					
TL.trend					< 1 year

Figures

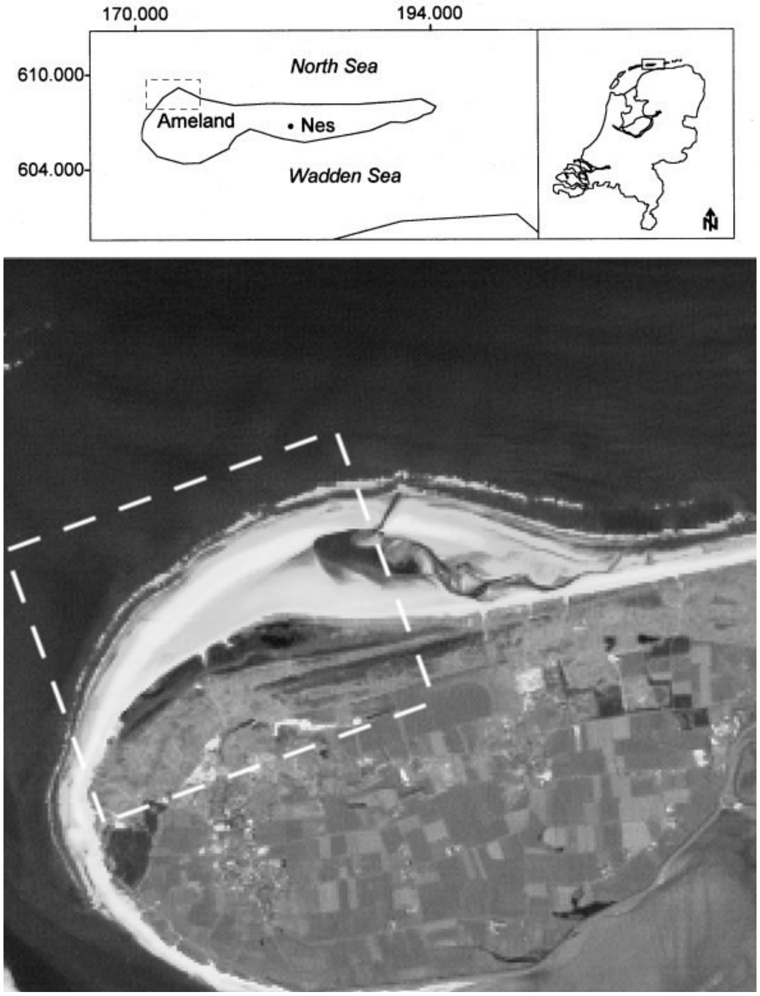

Figure 1. A landsat image (1999) from the north-western part of the Isle of Ameland. The bottom part of the study area contains mainly dunes, the middle part is beach, the upper part is sea.

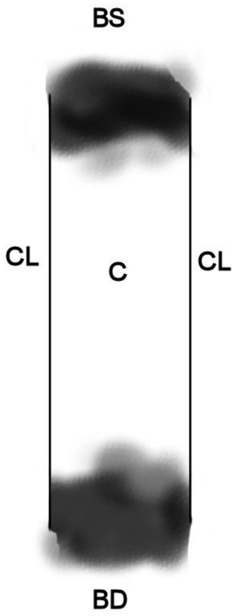

Figure 2. The limits of a fuzzy compartment, where *C* is the compartment, *BS* is the fuzzy boundary between beach compartment and sea, *BD* a fuzzy boundary between beach compartment and dune and *CL* are crisp boundaries separating beach compartments.

