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Real-time validation of a digital flood-inundation model: A case-study from Lakes Entrance, Victoria, Australia

P.J. Wheeler, J. Kunapo, M.L.F. Coller, J.A. Peterson & M. McMahon
Monash University, Victoria, Australia

ABSTRACT: Extensive flooding in the Gippsland Lakes catchment (Victoria, Australia) during June/July 2007 caused much damaging urban area inundation within townships located on subdued, low-lying areas along semi-enclosed coastal lagoon shores. Data capture during the 2007 flood event facilitated 'real-time' validation of a photogrammetrically-derived high-resolution bare-earth terrain model, suitable for flood and storm surge/storm tide inundation modelling, which was independently developed for the townscape of Lakes Entrance, Victoria, Australia, by Wheeler *et al*. (2007). A lack of Integrated Coastal Zone Management (ICZM) stakeholder flood-risk digital spatial decision-support characterised this flood event, despite these stakeholders experiencing a similar serious flooding event taking place some nine years previously (in late-June 1998). The results presented here indicate the immediate need for deployment of 'detailed geography'; namely, the high-resolution digital elevation modelling of low-lying townscapes located along the shores of the Gippsland Lakes. It is argued that this type of modelling, and subsequent spatial data dissemination and stakeholder access (via regional SDI or issues-based web-map server) is essential to provide sectorally-based public and private management agencies with an integrated spatial decision-support capacity *vis a vis* future flood inundation risk, planning and management, in support of ICZM initiatives.

1 INTRODUCTION

Low-lying areas adjacent to coastal lagoons, tidal inlets and/or estuaries experience inundation conditions when certain environmental 'forcings' (Tan *et al*., 2002, Townend and Pethick, 2002), primarily act in concert: high influent catchment streamflows (caused by periods of extreme catchment rainfall), temporarily elevated coastal tidal and sea levels, and the regional effects of strong winds, not to mention storm surges (refer Bird, 2000: 20–21), can all act to temporarily raise coastal lagoon, tidal inlet or estuary water levels, especially if corresponding with highest astronomical tides. These locations often harbour high-value real estate and infrastructure developments, which have been constructed over long periods under the controls of changing land-use planning schemes. Vital to land-use planning scheme credibility is the timely supply and mandating of accurate data and information on possible inundation scenarios for use in a stakeholder decision-support capacity.

The shorelines of the coastal lagoon system known as the Gippsland Lakes (comprising three interconnected 'lakes': Lakes King, Victoria and Wellington), located in Victoria, Australia (refer Figure 1) possess extensive low-lying areas of subdued terrain which are subject to periodic inundation, and which contain areas of high-value urban development. Located at the eastern extremity of this lagoon system is the township of Lakes Entrance (refer Figure 2). Here, urban development which began in the mid-Nineteenth Century now extends over an area that has become officially classed as 'land subject to inundation' (DSE, 2006). Over the past decade (in late-June 1998 and June/July 2007), two damaging inundation events have occurred at the Lakes Entrance township, which were caused by convergence of environmental forcings mentioned

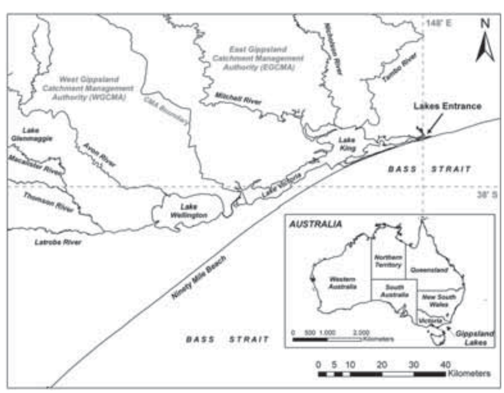

Figure 1. The Gippsland Lakes (Victoria, Australia): location.

Figure 2. The township of Lakes Entrance, showing proximity to the Gippsland Lakes artificial entrance.

above. During both events, Gippsland Lakes catchment floodwaters produced the dominant environmental forcing contribution. In both cases, as Gippsland Lakes catchment floodwaters travelled through the lagoon system in their attempt to escape to sea through an artificially engineered entrance (located adjacent to the Lakes Entrance township—refer Figure 2), widespread inundation of the Lakes Entrance township occurred. Both events were notably characterised by a lack of inundation information of a 'spatial' nature, to enable inundation scenario event planning and management by sectorally-based regional public Integrated Coastal Zone Management (ICZM) (refer Cicin-Sain and Knecht, 1998) stakeholder agencies. Given the growth in coastal township property values over the past decade (part of the Australian demographic 'sea-change' phenomenon—refer Salt, 2004), both planners and landholders have an interest in upgrading vulnerability assessments.

