SEASCAPE GEOVISUALIZATION FOR MARINE PLANNING

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Landscape visualization, integrating geographic information science and virtual reality, has been used as a tool for decision support and public engagement in land-use planning, particularly by enabling representation and exploration of different development scenarios. Given the comparative lack of experiential knowledge most of us have of the marine environment and its inherent 4D nature—where the sea surface, water column, seabed and sub-bottom are dynamic and all are integral to the distribution of natural processes and human activities—seascape geovisualization has lagged behind landscape visualization. This paper explores the opportunities and challenges of geovisualization for marine planning, with an emphasis on seabed visualization. Research to arrive at a new seascape geovisualization paradigm is rooted in various technologies and techniques; namely geographic information systems, landscape visualization, ocean modelling, gaming and virtual reality. Technological advances, however, must be informed by a user requirements analysis and evaluation of visualization effectiveness for marine planning.

La visualisation du paysage terrestre, intégrant la science de l'information géographique et la réalité virtuelle, a été utilisée comme outil d'aide à la décision et de mobilisation du secteur public pour l'aménageme du territoire, particulièrement en permettant la représentation et l'examen de différents scénarios de développement. En raison du manque relatif de connaissances expérientielles que la plupart d'entre nous ont de l'environnement marin et de sa nature quadridimensionnelle inhérente—où la surface de l'eau, la colonne d'eau, le plancher océanique et le sous-sol du fond de la mer sont dynamiques et tous intégrés à la distribution des processus naturels et des activités humaines—la géovisualisation du paysage marin accuse du retard par rapport à la visualisation du paysage terrestre. Le présent article examine les possibilités et les défis de la géovisualisation pour la planification marine en mettant l'accent sur le visualisation du plancher océanique. La recherche visant à trouver un nouveau paradigme de la géovisualisation du paysage marin est enracinée dans diverses technologies et techniques, notamment les systèmes d'information géographique, la visualisation du paysage terrestre, la modélisation des océans,les simulations et la réalité virtuelle. Les progrès technologiques doivent toutefois être éclairés par une analyse des besoins des utilisateurs et une évaluation de l'efficacité de la visualisation pour la planification marine.

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1. Introduction

As energy, food and other land resources become strained with the demands of a growing population, the coastal and marine environment is becoming an increasing focal point for human development, economic opportunity and marine conservation [*United Nations Environment Program* 2006; *Food and Agriculture Organization* 2007]. For example, offshore wind and ocean energy opportunities are being explored, aquaculture is expanding as wild fisheries resources decline, and marine protected areas are being designated to protect sensitive habitats and species at risk. When resource and space demands compete, governments have turned to more strategic planning and management of the marine environment, resources and uses to examine risks, balance the use of resources and space among users, identify appropriate sites for new development and conservation areas, and zone marine areas. Environmental planning and management aims to minimize potential and mitigate existing impacts on the environment, e.g., sea level rise, flooding, habitat loss. Resource management aims to regulate the sustainable use of biological resources, such as fisheries; and geological resources, such as marine aggregate and hydrocarbons. Marine-use planning aims to regulate where activities are located, e.g., fish farm, oil and gas platform, marine protected areas.

These decisions have local repercussions. At a minimum, those with decision-making responsibilities inform or consult with the public. Many communities are not satisfied with being consulted and are demanding a greater role in coastal and marine planning. As a result, governments now embed a range of public consultation and direct involvement approaches in planning processes. For example, in British Columbia, the Pacific North Coast Integrated Management Area planning process confirms a "collaborative, inclusive and consensus-based planning process that includes participation by all levels of government including First Nations, stakeholders and coastal communities" [*Fisheries and Oceans Canada* 2006, p. 5].

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Planning and management in the marine environment has a range of challenges, particularly when taking it into the public realm. Other than scientists and those who SCUBA dive, the public and even decision-makers have relatively less experiential knowledge of the marine environment compared to that which they can bring to land-use planning. In addition, there are limits to our observational and surveying capabilities of the marine environment. Therefore, visual communication to bridge the lack of experiential knowledge with the need to understand the environment is particularly important in marine environmental and resource planning and management.

Maps have long been the predominant visual communication currency for land-use planning. They provide a planimetric view of locational information depicting features on the ground in a planning scenario. While they capture essential information for planning, it is argued that maps are often too abstract or schematic, making it difficult for the layperson to relate mapped information to their real-world experience or cognition [*Paar* 2006], and in fact they can contribute to confusion and errors in orientation [*Lewis and Sheppard* 2006].

With digital maps, geographic information systems (GIS) became the common communication currency for planning. GIS allowed uses to go beyond just visual communication to more interactive browsing and spatial analysis. In marine planning, GIS have been used extensively for identifying conservation hotspots, finding optimal areas for aquaculture, mapping oil-spill sensitivity regions, and the interaction between shipping activity and whale distribution, to name a few. While previously in the domain of researchers and technical specialists, communities are now taking on a more direct role in undertaking GIS analysis for marine planning [*Canessa* 2007].

With the increasing role of the public in coastal planning, *Jude et al*. [2007] argue that new techniques beyond conventional GIS are required to communicate complicated and diverse coastal information. Further offshore, the dimensionality of the marine environment sets it apart from the coastal and terrestrial environment. The marine environment is fundamentally four-dimensional (4D). Not only the seabed, but also the water column and sea surface, are integral to both ecological and socio-economic processes. In addition, the marine environment is a fluid medium, constantly in motion horizontally and vertically by oceanographic processes such as tides, currents, upwelling, downwelling and gyres. These oceanographic processes not only move the water, but those organisms and chemical properties within. In addition, organisms small and large, and underwater vehicles, are also in motion in three-dimensional space.

Despite its profound four-dimensionality, most marine planning is undertaken in two dimensions, and even benthic or midwater features and processes are visually represented in 2D on the sea surface. It is the complex dimensionality of the marine environment that almost demands enhanced visualization for effective planning and management.

As an alternative to conventional maps and GIS, landscape visualization has been promoted as the new common communication currency integral for land-use planning [*Lange* 2001, *Orland et al*. 2001]. Landscape visualization attempts to represent, in a terrestrial scene, actual or future places and land cover in 3D perspective view [*Sheppard et al*. 2004]. Combining graphics technology and art to create varying degrees of realism, landscape visualization aims to place the user within the simulated landscape. For example, a new golf course can be digitally created and placed on the proposed development site for the public to see it completed before any earth has been turned over. Similarly, forest-logging plans can be digitally generated to examine visual impact before trees are harvested.

The integration of map-based geography with visual simulation gives rise to the term 'geovisualization'. Geovisualization reflects rising literacy among the public, who are increasingly exposed to simulated games, virtual reality and Google Earth. Thus the public has high expectations for a more realistic, accurate, intuitive, engaging and accessible representation of the world, rich with structure, texture and movement [*Paar* 2006]. Google Earth, in particular, has placed geographic information sciences and visualization into the hands of the layperson and has been instrumental in breaking the technological barrier that has limited the accessibility of geographic information technology to the layperson.

Geovisualization has proven effective in educating communities in land-use planning, particularly through the generation and evaluation of alternative scenarios [*Al-Kodmany* 2002; *Lewis and Sheppard* 2006; *Jude et al*. 2007; *Stock et al*. 2007]. In a study with First Nations, *Lewis and Sheppard* [2006] found that compared to conventional 2D thematic maps, visualization tools were more likely to encourage "more in-depth and lively discussion, and seemed to help participants articulate more clearly their preferences for landscape conditions" (p. 291). As a result, landscape visualization is now widely used to simulate and explore future scenarios of landscape change and management, such as grazing, forest management, riparian management and agriculture [e.g., see *Lewis and Sheppard* 2006; *Stock et al*. 2007; *Soliva et al*. 2008]. Increasingly, it is being used to simulate and communicate the potential impacts of sea-level rise [*Jude et al*. 2007] and the visual impact of new development, such as wind energy installations on land [*Bishop and Miller* 2007].

