Environmental Modelling & Software 68 (2015) 98–109

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Coping with climate change: The role of spatial decision support tools in facilitating community adaptation

David J. Lieske

Department of Geography and Environment, Mount Allison University, 144 Main Street, Sackville, New Brunswick, Canada

A R T I C L E I N F O

Article history:
Received 22 May 2014
Received in revised form
9 February 2015
Accepted 12 February 2015
Available online

Keywords:
Web-based software
Spatial decision support
Climate change
Adaptation
Flood risk

A B S T R A C T

Climate change challenges communities to visualize spatial patterns of risk, assess their vulnerability to those risks, and prepare adaptation plans to lower vulnerability. This paper outlines the design and implementation of a prototype web-based spatial decision support system (SDSS), referred to as the Community Adaptation Viewer (CAV), to assist adaptation planning. Thin-client, Javascript enabled web-SDSS software was constructed to allow interaction with urban infrastructure, and support “on-the-fly” assessment of social and economic vulnerability. Facilitated, decision-making workshops were conducted with small groups of stakeholders to evaluate the effectiveness of the prototype. The test case illustrates that high levels of information integration are practical to achieve, and that the SDSS can significantly enhance the ability of communities to conduct elaborate, geographically-specific climate change adaptation planning. Given the long time frame required to fulfil some adaptation plans, it is crucial that communities begin to develop and invest in adaptation strategies as soon as possible.

Software availability

Name of Software: Community Adaptation Viewer (CAV)
Developer: David J. Lieske
Contact Address: Dept. of Geography and Environment, Mount Allison University, 144 Main Street, Sackville, New Brunswick, Canada, E4L 1A7
Contact E-mail: dlieske@mta.ca
Available Since: 2013
Programming Language: Javascript
Availability: http://arcgis.mta.ca/toolkit
Cost: Free

1. Introduction

Decision analysis centers on taking problems, dividing them into small, more manageable parts, analysing each of those parts, and integrating the findings to produce logically meaningful solutions (Karnatak et al., 2007). With regards to climate change adaptation planning, with its implicit aim of reducing community vulnerability, the problem domain is “ill structured” (Sugumaran and DeGroote, 2011) in a number of ways. First, it involves complex social, environmental and economic dimensions which are not easy to quantify. In the case of social vulnerability, there is a wide consensus that it is, in part, a socially-constructed consequence of uneven access to economic, social, and informational resources (Cutter et al., 2000; Wu et al., 2002; National Research Council, 2006, Füssel, 2007; Hebb and Mortsch, 2007, Wilby and Keenan, 2012). Assuming that a set of measurable social vulnerability indicators are agreed upon to capture this reality, there are intangibles presented by the socio-political landscape that will impinge upon and determine the acceptability of any potential risk reduction solution. Other facets of the climate change adaptation problem include the fact that the goals and objectives of community stakeholders may not be completely definable, even in the minds of the stakeholders themselves. Furthermore, the goals may be competing or even in opposition to each other. We can also expect there to be many possible candidate solutions, the efficacy of which will be plagued by uncertainty.

There is a growing body of applications illustrating the utility of spatial decision support system (SDSS) and visualization tools for adaptation planning, of which this study is one example. But consideration of the role of SDSS might be best conducted within the framework of Risbey et al. (1999), where the components of adaptation decision making are clearly delineated.

The first phase of adaptation planning is *signal detection*, which involves perception of relevant patterns (e.g., trends in time or

---

E-mail address: dlieske@mta.ca.

http://dx.doi.org/10.1016/j.envsoft.2015.02.005
1364-8152/© 2015 Elsevier Ltd. All rights reserved.

space, Chen, 2005). Without awareness of the state of the system, and the impact climate change may have in perturbing this state, effective decision making cannot proceed. Being able to quantify and visualize the state of the system, as well as its response to climate change, is itself a common reason for turning to SDSS in the first place. For example, a key motivation for the project of Strasser et al. (2014) was to connect the snow pack predictions from broad-scale climate models with the economic and social impacts on Austrian ski facilities. Wan et al. (2014) provided a demonstration of the value of web-based visualization of volunteered flood disaster information. Haasnoot et al. (2014) were concerned with providing faster, more efficient decision support information to help manage flood and drought risks downstream of the Rhine. Achieving this goal required decision support tools for assessing water distribution within the Rhine delta, along with indicators of system state, for example, perilously low water levels in the IJsselmeer. For Rosenzweig et al. (2011, Figs. 14 and 15), key visualizations were 1-in-100-year flood-risk maps for New York City. These studies and others illustrate the important role SDSS and visualization tools have to play (Eppler and Aeschimann, 2009). In addition to mapping risk information they also provide a means to visualize temporal trends. Models can be used to depict the outcome of different climate change scenarios, and animations can provide powerful impressions of particular events. For instance, infrastructure impacts can be depicted using computer-generated graphics or historical images, as in the case of the Tyndall Coastal Simulator (Mokrech et al., 2011). Studies have shown that such imagery can strongly impact risk perception and deepen understanding of the problem (Lieske et al., 2014).