Research and development of a digital inundation modelling package for the Lakes Entrance township was commenced in early 2006 independently by Wheeler *et al*. (2007, 2008). The rationale for this research project was to produce Geographic Information Systems (GIS)-based outputs and tools suitable for flood inundation extent modelling and inundation event scenario visualisation for the Lakes Entrance townscape to enable: a) possible future inundation extent estimation/prediction with individual land parcel resolution; b) the integration of digital spatial information to assist future land-use planning and decision-making regarding inundation events; c) the integration of digital spatial inundation information into local emergency services information systems to support flood event contingency planning; d) the provision of rapid ICZM stakeholder 'mental map' stabilisation and consensus-building regarding inundation event scenarios, and; f) the assessment (including land parcel attribute documentation and geographical partitioning) of the relative inundation risk implications for insurance purposes.

During the inundation event of June/July 2007, data capture at the Lakes Entrance township, involving both ground-based oblique and aerial vertical and oblique photography, was completed. This data has been used to validate the GIS-based inundation modelling outputs derived from this research project. We report here the results of GIS-based inundation extent modelling and 'open-access' inundation visualisation 'tool' development and validation. This type of research, when applied to other coastal low-lying settled areas on the shores of the Gippsland Lakes, could be applied and integrated into future land-use planning schemes so that regional ICZM stakeholder groups can obtain detailed inundation scenario decision-support. Interest attaches not only to new model and visualisation development, but to modelling with more detail than has hitherto been possible.

2 CONTEXT

2.1 *The study area*

Lakes Entrance, situated in the East Gippsland region of Victoria, Australia, is located adjacent to an artificially engineered entrance to the 400 km^2 Gippsland Lakes. The artificial entrance to the Gippsland Lakes was engineered through a Holocene sandy barrier formation (see Bird, 1965) and opened in 1889. The contributing catchments of the Gippsland Lakes total 20,000 km^2 in area. The western rivers (the Latrobe, Thomson and Macalister Rivers) are highly regulated via large impoundments. The eastern rivers (the Avon, Mitchell, Nicholson, and Tambo Rivers) are presently ungated, excepting a small dam on the Nicholson River.

The progressive development of the Lakes Entrance urban townscape has taken place upon a former sandy barrier (Bird, 1965) whose terrain is now mostly below 1.8 m above Australian Height Datum (AHD). Since being dissected by streams during periods of lower sea levels, and eroded by post-Flandrian wave attack, it has been protected from swell wave attack by the development of an outer Holocene sandy barrier. It persists to the present as a chain of islands, extending seaward of the marginal bluff that marks the pre-depositional interglacial marine limit.

2.2 *Historical flooding at Lakes Entrance*

The Victorian State Rivers and Water Supply Commission (SRWSC) (1952) identified that during a severe flood event at Lakes Entrance in June 1952, areas of the township experienced floodwater inundation heights of between +1.844 m AHD and +1.392 m AHD. The current 'Land Subject to Inundation Overlay' (LSIO) value for the Lakes Entrance township is based on the 1:100 year return flood level height value of +1.8 m AHD (DNRE, 1998). The Victorian Government defines the LSIO as an area that can be 'used as an interim measure to identify flood-affected areas where detailed information to define the floodway is not available' (VPP, 2000). This value (+1.8 m AHD) was initially derived by application of the 1952 inundation event data.

A major inundation event took place at Lakes Entrance during late-June 1998, caused by heavy sustained rainfall in the eastern sections of the Gipp-sland Lakes catchment (Rooney, 1998). Research by Tan *et al*. (2002) found that streamflows from eastern rivers (the Avon, Mitchell, Nicholson and Tambo) dominated Gippsland Lakes inflows over the course of this event, contributing a combined flow of 320,000 ML/day. At Lakes Entrance, floodwater inundation levels of up to +1.3 m AHD were sustained during this event. McMaster (1998) relates that the water levels at Lakes Entrance reached their maximum height when the peak of the spring (flood) tide through the artificial entrance met the outgoing floodwaters on the evening of 24 June 1998. The event coincided with the passage of a low pressure system across the Gippsland Lakes catchment (e.g. an East Coast Cyclone, or East Coast Low—refer Sturman and Tapper, 2001: 192) with concurrent winds of 10 m/s (Tan *et al*., 2002). Damages in the entire East Gippsland region from resultant flooding totalled $AU 77.5 million (Yeo, 2002).

Recent inundation height estimates for Lakes Entrance by Grayson *et al*. (2004: 6) recommend a 1:20 year return flood level of +1.3 m AHD; a 1:50 year return flood level of +1.6 m AHD; and a 1:100 year return flood level of +1.8 m AHD. Given the low-lying nature of the terrain upon which the Lakes Entrance township has been developed, it is clear that varying areas of the townscape are at risk of inundation. However, until GIS-based inundation extent research by Wheeler *et al*. (2007) was carried out prior to the June/July 2007 flood event, there existed no means of digitally visualising (in two and/or three-dimensions) any recommended or stakeholder-defined inundation extent scenarios for the Lakes Entrance township. Phase 1 of this research was devoted to development of an accurate bare-earth digital elevation model (DEM) of the Lakes Entrance township, such that this model could be deployed as suitable for inundation extent mapping.