In contrast to landscape geovisualization, research, development and application of seascape geovisualization lag far behind. This is not surprising. The oceans are more remote to the public and most people, particularly those who do not live along the coast, believe that they are not as directly affected by the oceans as they are by what occurs on land. However, our realization of the important role the oceans are playing in our terrestrial lives is increasing as we more fully understand the depth of our reliance on the oceans for our food, energy, global transportation of goods and climate control.

This paper explores the opportunities and challenges of seascape geovisualization for environmental and resource planning and management in the marine environment. Seascape geovisualization encompasses a three-dimensional marine scene, including the water column and, where relevant, the temporal processes within. The emphasis of this paper is on seabed visualization, although oceanographic visualization of water-column properties is also addressed. The paper begins with a review of visualization within the context of land-use planning, followed by current development and implementation of seascape geovisualization. The discussion compares landscape visualization with seascape visualization, pointing towards advancing seascape geovisualization for marine planning.

2. Landscape Visualization

2.1 Land-Use Planning and Management

Land-use planning includes town planning, evaluating residential, commercial and industrial development proposals, and transportation routing. Beyond the urban setting, land-use planning includes managing agricultural and forestry lands and resources, such as forest harvesting and silviculture planning; and civil engineering infrastructure, such as modelling flooding associated with dam construction. All of these can be contentious issues and communicating these plans to the public is increasingly important, requiring more sophisticated tools which assist decision-makers and the public to anticipate, envisage and assess such future land-use changes.

Landscape visualization has a technical-user group and an audience-user group. The technical-user group includes experts in computer software, geographic information, modelling, digital graphics, graphic design and animation. The technical-user group generates landscape visualization scenarios. The technical-user group may include architects, artists, engineers, graphic designers and scientists. The audience-user group comprises those who interpret the visual scenes to determine, for example, acceptable visual impact, future land-use allocation, future agricultural productivity and future silviculture practices. The audience-user group may include local planners, industry managers and the public.

2.2 Forms and Functions of Visualization

Visualizations can be grouped into three types: still imagery, animation and interactive. Still imagery comprises single images of a scene at a single scale and perspective. Still imagery represents a snapshot in space and time. Animation comprises a series of still images captured over a set of time intervals which, when shown in rapid sequence, give the appearance of movement. The most common example is a 'fly through', which captures a sequence of images along a pre-set path and potentially varying scales. Interactive visualization allows users to navigate through a scene, with potentially the capability to query and analyze the scene. Users can manipulate the scene by choosing their route, viewing angle, viewing height, perspective, scale and visual elements, such as objects, colour, texture and effects.

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These types of visualization vary, depending on degree of realism, rendering speed, accessibility and function (Table 1).

There is a trade-off between increased interactivity, and detail and realism [*Appleton et al*. 2002]. Static visualization tends to offer more realism and is less stylized, with faster rendering and more detail [*Jude et al*. 2007]. Interactive visualization is computationally more complex than static or animated visualization, as scenes need to be continuously rendered to generate new scenes at a different point in time or space. Although computer game and animation technology are rapidly improving, interactive visualization tends to have more limited

Table 1. Trade-offs in types of visualizations.

Type	Criteria				
Still	Realistic	Fast rendering	Accessible	Developer-defined	Pictorial
Animation	▼	▼	▼	▲	▲
Interactive	Stylistic	Slow rendering	Less accessible	User-defined	Analytic

visual elements, such as tones and textures, compared to still images.

There is also a trade-off between increased interactivity and public accessibility. Still images are easier to reproduce and distribute, and therefore can be more accessible to the public. To a lesser extent, animations can be captured as digital videos and distributed or made accessible for replay on desktop multimedia players. Interactive visualization requires more specific software and hardware, which are not commonly available to the public. However, when available on a console at public consultation forums, interactive visualizations can provide the user with more flexibility and control in exploring and customizing the visualization to answer user-specific questions [*Jude et al*. 2007; *Stock et al*. 2007]. As such, the public can have more control over interactive visualization, compared to still imagery or animations that are pre-defined and generated by individuals in the technical-user group.

Orland [1992] argues that analytical and modelling tools are important in visualization when used for environmental management. Still images and animation are primarily for pictorial purposes, to communicate a particular visual representation. As preconfigured images, public users cannot query or modify the results. However, visualization developers can create and analyze alternative scenarios; for example, modelling and comparing land cover and different development scenarios or impact under different sea-level scenarios. The results are then captured in still images or animations. When linked to modelling and analytical tools through a customized interface, interactive visualization can allow non-technical users the opportunity to generate and evaluate alternative scenarios.

Given the various trade-offs, different types of visualizations have their strengths and weaknesses, and which one is appropriate in planning depends on the complexity and scope of the planning problem, as well as the level of involvement and technical expertise of the audience.

2.3 Visualization Data, Elements and Techniques

Terrain data used to build a digital elevation model (DEM) are the fundamental building blocks of landscape geovisualization. A DEM provides the physical structure of the ‘lay of the land’ in 3D. A DEM may then be augmented with visual elements to provide textures and composition. *Appleton and Lovett* [2003] describe three main visual elements deemed to be most relevant for environmental decision-making which could generally be applied to seascape geovisualization: (1) ground surface, either procedural texture generated within the software or image texture derived from aerial photography; (2) foreground vegetation; and (3) building faces and other 3D objects representing features such as trees, fences and roads.

Draping an airphoto over a DEM is a fundamental image-texturing technique to provide accurate thematic content to the DEM [*Appleton and Lovett* 2003; *Jude et al*. 2007]. However, depending on the scale of the orthophoto, it may not provide sufficient detail. In such cases, land cover can be simulated with procedural textures. In some cases, visualization software offers a range of pre-generated textures for vegetation composition, such as coniferous forest, mixed forest, grass lands, etc. However, this range is limited and customized textures often must be created by the user for specific habitats and foliage composition present in a given study area [*Jude et al*. 2007]. Three-dimensional objects representing features such as buildings, trees, fences and roads can be placed on the scene by importing from topographic mapping, digitizing from aerial photographs or generating using image software [*Jude et al.* 2007; *Stock et al.* 2007].

Appleton and Lovett [2003] further define auxiliary elements as those which are not the main focus of decision-making, but draw the viewer to relate to the visualization in real life. These auxiliary elements include the sky, clouds and other atmospheric conditions; water, including surface structure such as ripples; shadows cast from buildings and trees through illumination and lighting techniques; and motion, such as moving wind-turbine blades [*Bishop and Miller* 2007].

Although the observer can appear to be moving in a landscape scene in a fly-through, most landscape visualization depicts static features of the landscape, e.g., trees, roads, buildings. In a few cases, the temporal dimension is introduced by, for example, modelling the progression of flooding or forest fires, rotation of wind-turbine blades or movement of vehicles along a road network.

2.4 Visualization Technology

Geovisualization brings together geographic information technology and visualization technology. As *Jude et al*. [2007] argue, much of the potential of GIS as a communication tool has remained unfulfilled, and the integration of GIS and visualization promises to fulfil some of that potential.

A range of software exists that integrates the two technologies to varying degrees. It is beyond the scope of this paper to give a comprehensive treatment of landscape visualization technologies, given the rapidly evolving software and hardware technologies. Readers are referred to *Appelton et al*. [2002] for a thorough comparison of various visualization software systems. However, to demonstrate some of the differences among visualization technologies, several are discussed below with an emphasis on integrating GIS with visualization and virtual reality.