The second aspect of adaptation planning identified by Risbey et al. (1999) is *evaluation*, where the interpretation of future projections and assessment of the forseeable impacts are conducted. In climate change adaptation, this constitutes “vulnerability analysis”, and involves the identification of at-risk “hot spots” along with the economic, social and environmental implications, for example, Romañach et al. (2014). Giupponi et al. (2013) conducted a very sophisticated analysis of community vulnerability for the headwater basins of the Danube and Brahmaputra, which involved the integrative modelling of participants' risk perception. In addition to deepening understanding of vulnerabilities, these types of analyses are a necessary prerequisite to prioritization of the right courses of action.

The final phases of Risbey et al. (1999) involve *decision and response*, and *feedback*, both of which could be greatly augmented by SDSS. Padgham et al. (2013) illustrated how ineffective adaptation pathways can be avoided in the first place through application of agent based modelling and simulation (ABMS). In the Australian case study, the ABMS models confirmed suspicions that the public provisioning of sand bagging depots was not an effective measure for mitigating flood vulnerability (Padgham et al., 2013). In addition to allowing for the simultaneous assessment of the potential lowering of vulnerability with respect to implementation cost, SDSS can act as a living database of the risk appraisal process, inviting re-analysis and reflection at any point. Different audiences or constituencies can use the SDSS to draw their own conclusions, thereby diversifying the portfolio of possible risk reduction strategies as well as flagging different aspects of community vulnerability. The creation of user-identified features and annotations within SDSS software acts as a record (“shared memory”) inviting further and subsequent analysis (Andrienko et al., 2007), thereby preserving the “derived knowledge” of the adaptation planning process (Peuquet and Kraak, 2002, Mennis and Peuquet, 2003; Andrienko et al., 2007; Hopfer and MacEachren, 2007).

In order for communities to make meaningful progress in planning for and implementing necessary short- and long-term changes, there is a need for information systems which allow community stakeholders to visualize climate change risk information together with various aspects of community vulnerability (Flax et al., 2002). Such systems are most effective when they are developed in a participatory manner (McIntosh et al., 2011), when they encourage collaboration by diverse groups of stakeholders of differing competencies, interests, and political agendas, and when they facilitate knowledge sharing (Jankowski et al., 1997); yet, they should also help users to discern critically vulnerable locations, better understand the risks and vulnerabilities involved, and create plausible scenarios representing multiple courses of action. By assisting in the computation and visualization of the impacts of various adaptation measures, it should help users to articulate goals and priorities, thereby identifying the right course of action for the community. Software has tremendous potential to provide the information framework necessary to support all aspects of adaptation planning, and to “complement the power of computational methods with human background knowledge, flexible thinking, imagination, and capacity for insight” (Andrienko et al., 2007: 840).

The studies previously cited serve to illustrate the potential of a new generation of SDSS, and this paper reports on a project that originated with the findings of earlier climate-change visualization work (Roness, 2013). Through public consultation, a need was identified for software capable of displaying flood risk and community vulnerability, along with the interactive identification of locations of concern (LOCs) and candidate adaptation planning zones (APZs). In order to maximize the accessibility and ease-of-use of the software, a design decision was made to implement a prototype web-based spatial decision support system (web-SDSS) using a thin-client (see Power and Kaparthi, 2002), Javascript user interface. This conferred significant advantages, such as the central storage of data and ability to run in ordinary web browsers. The software, referred to as the Community Adaptation Viewer (CAV), also provided functions for assessing economic and social vulnerability “on-the-fly” at a high level of detail.

The second phase of this project involved test deployment of the software in a community in south-east New Brunswick, Canada, which is at significant risk to sea-level rise-related coastal flooding. Through the use of facilitated workshops, small groups of stakeholders were brought together to use the CAV. This allowed a progression from problem identification and characterization to adaptation planning zone delineation, and resulted in the brainstorming of possible risk reduction strategies. This paper reviews both the software and the community case study, and offers suggestions for how this (or similar) software can help advance the world-wide adaptation agenda.