2.3 *Phase 1: Inundation extent modelling*

The study area bare-earth DEM suitable for inundation extent modelling was produced by Wheeler *et al*. (2007) via deployment of stereo photogrammetry (using *Leica LPS*). Ground Control Point (GCP) collection was undertaken using survey-level RTK differential GPS (using *Trimble R8*). After manual validation of the bare-earth DEM and GCPs, contours at 0.1 metre intervals, and flood inundation extent polygons (using *ESRI ArcMap*) were extracted. Separation of ground and non-ground height point clouds and digitisation of individual roofs allowed the true height of townscape buildings to be applied for three-dimensional visualisation purposes. These outputs are capable of being deployed within a GIS environment two or three-dimensionally, so that flood inundation scenario analysis can be supported with individual land parcel resolution.

The inundation modelling in this project refers to a uniform elevation of water heights in the North Arm, the Cunninghame Arm and the Reeves Channel (surrounding the Lakes Entrance township) and, it is in these terms that the probable maximum extent flood inundation (called the probable maximum flood, or PMF) for each inundation height above 0 m AHD is visualised. Floodwater behaviour in an urban environment (e.g. refer Hingray *et al*., 2000; Tanguy *et al*., 2001; Aronica and Lanza, 2005) imposes more complexity upon scenario modelling than can be represented using this methodology. However, Smith (2002) suggests that to be useful for a variety of purposes, including insurance appraisal, inundation mapping must extend to the level of the worst case event (e.g. the PMF). It is also recognised that the duration of each respective flood height 'peak' at Lakes Entrance, which would be sustained by a combination of environmental forcings (such as highest astronomical tides), will influence the area and duration of maximum floodwater inundation extent.

2.4 *Phase 2: Inundation scenario visualisation*

Phase 2 of this project (carried out in the post-June/July 2007 flood event period) entailed the construction of an *Adobe Flash*-based inundation visualisation 'tool' for the Lakes Entrance township study area, derived from the GIS-based inundation modelling outputs previously generated (refer Wheeler *et al*., 2008). This inundation visualisation allows public and private ICZM stakeholder groups, many of whom possess no GIS capabilities, to access inundation scenario information for the Lakes Entrance township freely via the internet. The internet and the World Wide Web have long been recognised as having the potential to transform the often closed view of GIS by dramatically increasing GIS applications to create new forms of geographic information representation, and to present new ways of addressing problems important to society (MacEachren, 1998). Our approach has been to produce a visualisation tool that focuses specifically on local flood risk, employing an interface following the principle of 'functional minimalism' to maximise ease of use and rate of adoption by new users. Carver (2001) suggests that application of intelligent interfaces to specific problem areas would encourage greater use by all stakeholder groups. The resultant zoomable and pannable interactive flood modelling visualisation 'tool' (refer Figure 3) enables all non-expert ICZM stakeholders to obtain an overview of the effect of flooding at the Lakes Entrance township. The final visualisation has been deployed on the Web, and can be freely sourced at: http://sahultime.monash.edu.au/LakesEntrance/.

McGlashan and Williams (2003) suggest that often, frameworks for coastal zone decision-making exclude participation by individuals and those without institutional representation. Innovative participatory techniques and tools, such as the interactive flood visualisation developed during Phase 2 of this project, can potentially strengthen the role of all coastal stakeholders, especially those lacking institutional representation, by providing spatial information which is easy to access and comprehend.

2.5 *2007 flood event—description*

A synthesis of data from the Commonwealth Bureau of Meteorology (BOM, 2008) for the Gippsland area for the months of June/July 2007 shows that a complex low pressure system caused locally heavy rainfall in sections of the Gippsland Lakes catchment during 18–19 June 2007. This rainfall event caused minor flooding in the Mitchell River and Macalister River catchments. Between 26 and 28 June 2007, an intense East Coast low pressure system made landfall over the Gippsland Lakes catchment, which produced extremely heavy rainfall (in the order of over 300 mm over a 24 hour period at some locations within the catchment). Most sub-catchments in the Gippsland Lakes catchment were already saturated due to the earlier rainfall event of 18–19 June 2007. Rainfall to runoff yields in some catchments (such as the Macalister River catchment) were increased during these rainfall events due to the effects of intense bushfires experienced in Gippsland during the summer of 2006/7. For example, geomorphological studies of small montane catchments in the Macalister River catchment by Dunkerley (2008) shows that extraordinary runoff efficiencies of up to ~50 $m^3/s/km^2$ were achieved, which are presently amongst the highest known from any part of the world.