Within the GIS realm, ESRI's 3D Analyst and ArcScene are strongly rooted in geographic information technology, enabling overlays onto terrain models, extrusions of buildings, and interactive fly-throughs. However, they are limited in the textural and photorealistic elements of visualization technology. As an alternative, the results of analysis in GIS can be exported to visualization software to enhance the photorealistic rendering. For example, quantitative and georeferenced mapping generated in GIS can be imported into Visual Nature Studio (VNS) from 3D Nature and augmented with photorealistic rendering [*Paar* 2006]. While visualization can be updated in real time in 3D through 3D Analyst, VNS requires an image to be rendered for results to be seen. In contrast to importing GIS into visualization software, photo-imaging software can be used to generate customized textures which can then be imported into GIS or geovisualization software.

Taking GIS and the public into the virtual reality world through the Internet has been explored since the 1990s [*Rhyne* 1997; *Doyle et al*. 1998], particularly in the fields of urban and regional planning, and environmental planning, modelling and impact assessment [*Haklay* 2002]. Development of Virtual Reality Markup Language (VRML), which models and enables viewing of 3D georeferenced data over the Web, has been ongoing for over a decade [*Huang and Lin* 1999] and *GeoVRML* [2008] was established as an official working group of the Web3D Consortium in 1998 [*GeoVRML* 2008].

2.5 Implementation and Effectiveness

Advances in visualization techniques and technology for planning are only as good as their ability to effectively support decision-making. Towards this end, evaluation of landscape visualization technology has focused on the two user groups defined earlier. The technical-user group manipulates the software to generate visualization products and is concerned with user-friendliness, interoperability between GIS and visualization technology, data formats, management of large data sets, processing speed and resolution. The audience-user group interprets the visualization products and is concerned with realism, visual appeal and interactivity that go beyond 'pretty pictures' to exploration and understanding that enhance a particular issue, problem or decision.

Geovisualization brings together geographic information technology and visualization technology.

From a technical-user perspective, *Paar* [2006] found that interoperability and ease of learning ranked as the most important feature of 3D simulation software. *Appleton et al.* [2002] evaluated the functional capability of several visualization technologies and software considering ease of data import, manipulation of terrain surface, navigation, drape image quality, manipulation of 3D objects, photorealistic rendering and processing time. They found, for example, that GIS packages, such as ArcGIS 3D Analyst and IMAGINE VirtualGIS, compared to photorealistic rendering and virtual-world packages, were more able to import a wide array of data formats without extensive data manipulation. They also add more functionality to image draping, such as querying and changing visual attributes. While 3D Analyst and VirtualGIS allow vertical extrusion of objects, they are limited in adding form and texture, such as roofs. In contrast, photorealistic packages are better able to include landscape features with more extensive libraries of land cover and objects, and the ability to randomize and vary vegetation elements. These features enable them to model not just current landscape scenes, but create scenes of future potential scenarios.

In addition, *Appleton et al*. [2002] concluded that in comparison to photorealistic rendering packages, packages designed for virtual-world visualization more greatly simplify landscapes and features to enable efficient processing necessary for interactivity.

Many of the functional capabilities discussed above are geared towards increased realism. Given that one of the aims of visualization is to produce an intuitive, natural simulation of the real environment, the question of what is a sufficient and appropriate level of realism has been the underlying focus of studies. This line of research addresses questions such as, "Can hyper-simulated images be counter-productive?" or "What level of detail is appropriate?" A second type of study focuses on user preferences and reactions to specific design elements and scene composition designed for realism, such as vegetation, sky and water, buildings, scale and perspective. While some users were found to be highly affected by lack of photo-realism [*Stock et al*. 2007], other users ranked photo-realism and qualities such as representation of ecological process to be less important when compared to interoperability [e.g. *Paar* 2006]. Variation in the landscape, such as visual biodiversity for vegetation, has been found to be important from an audience perspective to compensate for an image that is too 'smooth', 'perfect' or 'regular' [*Appleton and Lovett* 2003; *Paar* 2006]. *Appleton and Lovett* [2003] suggest that simulating variation with random procedural textures may be worthwhile, although they caution that increased manipulation of a scene erodes the geographic accuracy of a scene. Level of detail and resolution is also important from a user perspective [*Appleton and Lovett* 2003]. It has been suggested that there might be a "'lowest common denominator' effect, whereby the low-detail elements distract from or appear inconsistent to the rest of the image" [*Paar* 2006, p. 833].

Parallels between marine planning and land-use planning can be made.

Finally, there has been a range of studies, primarily case studies, which examine the effectiveness and contribution of landscape visualization for planning and decision support. Some of these evaluate quantitative measures, such as correctness of response to knowledge-based questions, on the interpretation of scenes and time to complete tasks [*Koua et al*. 2006]. Others more qualitatively examine users' preferences, compatibility with expectations and level of satisfaction, as well as observations on user manipulation and discussions [*Al-Kodmany* 2002, *Appleton and Lovett* 2003; *Sheppard and Meitner* 2005; *Koua et al.* 2006; *Stock et al*. 2007]. For example, *Stock et al.* [2007] conclude that the manner in which visualizations are presented and integrated into decision-making and resulting workshop dynamics plays an important role in effectiveness. While these case studies illuminate the value of visualization, there needs to be sufficient replication and standardization of these case studies to validate observations and findings, and to "support more robust guidance for their use in practice" [*Lewis and Sheppard* 2006, p. 291].

3. Seascape Geovisualization

3.1 Marine Planning and Management

Marine planning and management entails organizing and regulating marine activities with respect to other marine activities and the natural environment. In contrast to land-use planning, planning in the marine environment is relatively new and more complex. In part, this is due to the fact that the marine environment has been viewed as vast and plentiful to accommodate our needs and demands and, therefore, not something that needs organizing and regulating. Customary law and the notion of 'freedom of the seas' traditionally maintain marine resources and space as public property to be shared and freely accessed. Therefore, users resist any infringement on these public freedoms that are an inevitable outcome of planning. Finally, responsibility for planning and management in the marine environment is subject to multiple levels of jurisdiction and even multiple agencies within a jurisdiction, making coordination for marine planning and management fraught with overlapping mandates.

Nevertheless, with increasing coastal populations, growing marine tourism, expansion of marine sectors such as aquaculture and offshore energy, and an increasing recognition of the threats to marine resources and habitats, marine planning and management is gaining prominence. Parallels between marine planning and land-use planning can be made. Marine planning includes identifying appropriate sites for and managing infrastructure anchored to the seabed, such as docks, aquaculture operations and pipelines. It also includes siting and managing log-booming grounds, aggregate dredging and vessel movement. From a conservation perspective, marine planning includes establishing marine protected areas to conserve or preserve vulnerable or critical species and habitats. Typically, marine planning has been undertaken on a sector basis; however, decisions made at one site or on one activity can have wider implications for other activities and for the broader marine environment. This has led to an integrated area-based approach that takes into account all uses and biophysical values to try and achieve a socio-economic and environmental balance.

Given its breadth, there is a range of people involved in marine planning for whom seascape geovisualization could be relevant. These include government regulators and planners at various levels, including First Nations with responsibilities for a particular activity or for an area as a whole. Scientists provide the expertise on the biological and physical environment and processes that have implications on and can be affected by activities. At a site level, industry will also undertake marine-planning activities to design and appropriately site their operations. Increasingly, although they have no jurisdiction, non-government organizations such as conservation groups are undertaking planning exercises to prompt government into action. At all levels, the public and local communities also play a role as a discriminating audience with an effective voice.

In marine planning, geographic visualization using GIS has been primarily used for generating 2D thematic and general-purpose maps such as hydrographic charts. Even when mapped features and processes occur on the seafloor or in the water column, they are often represented in planimetric view, as if located on the sea surface. Yet, the marine environment is fundamentally four-dimensional from the sea surface through the water column to the topography of the seabed and beneath, along with the constant vertical and horizontal motion of the water, and the organisms which float or swim within the water column. Despite this, there has been limited but gradually growing development of seascape geovisualization relevant to marine planning. The following section introduces some of these applications and explores some of the technical issues associated with data, techniques and software.