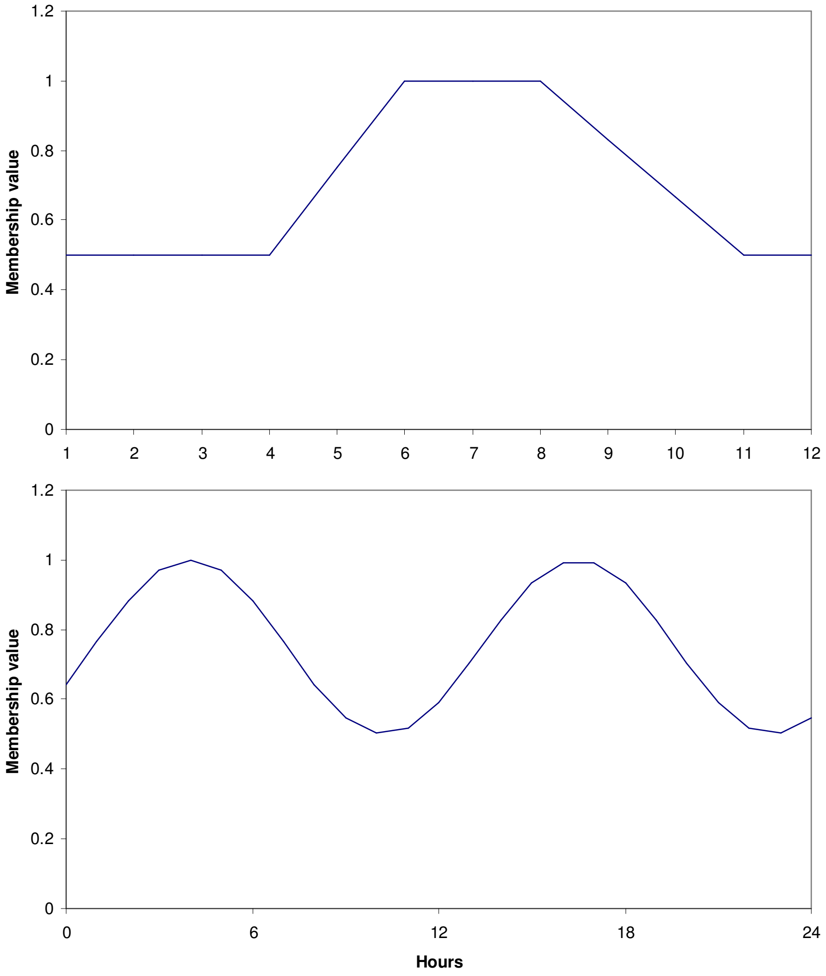

Figure 3. Semantic import models for temporal uncertainty, the *nv*(*t*) (top) and the *nd*(*t*) (bottom) membership functions.


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

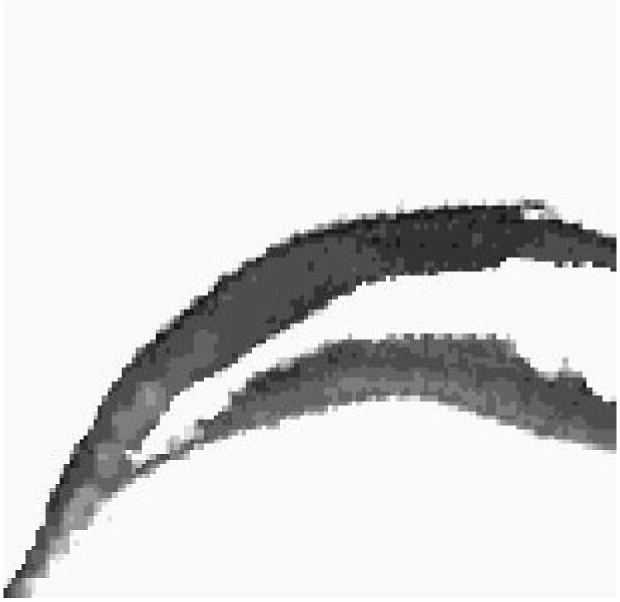

Figure 4. Beachplain classification, using a crisp (top left), fuzzy (top right) and temporal fuzzy (bottom) method. Legend is membership values, with 0 is no membership and 1 is full membership.

Figure 5. Final result of crisp compartmental (top left), fuzzy compartmental (top right) and temporal fuzzy compartmental (bottom) method. Legend is membership values, with 0 is no membership and 1 is full membership.