Figure 3. The *Flash*-based open-access Lakes Entrance inundation visualisation tool interface.

Due to the extreme nature of this event within the Macalister River catchment, both rainfall and streamflow gauges at some locations were washed away, and thus, their data could not be consulted. Discharges from Lake Glenmaggie to the Macalister River peaked at 147,000 ML/day, recorded at 1000 hrs on 28 June 2007. This figure is 112,000 ML/day higher than the recognised major flood class (which is 35,000 ML/day) for this stream, and this figure represents 46% of the total peak flow contributed by all four eastern catchment rivers (the Avon, Mitchell, Nicholson and Tambo Rivers) during the 1998 floods. Flood peaks recorded along the Macalister River during this event were the largest on record. The Latrobe River, Thomson River, Avon River and Mitchell River catchments also experienced major levels of flooding during this event.

Gippsland Lakes catchment floodwaters travelled through the coastal lagoon system towards the artificial entrance, and caused elevated water levels at Lakes Entrance township from 28 June 2007 until floodwater levels gradually subsided after approximately one week. During this inundation event, apart from the GIS-based flood extents derived via Phase 1 of this project (which were made available to ICZM stakeholders involved with inundation event management), no regional ICZM agency possessed any high-resolution spatial information to facilitate user-defined inundation scenario decision-support for Lakes Entrance emergency management. Maximum floodwater heights reached at Lakes Entrance township during this event were recorded at 15 separate locations by the East Gippsland Catchment Management Authority (EGCMA) as ranging from +1.055 m AHD to +1.292 m AHD. This variation is consistent with recorded variations in maximum floodwater height obtained during the 1952 Lakes Entrance inundation event.

3 RESULTS

3.1 *Validation of modelled inundation extents*

Real-time capture of ground-based and aerial vertical and oblique imagery during the June/July 2007 Lakes

Entrance inundation event facilitated limited validation of modelled inundation extents. Aerial oblique digital imagery capture took place during two flights in light aircraft on 30 June and 2 July 2007 respectively, with collectively 300 separate digital images taken from a flying height of 500 ft above mean sea level. As successive flood peaks at Lakes Entrance corresponded with highest astronomical tides at night, no imagery could be obtained representing the maximum extents reached during this event; the only record of maximum floodwater heights reached being recorded via manual survey by EGCMA of water level marks left by receeding floodwaters on standing infrastructure. Ground-based imagery was collected at various times throughout the inundation event. Vertical aerial imagery was obtained during 1 June 2007 was made available by the West Gippsland Catchment Management Authority (WGCMA). Vertical aerial imagery capture at other times was restricted by the presence over Lakes Entrance of meteorological conditions unsuitable for air photo acquisition.

Three well-known townscape areas have been chosen to exemplify our imagery-intensive visual validation process (refer Figure 4). Modelled inundation extents were compared with vertical and oblique aerial imagery using *ESRI ArcMap*. Three-dimensional modelled extent validation was carried out by deployment of GIS-based inundation extent layers in *ESRI ArcScene*, and use of the ‘fly’ tool to position the on-screen visualisation to approximately match the position of the aerial oblique imagery.

Additionally, the Lakes Entrance visualisation tool provides scope for further modelling validation, as digital flood imagery collected during the inundation events of June/July 1998 and June/July 2007 has been incorporated as an interactive layer. Using this tool, images can be displayed on screen alongside inundation extents, which can be altered using the interactive flood slider to resemble inundation extents captured in real-time imagery.

3.2 *Location A: Apex Park, Lakes Entrance*

Apex Park is located at the western end of the Lakes Entrance township. Oblique aerial imagery data capture of this location was obtained at 1132 hrs on 30 June 2007 (refer Figure 5). Comparison of figure 5 with modelled inundation extents (refer Figure 6) at this time shows that actual floodwater inundation height was between +1.1 m AHD and +1.2 m AHD. Modelled extents at +1.2 m AHD compare favourably with actual photographed extents at this location. At Apex Park, there are no protective seawalls or coastal armouring for floodwaters to surmount before inundating townscape urban areas.

Figure 5. The Apex Park area, Lakes Entrance. Imagery captured 1132 hrs on 30 June 2007.

Figure 4. Locations of Lakes Entrance township areas chosen to exemplify modelled inundation extent validation.

Figure 6. 2D modelled inundation extent image (+1.2 m AHD) for the Apex Park area, Lakes Entrance township.

3.3 *Location B: 'The Oval' area, Lakes Entrance*

The area to the north-west of the Lakes Entrance cricket oval ('The Oval') was used as an area to exemplify the validation process. Aerial oblique imagery at Figure 7 shows actual flood extents reached at this location on 30 June 2007 at 1133 hrs. Figure 8 shows the +1.2 m AHD modelled inundation extent, displayed three-dimensionally. It is estimated that actual flood heights at this location at this time were between +1.1 and +1.2 m AHD. At this location, modelled extents again compare favourably with actual extents captured in aerial imagery.