3.2 Seascape Geovisualization Applications

Seascape geovisualization has been applied to three main areas in marine planning: (1) the physical structure of the seabed, including the substrate; (2) navigation; and (3) moving features, such as remotely operated vehicles (ROVs), vessels and marine mammals. In addition, seascape geovisualization has been applied to oceanographic processes and mid-water properties. While not directly relevant to marine planning, visualization of oceanography does augment the scientific basis of marine planning.

Seabed Structure and Bathymetry

Seabed structure and bathymetry are defining elements of marine environments. They influence biological structure and oceanographic processes. Not surprisingly, 3D representation of the seabed was the initial focus of seascape geovisualization, particularly with advances in sonar and multibeam data acquisition of the seabed. These advances have enabled the capture of high-resolution bathymetry in extensive areas, limited only by the data-processing capability of software and hardware [*Depner et al.* 2002]. While relatively simple, a digital bathymetric model (DBM)—akin to a digital terrain model (DTM)—and its derivatives, such as slope, exposure angle, complexity and rugosity, can reveal and broaden our understanding of marine features and bottom habitats; an understanding that is paramount for marine planning, such as cable and pipeline routing [*Mayer et al.* 2000], navigation safety [*Arsenault et al*. 2003], distribution of benthic habitats [*Ardron* 2002; *Bates and James* 2002; *Conway et al.* 2005] and marine conservation [*Canessa et al*. 2003].

Watford et al. [2005] demonstrate the value of 3D visualization in understanding the bathymetric complexity of the Australian seabed, including canyons and cliffs, thus enabling the public to relate it to terrestrial topography. Images captured from a display of a DBM of a remote seamount displayed from various viewpoints allowed marine planners and scientists to get the first comprehensive overview of the form and structure of the seamount, revealing ridges, plateaus and mounds (Figure 1) [*Canessa et al.* 2003]. This was further enhanced by their ability to 'fly through', or more appropriately 'swim through', the underwater scene, allowing closer inspection of the seamount.

Navigation

Seascape geovisualization has also been explored and applied to planning surrounding navigation, starting with the production of 3D navigational charts. In research on navigation systems, *Ford* [2002] argues that interactivity allows geovisualization to play a decision-support role beyond that of just displaying just 'pretty pictures'. Extending *Ford's* [2002] work in 3D navigational charts, *Gold et al*. [2005] sought to develop a graphical and interactive version of the Pilot Book, text-based procedures for vessel operators to navigate in major ports, using geovisualization. For example, ship operators are able to query objects such as navigational buoys, navigational lights and mooring buoys, and detect potential collisions with other ships or the coastline in two dimensions on the sea surface.

Seabed structure and bathymetry are defining elements of marine environments.

From a 3D perspective, one technique that is widely used to assess underkeel clearance and grounding avoidance is a navigation surface. A navigation surface is a modified bathymetric model that takes into account safety of navigation issues such as underwater wrecks, submerged rocks and

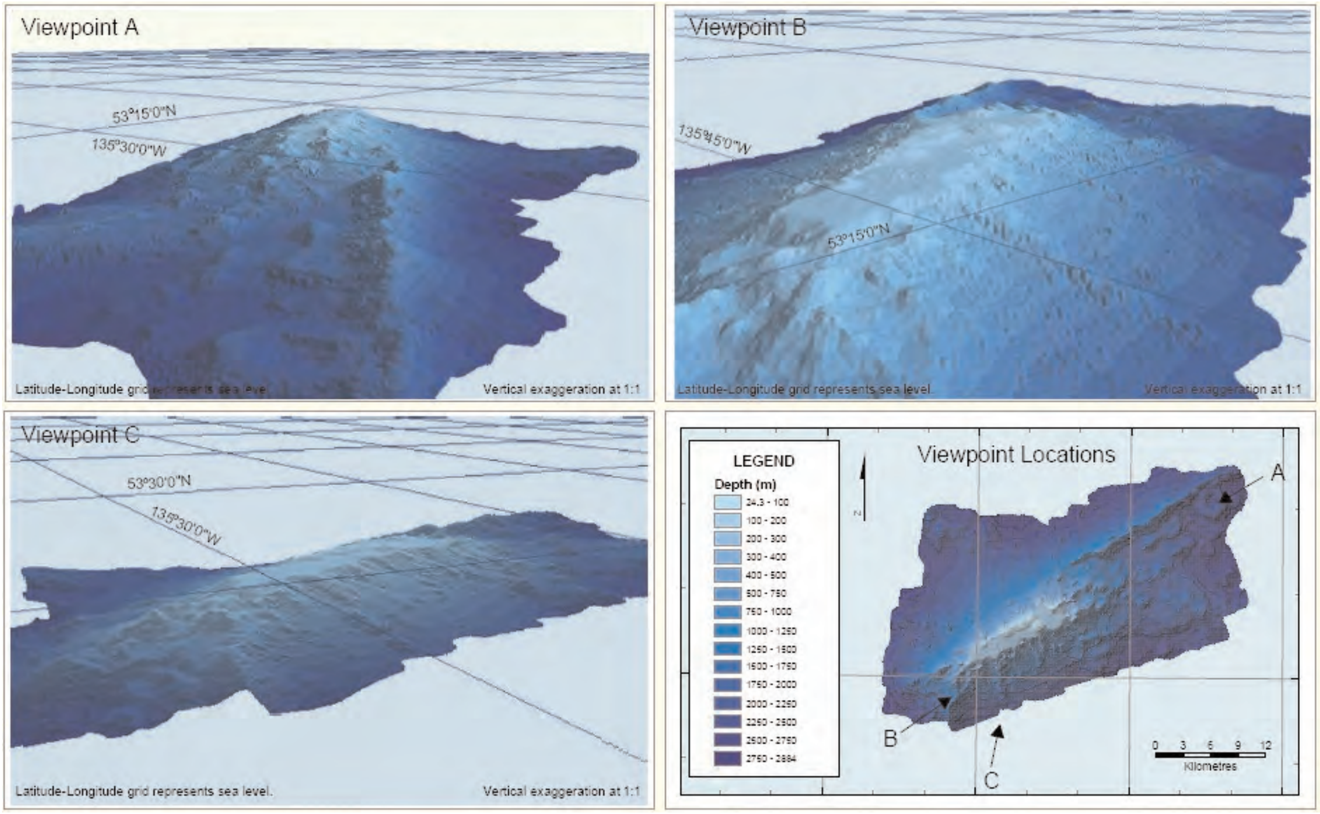

Figure 1. 3D bathymetric model of Bowie Seamount [*Canessa et al.* 2003].

tides [*Mayer et al.* 2000; *Arsenault et al.* 2003; *Gold et al.* 2005]. *Arsenault et al.* [2003] developed an interactive decision-support tool for mariners, which incorporates a dynamically changing tidal model allowing a navigation surface to be generated in real time as a ship is en route. The tool can also be used for advanced route-planning to predict how tidal levels will change over the vessel's course and time of a transit [*Arsenault et al.* 2003].