2. Design considerations

Due to time and manpower constraints, as well as limitations in the availability of project stakeholders, development could only be described as partially user-centred (see Maguire, 2001; Gulliksen et al., 2003). Users were not involved in all stages of project development (as would be expected in a true user-centred iterative approach), but data requirements and overall functionality was derived from feedback received during two earlier phases of consultation: (1) seven meetings held between November 5 and 18, 2013 to identify and discuss the concept of “vulnerability”, and (2) an earlier study involving ten attendees from six of the twelve then-existing provincial planning districts (Roness, 2013). The flexibility of web-based software was uniformly appreciated, and functionality such as ability to estimate the economic costs of potential flood events was suggested as key information to support decision making. Previous efforts excluded social vulnerability indicators, so this was considered an important data component that needed to be developed.

A design decision was made to adopt a "thin client" approach (see Power and Kaparthi, 2002; Rinner, 2003) and build a web-enabled user interface using the Javascript API and Dojo Toolkit. As pointed out by Chen et al. (2007), this eliminates the need for users to have to download and install software or manage updates ("thick client"), thereby increasing flexibility and long-term usability (Bhargava et al., 2007). Previous work has argued that interactivity enhances the quality of generated solutions (Andrienko and Andrienko, 2006; Andrienko et al., 2007) so a high level of user-interface interactivity was considered necessary. Interface development proceeded in accordance with Schneiderman's "Information Seeking Mantra" of *overview first, zoom and filter, and then details-on-demand* (Schniederman, 1996), allowing users to actively guide/influence the analysis, reduce the breadth and/or depth of the search (saving on computation time) and focus attention on the relevant output.

Real-time responsivity was considered an important design goal given the need for users to be able to receive immediate feedback in an "appropriate" form (Andrienko et al., 2007). In order to work through the implications of the emerging community vulnerability patterns (the "hot spots") during the course of a typical focus group, users must be able to rapidly assess the risk exposure in these areas.

Underlying spatial data (e.g., LiDAR used to accurately measure surface elevation at 1-m spatial resolution and produce maps of potential flood extents) were housed in a single, integrated geodatabase to be hosted as map service layers on ArcGIS Server 10.1 (ESRI, 2014). Infrastructure at-risk (e.g., highways, institutions, properties) were also gathered within the same database, and included other information such as potential economic impacts and social vulnerability information. This approach centralized important risk and vulnerability layers, and rendered them accessible from any location connected to the internet.

Finally, visualization research has pointed to the importance of storing the valuable, intangible, and largely unanticipated knowledge provided by users (Peuquet and Kraak, 2002, Andrienko et al., 2007). Referred to as "shared memory" (Andrienko et al., 2007) or "derived knowledge" (Mennis and Peuquet, 2003), web-accessible annotation tools are considered an ideal way to gather such data (Hopfer and MacEachren, 2007). The need to support user-provided data is expected to be especially crucial in climate change vulnerability assessments when expert knowledge is available to supplement existing information. For spatial decision support systems, this requires tools for drawing point and areal features, assigning attribute information to those features, and storing them in the centralized database.

As a final design note: while ultimately not pursued due to time and resource limitations, previous research has pointed to the value of archiving hyperlinked information, e.g., pictures of affected or vulnerable areas (Aggett and McColl, 2006), climate change projections, IPCC reports, and model simulations/animations. This ensures that supporting documentation and resources are centrally gathered and accessible, and can potentially extend the utility of climate change adaptation software. However, developers need to balance the temptation to extend the functionality of SDSS tools with the need to efficiently address key project goals.

3. System architecture

The CAV architecture consists of three interlocking layers: a data layer (consisting of physical infrastructure as well as economic and social vulnerability data), a visualization layer (the GUI interface), and a processing layer (Fig. 1).

3.1. Data layer

Physical infrastructure data (e.g., roads, schools, high density housing; Table 1) were compiled to support potential user-directed queries. Some information was obtained directly from the Province of New Brunswick's geospatial data gateway (http://www.snb.ca/geonb1/e/index-E.asp), while others were derived products (e.g., building footprints created by digitizing orthophotos).

Map layers are served using the ArcGIS Server REST API (ESRI, 2014), which provides a simple and open (though stateless) web interface to map services through a hierarchy of uniform resource locators (URLs). Other services supported by the REST API include geoprocessing services, which perform server-side geoprocessing tasks, and geometry and feature services, for drawing and interacting with geodatabase feature objects. Feature objects used in this project included locations of concern (LOC) and adaptation planning zones (APZs), discussed in Section 3.2.