3.4 *Location C: Mechanics' Hall, Lakes Entrance*

The Lakes Entrance Mechanics' Hall is a prominent local landmark, which is situated in the approximate centre of the township. This area is located some distance from shorelines and protective seawalls. Aerial oblique imagery at Figure 9 depicts the actual

Figure 7. 'The Oval' area at Lakes Entrance township. Imagery captured at 1133 hrs on 30 June 2007.

Figure 8. 3D modelled inundation extent image (+1.2 m AHD) for 'The Oval' area of the Lakes Entrance township.

Figure 9. The Mechanics' Hall area at Lakes Entrance township. Imagery captured at 1254 hrs 30 June 2007.

Figure 10. 3D modelled inundation extent image (+1.0 m AHD) for the Mechanics' Hall area of the Lakes Entrance township.

Figure 11. 2D modelled inundation extent image (+1.0 m AHD) for the Mechanics' Hall area, showing contribution of the stormwater network to inner-township floodwater inundation.

inundation extent at this location when captured on 30 June 2007 at 1254 hrs. A modelled inundation extent scenario of +1.0 m AHD most favourably matches the actual extents reached at this time (refer Figure 10). Modelled inundation extents for this area shows that inundation occurs due to floodwater backflow along the stormwater pipe network (refer Figure 11) before floodwaters can overtop seawall and shoreline areas.

4 DISCUSSION

Outcomes from this research project produced thus far can be seen as exemplifying the utility of GIS technologies in support of ICZM initiatives. Within the overall context of ICZM, it is clear that GIS has the potential to act as an important tool not only for coastal zone inundation risk assessment, but also in support of many coastal planning and management issues and problems (e.g. see Bartlett and Smith, 2001). As Uttal (2000) and Golledge (2002) relate, the preparation and use of spatial representations provide a perspective and understanding of human and natural phenomena and environments that is not matched by any other means. In this case, the research outcomes can be readily applied to provide relevant 'user-defined' spatial inundation scenario information to all public and private ICZM stakeholders. As Eves (2004: 85) suggests, continued stakeholder flood awareness in inundation-prone areas is extremely important, due to post-inundation event decrease in public flood awareness, and a loss of public appreciation of flood event impacts.

Despite extensive flooding of Lakes Entrance township (and many other East Gippsland townships fringing the Gippsland Lakes) during June/July 1998 and June/July 2007, the development of any high-resolution spatial information regarding inundation extent modelling or mapping for terrestrial areas vulnerable to coastal area flooding is not yet in train. The enhanced level of inundation scenario decision-support offered to coastal zone decision-makers and managers via this kind of spatial data and representations exemplified in this paper is clearly applicable. The suitably accurate spatial information regarding coastal inundation scenario modelling that is now within reach shows that local government land-use planning schemes can be upgraded to: a) play a crucial role in the development of a regulatory framework regarding future sustainable planning and development; to b) involve a wide range of public and private stakeholders in consensus-building and decision-making activities, and c) to assist in achieving more efficient long-term ICZM programs and initiatives through land-use planning scheme evolution.

It is apparent that relevant Gippsland Lakes catchment decision-makers involved with land-use planning for low-lying coastal areas must consider future climate change scenarios and their likely impacts. For example, research by the Victorian Department of Sustainability and Environment (DSE, 2004) estimates that under future climate change scenarios for the Gippsland Lakes catchment, hotter, drier conditions will increase bushfire risk (and potentially increase rainfall to runoff yields), and extremely heavy rainfall events may become more intense. This information, combined with projected global sea level rise scenarios developed by the Intergovernmental Panel for Climate Change (IPCC, 2007), and also regional coastal storm surge scenarios developed for the Gippsland coastline by the Australian Commonwealth Science and Research Organisation (CSIRO) (McInnes, *et al*., 2005), suggests that flooding of low-lying Gippsland coastal areas may become more frequent and severe. In view of these projections, it is likely that in the future, Gippsland ICZM stakeholders will be faced with balancing 'mitigation and/or managed retreat' for vulnerable low-lying coastal townships such as Lakes Entrance. In the present, as McDonald (2007) suggests, with increased scientific consensus over the likely range of climate change impacts, every decision made carries a risk of legal exposure; decision-makers need to make the risks of climate change induced impacts an explicit part of their decision-making criteria, or risk unpredictable future liability.