Tracking Objects

The third area of seascape geovisualization applications engages the temporal dimension of the marine environment by representing tracks of moving objects. Using tags and telemetry, it is possible to track the movement of marine animals, such as whales and sea turtles, and visualizing these as 3D linear features [*Fedak et al.* 1996; *Schick* 2002]. Beyond tracking marine mammals, *Fedak et al.* [1996] mapped the movement and behaviour of marine mammals in relationship to the ocean environment by interactively integrating and visualizing telemetry data with oceanographic and environmental data, such as the coastline, bathymetry and sea surface temperature. *Arsenault et al.* [2004] extended the visualization at a smaller scale by generating a 3D model of a whale and tracking its horizontal and vertical movement, along with roll and pitch, when diving, feeding or travelling. Understanding the movement and behaviour of marine mammals is important when planning for their protection. In addition, research has explored ways to track and visualize ROVs and autonomous underwater vehicles (AUVs) on the seabed or in the water column, even in real time [*Mayer et al.* 2000; *Ware et al.* 2001; *Arsenault et al.* 2003].

Oceanographic Processes and Mid-Water Properties

While more attention is paid to the seabed in marine planning, understanding and geovisualization of oceanographic processes and mid-water properties is also relevant to sustainable management of ocean resources and uses [*Galloway* 1996]. Visualizing ocean models provides a predictive capacity for building planning scenarios. Oceanographic processes can influence, for example, connectivity among marine protected areas. They represent barriers to, or opportunities for, movement between water masses, which has implications for waste disposal and contamination. Due to their fluid and dynamic nature, geovisualization of oceanographic processes and mid-water properties is more challenging than visualization of the seabed. *Galloway et al*. [1996] argued that limitations of data-visualization technology have prevented exploration of large oceanographic field data sets. Perhaps more relevant to public involvement in marine planning, *Ware et al*. [2001] proposed that interactivity of seascape geovisualization can make oceanography more accessible to the public, allowing them to self-direct their exploration of seabed and oceanographic processes.

In one of the earlier attempts, *Su and Sheng* [1999] demonstrated that by mapping and modelling patterns of temperature, salinity and density at various depths over time, one could visualize and examine the characteristics of upwelling processes. *Arsenault et al*. [2004] interfaced geovisualization with estuarine and ocean flow models to view currents over time with particle tracers and floaters.

In addition to physical and chemical properties of the oceans, biological properties have also been investigated using geovisualization. *Mayer et al*. [2002] used seascape geovisualization to calculate fish biomass and stock assessment from midwater backscatter of fish populations, and to understand fish behaviour in relation to sampling tools. Kreusele [2000] examined the correlations between the distribution of fish and oceanographic parameters, such as temperature, salinity and oxygen concentration, through 3D visualization.

3.3 Technology

Data

As mentioned previously, bathymetry is the key element for almost all seascape geovisualization. Advances in sonar and swath mapping systems, notably multibeam sonar, have been the driving force in capturing georeferenced seabed data across large areas in high-resolution detail for seascape geovisualization [*Mayer et al*. 2002; *Bates and James* 2002]. Along with bathymetry, backscatter can be captured from multibeam sonar, from which substrate composition can be classified. With increasing computer capacity and processing speed, limitations in data density are decreasing. However, there are nearshore limitations to multibeam, as water depths are too shallow to be surveyed by most vessels, leaving a gap between offshore bathymetry and terrestrial elevation models. As an alternative, airborne laser bathymetry (ALB) systems can capture bathymetry (and backscatter) data to bridge the gap, particularly in clear coastal waters [*Finkl et al*. 2005]. Airborne LiDAR data can be integrated with offshore multibeam to extend the DBM [*Wilson* 2008]. Video monitoring networks have also been used to capture nearshore bathymetry [*Aarninkhof et al*. 2003].

In addition to bathymetry and substrate data, an array of other types of data has been used to generate seascape geovisualization. These include sensor data [*Arsenault et al*. 2004] from CTD [*Su and Sheng* 1999] and instrumentation on survey vessels [*Kemp and Meaden* 2002], data from satellite imagery [*Kemp and Meaden* 2002; *Ford* 2002], tide and current [*Arsenault et al.* 2003], pelagic fish populations from midwater multibeam sonar [*Mayer et al.* 2002], vehicle and vessel trajectory data, including Automatic Identification System for ships [*Arsenault et al.* 2003], and fishing vessels and activity [*Kemp and Meaden* 2002]. For applications in navigation, additional data such as navigation aids, mooring buoys, traffic separation scheme lanes, wrecks and ship models have also been captured for visualization [*Gold et al*. 2005].

Visualization Techniques

Researchers have developed visualization techniques for seabed texture, interactive manipulation of a scene and oceanographic modelling.

In the absence of comparable airphotos of the marine environment, sonar data, backscatter, sediment properties and scanned charts are often draped over the bathymetry model to provide texture [*Mayer et al*. 2000; *Ware et al*. 2001; *Bates and James* 2002; *Ford* 2002]. *Mayer et al.* [2000] demonstrate the ability to drape high-resolution backscatter or video imagery over lower resolution bathymetry without degrading the higher resolution data. High-resolution data offer greater detail, but slower rendering speed. An alternative solution is for users to select the desired level of detail, which reduces the resolution accordingly. Users thereby determine their own compromise between rendering speed and accuracy [*Kreuseler* 2000].

Seabed textures can also be generated from a more artistic, rather than geographic, perspective, as illustrated in Figure 2. Using World Construction Set by 3D Nature, manually drawn contour lines were used to define the marine floor and then 'billboards' (cut-out 2D images with alpha channels oriented to point to the 3D camera so they look real) of various corals were added [Roger Harris, pers. comm.]. The images demonstrate the creation of different substrate textures, the use of light in the foreground to reflect depth, and the use of a thin layer of cloud haze to show the ocean surface, turbidity or distance. The objective was visual representation of a scene for a magazine article on the film *Finding Nemo*, rather than an attempt to portray an actual georeferenced scene. However, the results demonstrate the potential for visually rich seascape visualization.

Seabed textures can also be generated from a more artistic, rather than geographic, perspective,…

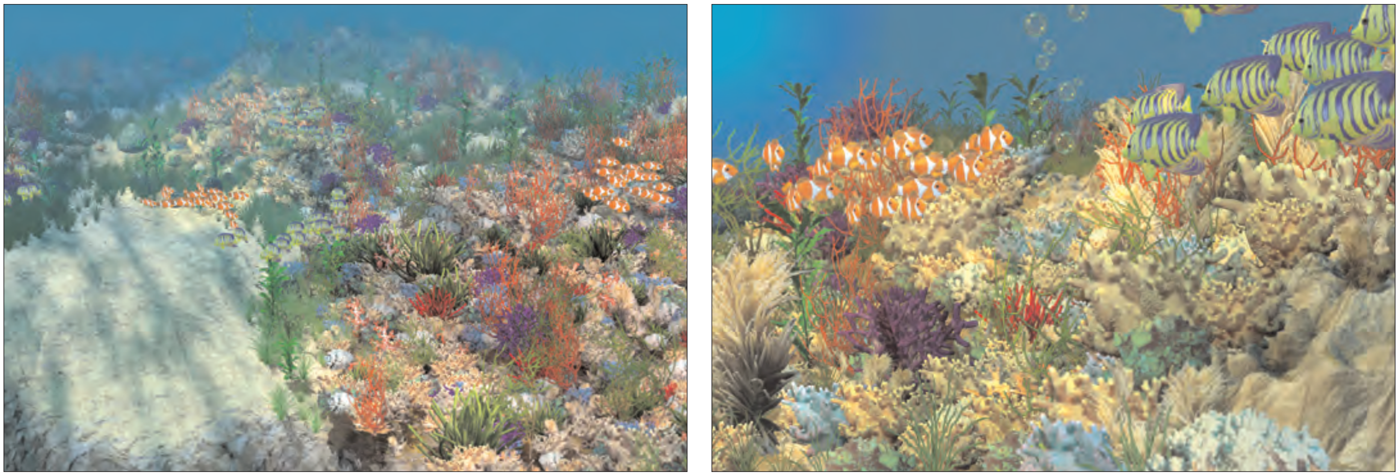

Figure 2. Coral reef seascape visualization generated in World Construction Set (reproduced with permission from Roger Harris).

In interactive visualizations, the freedom to manipulate and change views when observers and objects move in space and time, allowing the user the full capacity to explore a scene, is key to understanding the interrelationship of 3D features [*Gold et al*. 2005]. *Mayer et al*. [2002] describe a "mouse-controlled interface which allows the manipulation of a scene with six degrees of freedom so that it can be viewed from any perspective" (p. 222). This technology has been incorporated into the Bat device in the Fledermaus visualization software [*Interactive Visualization Systems* 2008].

As was discussed in Section 2.1, interactivity requires on-the-fly rendering of scenes, which is slower than rendering still images. *Ware et al.* [2001] report on various techniques to enhance interactivity with an animation governor to accelerate rendering. The animation governor integrated into GeoZui3D, an extension to the Fledermaus visualization system, allows for faster rendering (ten animation frames per second) by adjusting the resolution according to the time measured to render the scene during interactions.

Another advance in enhancing interactive seascape geovisualization is linking multiple 3D views such that features can be explored in detail within a smaller scale (broader context) [*Ware et al*. 2001]. The separate views, or 'zoomport' windows, are connected using tethers. *Arsenault et al*. [2003] describe this further by linking information from multiple views, e.g., plan view, side view, small-scale perspective view, and combining these views in a navigation system. Each view can be customized to address specific navigation issues, such as approach to navigation channels in the distance and proximity of navigation hazards in the immediate vicinity. In another application studying whale behaviour by visualizing movement of a tagged whale in relation to nearby vessels, one view was focused on an individual whale and another was focused on an overview of ship traffic. By switching between both reference frames and a time controller, it is possible to examine the behaviour of whales with respect to vessels at different spatial and temporal scales [*Arsenault et al*. 2004]. *Plumlee and Ware* [2003] have empirically evaluated the effectiveness of view proxies (representation of one view within another) and view couplings (both views having the same heading and central position), concluding that for a particular task errors can be reduced by 50 and 25 percent, respectively, while the benefits are cumulative.

To enhance interactive seascape geovisualization, *Gold et al*. [2005] incorporated an Animator component to GeoScene, a scene graph-based viewer developed by *Gold et al*. [2005], running in a separate thread to handle moving objects. By activating the animation mode, the movement of a ship model through a channel, for example, can be followed by using mouse clicks. In addition to modelling moving objects, the Animator can also model the changing illumination of a lighthouse or navigation buoy.

Other visualization techniques have been used to enhance seascape geovisualization often involving a hybrid of techniques and data sources [*Ware et al*. 2001, *Ford* 2002, *Gold et al.* 2005]. For example, the scene can be enhanced with a variety of imagery, such as vertical photographs placed along the shoreline in a 3D model [*Ware et al*. 2001]. Tubes can be used for remotely operated vehicle (ROV) tracks, and continuous water-column data can be represented as curtains [*Ware et al*. 2001].

Visual techniques can add to the sense of realism and 3D. To more realistically represent the visibility of navigation lights and buoys under different conditions, *Gold et al*. [2005] have incorporated fog and night settings. Gradually blending colours into the background colour as they are further from the viewer's perspective can heighten the impression of 3D [*Mayer et al.* 2002]. Dynamic colour-coding of bathymetry as water depth changes with the tide can enhance the role of visualization in a navigation decision-support tool in real-time and for planning purposes [*Arsenault et al.* 2003].

Early seascape visualization efforts represented chemical and biological variables referenced to the sea bottom using data pins. *Kreuseler* [2000] used data pins to mark the location of surveyed oceanographic data relevant to a digital bathymetric model with text tags at the water surface indicating the attribute value of the variable. Similarly, *Galloway et al*. [1996] visualized fish larvae catch data represented as pins, the location of which indicated a data-collection point, on a bathymetric surface. The heads of the pins are customized 'glyphs' and tubes representing the catch of a given species. A similar visualization approach was used to visualize salinity measurements at various depths with four colour-coded spheres arranged vertically on a pin, each sphere representing a different depth. Taking it one step further, oceanographic data can be represented as bar charts or depth profiles at individual sample locations [*Kreuseler* 2000].

In the above examples, oceanographic parameters are mapped relative to the seabed. Oceanographers have been developing and visualizing ocean models to understand oceanographic processes. Unlike the previous examples, ocean models emphasize ocean flows and volumetric analysis. *Su and Sheng* [1999] generated a 3D isosurface animation of oceanographic processes using temporal and vertical snapshots. More recently, attention is being paid to using unstructured meshes for ocean modelling. Unstructured grids in the vertical and horizontal direction are being explored to calculate volume, surface integrals and density fluxes [*Cotter and Gorman* 2008]. The advantage of an unstructured mesh is that it can simultaneously resolve both small- and large-scale ocean flows while smoothly varying resolution and conforming to complex coastlines and bathymetry [*Pain et al.* 2005].

Integration of GIS and Visualization

The key aspect of geovisualisation, compared to other visualization, is the integration of geographic information science with simulated graphics and objects, 3D dynamic game technology and modelling. Although growing, there has been limited research and development on seascape visualization that combines the improved realism of games and graphics technology with marine spatial-data handling [*Gold et al*. 2005]. Some off-the-shelf existing GIS, such as ESRI's 3D Analyst and ArcScene, and ERDAS Imagine, have been applied to seascape geovisualization, particularly for seabed mapping. Visualization tools such as 3DNature's Visual Nature Studio (VNS) have rarely been extended to the marine environment for scientific visualization. There is currently only a limited library of marine textures, such as coral, although landscape visualization features such as clouds can be applied to seascape visualization, as was shown in Figure 2. From an oceanographic perspective, software such as Matlab and Advanced Visual Systems (AVS) are used to model and map oceanographic parameters in the water column. Echoview (Myriax software) can be used to map fish schools in 3D using multibeam.

None of the above software approaches to seascape geovisualization possess the full functionality required for realistic and comprehensive seascape geovisualization. As a result, researchers have developed their own seascape geovisualization software, which may integrate one or more of these different approaches. Initially, these customized solutions were developed for particular applications, and have since been expanded for wider use. The following discussion highlights some of the research and development into software solutions integrating GIS and visualization.

MAMVIS was developed to display marine mammal behaviour in space and time, integrated with a three-dimensional terrain model overlaid with oceanographic data. It is based on a network of customized AVS three-dimensional visualization models [*Fedak et al*. 1996]. Similarly, a system called ViNeu was developed to visually examine spatial dependence between fish distribution and oceanographic variables [*Kreuseler* 2000].

Fledermaus, by Interactive Visualization Systems (IVS 3D), was developed at the University of New Brunswick as a marine 3D interactive visualization tool, particularly for the oil and gas industry and marine geology. Its application has been expanded to underwater cable and pipeline routing, vessel navigation and fisheries science [*Mayer et al*. 2000; *Interactive Visualization Systems* 2008]. It handles geographic information from a variety of conventional GIS packages and is founded on modelling topography, although water column processes and surface features, such as ships, can also be modelled and integrated within the 3D visualization. *Fonseca et al.* [2002] demonstrate the capability and advantages of coupling conventional GIS, namely ArcView GIS, with Fledermaus to manage, analyze and visualize large and complex marine databases. Using ArcConverter, a software filter, vector and raster files in ArcView format are directly transferred to Fledermaus.

…oceanographic data can be represented as bar charts or depth profiles at individual sample locations…

Designed as an extension to the Fledermaus visualization system, GeoZui3D (Geographic Zooming Interface) is an interactive 3D visualization system developed at the University of New Hampshire. It was designed for georeferenced and time-referenced data for marine scientists [*Ware et al.* 2001]. GeoNav3D is a marine navigation application based on GeoZui3D [*Arsenault et al.* 2003]. It incorporates two key design elements: (1) dynamically changing tidal model to adjust a navigation surface in real time or for route planning; and (2) linking multiple views.