This project has also exemplified the value of data sharing and integration. For example, the access and deployment of spatial information regarding Lakes Entrance stormwater network has allowed a greater understanding of the role this network plays regarding inundation of certain areas of the township. Analysis has shown that the stormwater network acts as a 'conduit' for the flooding of many low-lying inner-townscape areas at Lakes Entrance, in many cases *before* floodwaters can overtop shorelines and seawalls. The Lakes Entrance sewerage network overlay can also be applied to visualise 'at-risk' assets (for example, unsealed manhole covers and sewer vents), which can allow concurrent floodwater ingress into the sewerage system, and raw sewage egress from this system to coastal floodwaters and within dwellings. This scenario can potentially create both environmental pollution and human health risks, and much property damage.

In Victoria, despite the progressive development of a centralised statewide Spatial Data Infrastructure (or SDI—known as the Victorian Spatial Data Directory) since 1992 (e.g. see Jacoby *et al*. 2002), there currently exists no spatial data sharing framework in support of state-wide or regional ICZM programs. Globally, similar findings have been made by Bartlett *et al*.

(2004), whose research confirms that few of the extant national, regional or local SDI implementations make much provision for the inclusion of basic coastal and marine framework datasets. In consequence, Victorian ICZM stakeholders who currently utilise spatial technology as an intra-organisational decision support tool must assemble their own 'site-specific' spatial databases in order to provide an adequate decision support capacity with appropriate local resolution. In the absence of inter-organisational spatial data sharing agreements, it is only via *ad hoc* data sharing that this data can be utilised by other ICZM stakeholders. The contents of such intra-organisational datasets may be largely unknown to other integrated coastal zone managers and organisations, and thus, they are not available for inclusion in the decision support flowpaths of other stakeholder agencies. Furthermore, organisations may not wish to share their databases, nor have any incentive to share them. They are often compiled at high cost to the organisation concerned. Such fragmented and uncoordinated database activities often results in duplications and redundancies, and wastage of organisational/public resources, particularly in organisations with the same or similar administrative jurisdictions (Nedovic-Budic and Pinto, 1999). Such databases may also lack the common data standards and policies which are important to ensure the validity of spatial datasets for use in the decision-making process.

Phase 2 of this project has shown the value of open-access spatial information dissemination in terms of facilitating stakeholder consensus and capacity-building activities. 'Capacity-building' is a concept central to ICZM (UNCED, 1992), and is defined by Cicin-Sain *et al*. (2000: 294) as 'the design and conduct of a range of activities necessary to enhance the capacity of institutions and the individuals that comprise them to undertake effective ICZM programs'. In Victoria, development of a system of 'bottom-up' regionally-based and purpose-built SDI model for ICZM would offer potential to include all relevant regional and local stakeholder groups, so providing regional and localised user-based 'ownership' of spatial data and information collection, maintenance and dissemination (including high-resolution site-specific spatial information, such as data derived through flood inundation modelling). Thus the 'top-down' and 'centralised' state-wide SDI model which is currently adhered to in Victoria can be complemented with high resolution site-specific spatial data via such a 'grass-roots' approach. As Williamson (2003) suggests, user-needs will drive future development of SDIs, and this aspect will require a change in focus in the development of SDIs away from government directives to listening to the needs of the community. Accordingly, spatial data could be delivered not only via regional ICZM SDI, but also through an open-access web-map server, so as to allow the widest range of public and private ICZM stakeholder access. Thus, high levels of community and stakeholder agency inundation understanding, awareness, education and consensus-building would be supported. It is argued that these types of spatial data dissemination, which would enable ready access by sectorally-based public and private ICZM stakeholders, is essential to provide an integrated spatial decision-support capacity *vis a vis* future flood inundation risk, planning and management, in support of ICZM initiatives.

International experiences may provide valuable information to guide the effective integrated use of spatial technologies for ICZM in Victoria. For instance, in Europe, where ICZM initiatives often extend over not only *organisational* but *national* administrative boundaries, a concept known as *integrated coastal and river basin management* (ICARM) (UNEP, 1999) has evolved, which explicitly links coastal areas and their catchments in management and planning. ICARM is defined as the 'adoption of goals, objectives and policies and the establishment of governance mechanisms which recognise the interrelationships between coastal and river basin systems with a view for environmental protection and socio-economic development' (Coccossis, 2004:414). Central to the ICARM concept is provision of information and decision support using an integrated spatial technologies (GIS) capability. Advanced implementation of this approach is exemplified in parts of Europe. The Oder/Odra river basin, which spans geographical areas of the Czech Republic, Poland, and Germany, became the subject of an international ICARM case study (e.g. see Schernewski *et al*., 2005). Among the key recommendations of this study has been that provision of a regional information and GIS planning system is required in support of ICARM initiatives, and that such a system must contain different types of information, and must give stakeholders direct access to relevant spatial information of adequate spatial resolution required for management. Thamm *et al*., (2007) relate that in the Oder/Odra ICARM case study, an internet-based GIS regional information and planning system has been deployed since 2004, and the authors note that the way in which the various stakeholders utilised this system was very positive.