Gold et al. [2005] developed GeoScene to also address the integration of georeferencing and graphic simulation. Objects and features are georeferenced in a simulated world using a hierarchy of coordinate systems that is applied to all graphic objects using necessary transformation and rotation. The spatial (coordinate) relationships between graphic objects are managed with a Graphic Object Tree or scene graph. They implement data structures, such as the kinetic Voronoi diagram, for detecting occurrences of coincidence in space and time indicating collisions. Similar to GeoNav3D, a Marine GIS application for navigation was developed based on GeoScene [*Gold et al*. 2005].

As evidenced by Google Earth, the Web is a growing outlet for geographic visualization by the public. Google Earth is being used as a visualization tool for marine data. However, Google Ocean is expected to enhance this capability and presents equal promise in breaking the ocean barrier to the public [*Ellis* 2008]. Approaches to integrating geographic information science and visualization on the Web have focused on Virtual Markup Language (VRML). *Leaver* [1998] demonstrated the potential of GeoVRML in marine applications with the development of a 3D model of the Monterey Bay National Marine Sanctuary, including a preliminary 3D navigation tool. Given the georeferencing framework, the 3D seabed model could be augmented by additional scientific data by specifying the depth of the data to be represented. GeoVRML continues to be used by the Monterey Bay Aquarium Research Institute (MBARI) for modelling the seabed and visualizing daily ROV and AUV operations [*McCann* 2004; *MBARI* 2008]. The Consortium for Oceanographic Activities for Students and Teachers (COAST) has brought GeoVRML to a broader audience with their interactive bathymetry model builder [*COAST* 2008].

4. Discussion

This paper had provided an overview of seascape geovisualization for marine planning, particularly as applied from landscape geovisualization. This discussion section initiates some direction towards a research agenda to advance the further development and application of seascape geovisualization for marine planning.

Landscape Visualization Compared to Seascape Visualization

Landscape visualization has been used as the launch pad for examining seascape visualization. While there are some similarities between the two, there are also some differences (Table 2).

Landscape visualization has been used as the launch pad for examining seascape visualization.

The audience user groups of landscape and seascape geovisualization are similar, encompassing government planners, industry and the public. The technical-user groups, however, differ in that development of seascape geovisualization is primarily undertaken by the research and scientific community, but has broadened out of the research community for landscape geovisualization. This is reflected in the fact that while development of seascape geovisualization is progressing towards decision-support tools, many applications are proof-of-concept prototypes or demonstration projects using customized software, and still require maturation and testing to be used in actual planning. For example, the navigation decision-support tool developed by *Arsenault et al.* [2003] has been field-tested by installing it on operational ships for evaluation against other navigation tools, such as existing chart technology and Electronic Navigation Charts (ENC) technologies. In comparison, landscape visualization is well established as a decision-support tool for land-use planning, and there are several off-the-shelf landscape-visualization software, such as VNS and Community Viz. Similarly, landscape visualization is primarily used for developing future scenarios, while the emphasis of seascape visualization to date has been on representing and understanding existing conditions which are limited by our observational capacity in the marine environment. Another significant difference is the extent to which the temporal dimension is invoked in geovisualization. Landscape geovisualization is primarily stationary with limited animation, such as wind-turbine blades, automotive vehicles and the progression of forest fire and flooding. In seascape geovisualization, particularly when focused on oceanographic processes, the temporal dimension of currents, tides and upwelling is critical, as is the representation of the motion of marine vehicles and pelagic organisms.

The most relevant parallels between landscape and seascape geovisualization are in the handling of the physical surface, i.e., topography and bathymetry. In the majority of landscape visualization, the core visualization is referenced to the terrain. The

Table 2. Comparison of landscape and seascape visualization.

	Landscape Visualization	Seascape Visualization
Planning Applications	Future scenarios	Current seascape Future scenarios
	Real-life planning	Proof-of-concepts/Demonstration projects Real-life planning
	Forestry Agriculture Golf course development Sea-level rise Transportation planning Community development	Navigation Pipeline routing Conservation Offshore oil and gas development Animal tracking
Audience Users	Municipal planners First Nations Industry managers Environmental non-government organizations Public	Federal planners Provincial planners First Nations Industry managers Environmental non-government organizations Public
Technical Users	Architects Engineers Graphic designers Scientists GIS analysts	Researchers Scientists GIS analysts
Digital Model Data	Standard databases Topographic maps	Multibeam LiDAR Nautical charts
Topography Texture	Orthophoto Image libraries	Backscatter Customized images
Feature Objects	Buildings Roads Utility infrastructure Wind turbines Trees	Marine vessels Underwater vehicles Navigation markers Offshore platforms Pipelines Marine mammals
Auxiliary Elements	Sky Cloud Water ripples	Light Turbidity
Temporal Dimension	Wind-turbine blades Automotive vehicles Progression of forest fire Progression of flooding	Currents Tides Upwelling/Downwelling Marine vessels Marine mammals School of fish Underwater vehicles
Software Development	Off-the-shelf software	Customized software Off-the-shelf software

Results from landscape visualization implementation…can also be applied to seascape geovisualization.

focus of landscape visualization is the terrain, characteristics of the terrain and features on the terrain. Landscape visualization techniques for generating procedural textures and auxiliary elements, as well as mapping feature objects, can be applied to the bathymetry in seascape geovisualization. Results from landscape visualization implementation and effectiveness studies, such as the necessary degree of realism between simulation and geographic accuracy, can also be applied to seascape geovisualization.

Defining a Research Agenda

All too often, technology develops in isolation of, or in spite of, a user community. Visualization technology, which is enticing, has the potential to push users and audiences in directions where there is no need—or, at least, they don't know it yet. Despite benefits of visualization demonstrated for analysis and communication in landscape planning, seascape geovisualization rarely appears in the forum of public consultation in marine planning, nor at the forefront of government planners' and scientists' minds, nor in the desktop toolbox of GIS analysts who support planners and scientists. If seascape geovisualization is to be relevant, then it must be developed within the context of users—particularly the audience-user group who interprets and applies visualization for decision-making. Key questions to establish this context include: What are the current visualization limitations facing audiences? To what extent can seascape geovisualization overcome some of those limitations? What are the key technological and implementation issues to be addressed?

To answer these questions, it is suggested that a two-phased user-needs survey be administered to government planners, members of the public involved in marine planning initiatives, scientists, researchers and GIS analysts. Survey topics in the first phase targeting the audience user group can include:

- To what extent are marine-planning issues focused on the sea surface, water column, seabed and below the seabed?
- How important is 3D and 4D in planning?
- To what extent is marine planning done in 3D and 4D?
- What are the limitations in 3D and 4D planning?
- What current visualization tools are used for communication with planners and the public?
- What are the benefits gained from using seascape geovisualization?
- What are the limitations in using seascape geovisualization?
- To what extent are current visualization tools not meeting analysis and communication needs?

Survey topics in the second phase targeting the technical-user group can include:

- To what extent and in what form (e.g., still images, animation, interactive) do scientists, researchers and GIS analysts use seascape geovisualization?
- What are seascape geovisualization tools used for?
- To what extent and how is the temporal dimension visualized?

Modelling Continuous Relief in Coastal Areas

Because of the proximity to human activity and the impact of upland activities on marine waters, currently, most marine planning takes place in coastal areas. Although it is often useful and administratively necessary to define the coastline as a feature, in fact the coastal region is a continuous and shifting transition between sea and land. Challenges in developing a continuous digital surface model are emphasized by the use of different vertical datums to reference a coastline [*Bartier and Sloan* 2007]. For example, a coastline defined by lowest normal tide, as is used in nautical charts, will encompass more exposed rocks and reefs than a coastline defined by mean sea level, as is used in topographic charts. The coastlines will differ not only in configuration but also in location, depending on the purpose.

Spatial analysts continue to struggle with reconciling different vertical datums and representing the continuous transition in coastal areas. While bathymetric LiDAR can be used to fill in the nearshore gaps in bathymetry, further research and standards are still needed to create a seamless digital surface model in coastal areas. Towards this end, the U.S. National Oceanic and Atmospheric Administration (NOAA) has developed VDatum, a tool to convert and reconcile vertical datums. In addition to facilitating merging topographic and bathymetric models, users can delineate a shoreline based on their defined tidal condition or base sea level for their study [*Gesch and Wilson* 2002].

Seabed Visualization

Despite the recognition that the marine environment is four-dimensional (including the water column and ocean dynamics), as with land topography in landscape visualization, the seabed is a fundamental component of almost any seascape visualization. It can be argued that focusing seascape geovisualization on the seabed maintains seascape visualization in the 3D, or even 2.5D, realm. However, the seabed is a familiar visual concept, as human land-dwellers can relate it to land topography and the continuation of land topography under the sea in coastal areas. Marine tenures on Crown land for log-handling, aquaculture and offshore oil and gas, for example, are issued for the seabed and are a prominent aspect of marine planning. In coastal areas, planning jurisdiction of the seabed (a provincial responsibility) is distinct from planning jurisdiction for the water column (a federal responsibility). Furthermore, the seabed provides a spatial reference to mid-water processes and properties. Therefore, research emphasis on seabed visualization is warranted, and improvements are still necessary for more realistic visual modelling of the seabed.

All too often, the seabed in a digital bathymetric model is portrayed as a barren, inert surface, which belies the diverse benthic ecological communities that exist on the seabed; communities such as rocky reefs, sponge reefs, coral reefs, kelp forests, seagrass beds and sandy expanses. Representing the topography as a bare surface can lead to assumptions and varied interpretations of the landscape [*Bergen et al*. 1995]—more so in the marine environment, where most of us have little experiential knowledge and where there are limitations to observation.

In landscape visualization, land-cover texture can be addressed by draping an orthophoto on a DEM, the equivalent of which is not available for the marine environment. Interpreting and draping backscatter on a bathymetric model can shed some light on seabed composition. However, it still lacks the intuitive texture of not only the geological material, but perhaps more importantly, the biological communities which cover the seabed. In addition to land-cover image textures available in software libraries, other image textures or procedural textures can be created from imaging software or photos to enrich a DEM and make it more natural and realistic.

The technology for generating procedural textures in the marine environment exists, but libraries of marine images do not exist in visualization software. The VNS library only contains an image for coral. However, customized images of seabed cover can be added by capturing them from an underwater photograph and applied as a texture. In addition to building regional libraries of substrate images and objects, both geological and biological, research is needed on the use and quality of such images in seascape geovisualisation, particularly related to scale and diversity.

Oceanographic Data Structures and Modelling

As has been emphasized, the marine environment is fundamentally 4D. Advancing seascape geovisualization from solely a landscape geovisualization perspective will primarily address seabed geovisualisation but not visualization of the water column, nor of ocean dynamics. Research attention is particularly necessary on 3D dynamic data structures and modelling. One area currently being explored is unstructured meshes for ocean modelling, particularly for ocean flows. Attention needs to be paid to developing 3D dynamic data structures suitable not only for modelling ocean flow but also other mid-water features relevant to marine planning, such as schools of fish, marine mammals and ROVs. Those 3D data structures should facilitate attribute and temporal interrogation and analysis of oceanographic and feature properties beyond just visual imagery. Furthermore, research is required to integrate scientific visualization of the dynamic mid-waters with seabed visualization to enable comprehensive seascape geovisualization.

Evaluation, Use and Usability

Orland et al. [2001] warn that technology is fast outstripping our knowledge of when and how to apply it, and how well it works in eliciting responses applicable to the real world [*Appleton and Lovett* 2003]. The repeated need to evaluate visualization technology and users' responses [*Bishop* 1994; *Batty et al*.1998; *Sheppard* 2001; *Koua et al*. 2006; *Lewis and Sheppard* 2006] to ensure effective use and benefit of the technology has been heeded for landscape planning and environmental decision-making. Some studies have been systematic and empirical, and others have been more qualitative through focus group discussions and case-study implementations [*Appleton and Lovett* 2003; *Bishop and Rohrmann* 2003; *Lewis and Sheppard* 2006; *Bishop and Miller* 2007; *Jude et al*. 2007]. As a result, there is a growing body of knowledge on effective landscape visualization.

As seascape geovisualization is in its comparative infancy, there is a great opportunity to embed empirical and qualitative research on effectiveness in technology development as the technology evolves and implementation matures. Several studies have already begun to evaluate seascape geovisualization techniques [*Plumlee and Ware* 2003] and use [*Arsenault et al*. 2004], but the arena is ripe with exploratory questions such as:

- What main visual elements, such as geological and biological substrate, are most effective for seascape visualization?
- Do underwater cameras capture substrate texture with sufficient clarity for developing procedural textures?
- What auxiliary visualization elements, such as light, marine snow and shadow, are important?
- Is the resolution of marine GIS data adequate for visualization?
- What is the balance between realism, detail and accuracy?

As has been emphasized, the marine environment is fundamentally 4D.

- Is there a difference between users' responses to terrestrial visualization and marine visualization with respect to users' experiential knowledge?
- What planning applications are most suitable to 3D geovisualization?

5. Conclusion

Geovisualization, the integration of geographic information science and virtual reality, has been widely used for 3D display, scenario exploration and analysis in landscape planning. Case-study implementation and systematic evaluation have demonstrated that landscape visualization, whether through still imagery, animation or interactive visualization, can enhance stakeholder consultation and participation in landscape planning. Even though most of us have a comparative lack of experiential knowledge of the marine environment and its inherent 4D nature, seascape geovisualization, which could greatly enlighten our understanding of the marine environment for informed marine planning, has lagged behind that of landscape visualization. Over the last ten years, advances in multibeam and sonar bathymetric data acquisition have enabled the development of detailed and extensive digital bathymetric models, particularly for offshore areas—the fundamental building block of seascape geovisualization. With these bathymetric models, researchers have developed customized software integrated with GIS for geovisualization applications in navigation, marine animal- and vessel-tracking, and oceanography.

However, for seascape geovisualization to play a prominent role among planners, scientists and the public in marine planning, there are some technical and user needs that need to be further explored. These include improving the representation of coastal areas, typically the focus of marine planning, as a continuous transition between land and sea. In addition, image and procedural textures of the seabed need to be developed to drape over the bathymetry, and visualize more realistically the geological and biological characteristic of the seabed beyond what draping backscatter data currently permits. A technical solution to seascape geovisualization lies at the confluence of GIS, landscape visualization, ocean modelling, gaming and virtual reality. Fundamentally, what is needed is a new seascape geovisualization paradigm that integrates all five technological approaches to visualization.

It is tempting to allow the visualization technology to drive research, development and implementation of seascape geovisualization. However, focusing on technological research without a grounded context of who the users might be, how seascape geovisualization might be used in marine planning and how best to bridge technology to needs, will likely limit its effective use. Therefore, in the advent of seascape geovisualization, one research priority is to gain a comprehensive understanding of the seascape visualization requirements of planners, scientists, GIS analysts and the public. To further build a robust knowledge base on the effectiveness of geovisualization for marine planning, it is equally important to undertake systematic and case-study evaluation of the technology and its use. In this way, geovisualization could open the hatch to improved decision-making for the marine environment.

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