5 CONCLUSIONS

The outcomes from all phases of this research project so far completed constitute a 'proof of concept' in support of adaptive management and ICZM initiatives in Gippsland, Australia. Validation of inundation extents derived for the Lakes Entrance township via GIS-based modelling using actual inundation event imagery have validated the detail found in the model. Spatial information derived via GIS-based modelling has been transformed into an interactive visualisation 'tool' to support open-access user-defined stakeholder inundation awareness and consensus-building. However, it remains clear that when faced with future projected climate change scenarios, similar high-resolution inundation extent modelling needs to be completed for all other coastal townships in Gippsland (and potentially in other areas of Victoria) which are at risk of future inundation. The spatial data and information derived through such work can provide all stakeholders with a credible two and three-dimensional visualisation and decision-support capacity *vis a vis* current land-use planning and management, and most importantly, the ability to plan for likely future coastal inundation event scenarios. Stakeholder perception and participation are important components of inundation hazard awareness and control measures, and to achieve the necessary consensus, all relevant stakeholders must be involved in decision-making processes. In this regard, digital inundation modelling spatial outputs, when combined with an effective dissemination framework, have much potential to provide the tools necessary to enable stakeholder consensus-building and decision-making in support of adaptive ICZM and sustainable development concepts.

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REFERENCES

Aronica, G.T., Lanza L.G. (2005) 'Drainage efficiency in urban areas: a case study'. *Hydrological Processes*. 19(5): 1105–1119.

Bartlett, D. and Smith, J. (eds) (2001) *GIS for Coastal Zone Management*. London: CRC Press.

Bartlett, D., Longhorn, R., Garriga, M. (2004) 'Marine and coastal data infrastructures: a missing piece in the SDI puzzle?' *Marine and Coastal Data Infrastructures—GSDI-7 Conference*, February 2004.

Bird, E.C.F. (1965) A Geomorphological Study of the Gippsland Lakes. ANU: Canberra.

Bird, E.C.F. (2000) Coastal Geomorphology: An Introduction. New York: Wiley.

Bureau of Meteorology (BOM) (2008) *Information on the June/July 2007 Gippsland Lakes catchment floods*.

Carver, S. (2003) The future of participatory approaches using geographic information: Developing a research agenda for the 21st century. *Urban and Regional Information Systems Association (URISA) Journal* 15, APA I, 61–72.

Cicin-Sain, B. and Knecht, R. (1998) *Integrated Coastal and Ocean Management. Concepts and Practices*. Washington: Island Press.

Coccossis, H. (2004) Integrated Coastal Management and River Basin Management *Water, Air and Soil Pollution Focus*. 4 (5): 411–419

Department of Natural Resources and Environment (DNRE) (1998) *Victoria Flood Management Strategy*.

Department of Sustainability and Environment (2004) *Climate Change in East and West Gippsland*. Melbourne: Government Printer.

Department of Sustainability and Environment (DSE) (2006) *East Gippsland Planning Scheme*. Melbourne: Government Printer.

Dunkerley, D. (2008) (*in prep*.) Catastrophic runoff and regolith erosion following the 2003 and 2007 wildfires in the eastern uplands, Victoria, Australia. *Geophysical Research Abstracts* 10, EGU2008-A-05771.

Eves, C. (2004) 'The impact of flooding on residential property buyer behaviour: an England and Australian comparison of flood affected property'. *Structural Survey*. 22(2): 84–94.

Golledge, R.G. (2002) The nature of geographic knowledge. *The Annals of the Association of American Geographers*. 92: 1–14.

Grayson, R., Candy, R., Tan, K.S., McMaster, M., Chiew, F., Provis, D. and Zhou, S. (2004) *Gippsland Lakes Flood Level Monitoring Project: Final Report 01/04*. Centre for Environmental Applied Hydrology, University of Melbourne.

Hingray, B., Bouvier, C., Desbordes, M., Cappelaere, B. (2000) Urban flooding: a geometric indicator to describe the hydraulic behaviour of built-up areas. *Revue des Sciences de l'Eau/Journal of Water Science* 13(1): 85–100.

Intergovenmental Panel on Climate Change (IPCC) (2007) *Climate Change 2007: Synthesis Report—The Fourth Assessment Report of the IPCC*. Cambridge, Cambridge University Press.

Jacoby, S., Smith, J., Ting, L. and Williamson, I. (2002) Developing a common spatial data infrastructure between state and local government—an Australian case study. *Int. J. Geographical Information Science*. 16(4): 305–22.

McDonald, J. (2007) A risky climate for decision-making: The liability of development authorities for climate change impacts. *Environmental and Planning Law Journal*. 24(6): 405–416.

McEachren, A., Brewer, C. and Pickle, L. (1998) Visualising georeferenced data: representing reliability of health statistics. *Environment and Planning A*. 30: 1547–61.

McGlashan, D. and Williams, E. (2003) Stakeholder involvement in coastal decision-making processes. *Local Environment* 8(1): 85–94.

McInnes, K., Macadam, I., Hubbert, G., Abbs, D. Bathols, J. (2005) *Climate Change in Eastern Victoria. Stage 2 Report: The Effect of Climate Change on Storm Surges*. A project undertaken for the Gippsland Coastal Board by CSIRO Marine and Atmospheric Research.

McMaster, M. (1998) *Modelling the Hydrodynamics of Lakes Entrance*. Unpublished 4th Year Environmental Engineering Research Project, The University of Melbourne.

Nedovic-Budic, Z. and Pinto, J.K. (1999) Understanding inter-organisational GIS activities: a conceptual framework. *URISA Journal*, 11(1): 53–64.

Rooney, W. (1998) *The Heavy Rain Event in East Gippsland 22/23 June 1998*. Victoria: Bureau of Meteorology, Victorian Regional Office.

Salt, B. (2004) *The Big Shift*. 2nd Edition, Hardie Grant, Melbourne.

Schernewski, G., Löser, L. and Sekścińska, A. (2005) Integrated Coastal Area and River Basin Management: The Oder/Odra case study. At http://www.euccd.de/plugins/coastline_reports/pdf/cr6/06_schernewski_etal_.pdf (accessed 12 October 2006).

Smith, D.I. (2002) 'Background data and information on flood insurance', in D.I. Smith and J. Handmer (eds) *Residential Flood Insurance: The Implications for Floodplain Management Policy*. Water Research Foundation of Australia, Canberra: ANU.

State Rivers and Water Supply Commission (SRWSC) (1952) *Gippsland Lakes Floods 1952*.

Sturman, A.P. and Tapper, N.J. (2001) *The Weather and Climate of Australia and New Zealand*. Melbourne: Oxford University Press.

Tan, K.S., Grayson, R., Chiew, F., McMahon, T. and Western A. (2002) 'Exploring Cross-Correlations of Environmental Forcings in a Coastal Lagoon'. *27th Hydrology and Water Resources Symposium*. 20–23 May 2002, Melbourne, Australia.

Tanguy, J.M., Zhang, B., and Al Mikdad, O. (2001) 'The hydro-logical risk of urban rainfall events: a surface flow simulation tool'. *Bulletin Des Laboratories Des Ponts Et Chaussees*. 232: 87–100.

Thamm, R., Bock, S. and Schernewski, G. (2007) Regional information systems and coastal databases for ICZM in Germany—are they efficient and informative? In G. Schernewski, B. Gleser, R. Scheibe, A. Sekścińska and R. Thamm, *Coastline Reports 8(2007) Coastal Development: The Oder Estuary and Beyond*. EUCC, Warnemuende, 2007, ISBN 978-3-9811839-0-0.

Townend, I. and Pethick, J. (2002) Estuarine flooding and managed retreat. *Phil*. *Trans*. *R*. *Soc*. *Lond*. 360: 1477–1495.

United Nations Conference on Environment and Development (UNCED) (1992) *Agenda 21 and the UNCED Proceedings*. New York: Oceana Publications.

United Nations Environmental Program (UNEP) (1999) *Conceptual Framework and Planning for Integrated Coastal and River Basin Management*. Spit: Priority Actions Program.

Uttal, D. (2000) Seeing the big picture: map use and the development of spatial cognition. *Developmental Science*. 3: 247–286.

Victoria Planning Provisions (VPP) (2000) *Practice Note: Applying for a Planning Permit under the Flood Provisions: A Guide for Councils*, *Referral Authorities and Applicants*.

Wheeler, P.J., Kunapo, J., Peterson, J. and McMahon, M. (2007) Mapping relative inundation vulnerability of land parcels on low-lying ground: exemplification with a photo-grametrically-derived DEM-based model of Lakes Entrance, Victoria, Australia. *Spatial Science Institute Biennial International Conference*, May 14–18, 2007, Hobart, Tasmania, Australia. 902–915.

Wheeler, P.J., Coller, M.L.F., Kunapo, J., Peterson, J. and McMahon, M. (2008) Facilitating coastal zone inundation awareness using GIS-based scenario modeling and multimedia visualisation. *QSC2008 Queensland Spatial Conference Proceedings*, 17–19 July 2008, Gold Coast, Queensland, Australia.

Williamson, I. (2003) SDIs—setting the scene. In Williamson, I., Rajabifard, A. and Feeney, M.F. *Developing Spatial Data Infrastructures: From Concept to Reality*. London: Taylor and Francis.

Yeo, S. (2002) 'Flooding in Australia: a review of events in 1998'. *Natural Hazards*. 25: 177–191.