The integration of economic (Section 3.1.1.) and social vulnerability information (Section 3.1.2) was an important design criteria for the CAV, as such information is normally scattered or unavailable. However, special processing was required to prepare this data.

3.1.1. Quantification of economic vulnerability

Flood damage information, based on the work of Wilson et al. (2012), was calculated for current (2000) and projected (2025, 2055, 2085 and 2100) 1-in-100 year sea levels. Damage depth curves relate the depth of floodwater to the expected severity of damage, and were obtained from the U.S. Army Corps of Engineers. The damage costs are based on flood depth, property value, and are weighted by the percentage of the building footprint flooded on any given parcel. Vehicle costs were only calculated for residential buildings that were flooded and number of vehicles was determined from Natural Resources Canada (NRCAN) assessment of NB households, and market values assessed from a review of local used vehicle prices. Total economic vulnerability was estimated by summing the value of exposed building structures, building contents, vehicle values, and (where relevant) agricultural crop values. Agricultural damages considered the value of the crop type at different times of year, and the percentage of active agricultural land flooded. It was assumed that damages to residential, commercial, and public parcels are tied to the structures on the parcels.

It should be noted that estimates of repair costs to public infrastructure (e.g., roads, bridges, culverts) were unavailable. For this reason, economic vulnerability should be treated as an underestimate of the likely damage costs.

3.1.2. Quantification of social vulnerability

Social vulnerability was assessed using a social vulnerability index (SVI) to reflect residents' relative ability to prepare, respond and recover from flooding. When creating the SVI, care was taken to ensure that the range of social vulnerabilities to flooding were reflected, that the vulnerability types were equally weighted, and that the index was easily interpretable.

King and MacGregor (2000), Cutter et al. (2000) and Wu et al. (2002) identified the types of social vulnerabilities that can make it difficult for neighbourhoods to prepare, respond and recover from flooding. Analogues of these indicators were obtained from the 2006 Canada Census (Statistics Canada), and Principal Component Analysis (PCA) was used to group similar, or correlated, indicators together. Interpretation of the PCA shows that four socially-vulnerable groups exist in New Brunswick: those with lower socioeconomic status (income poverty, lack of education and skills training, and instability in employment status), minorities and renters, elderly, and youth.

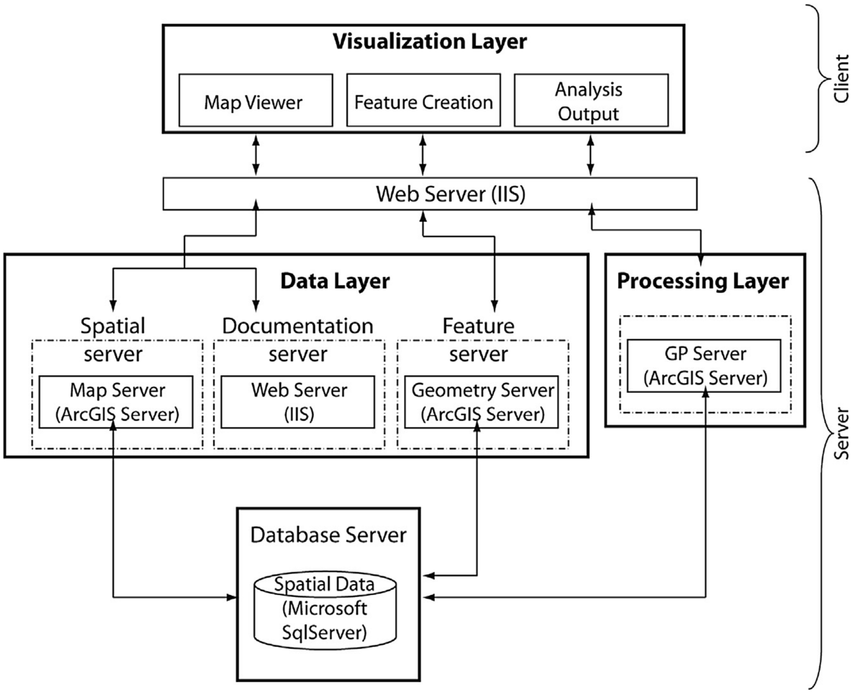


Fig. 1. System architecture of the Community Adaptation Viewer (CAV).

When creating the SVI, a single representative measure was selected from each of the 4 vulnerability groups: median income, percentage of dwellings that are rented, aged dependency (the ratio of persons over 65 to the population aged 15–65), and youth dependency (the ratio of persons under 15 to the population aged 15–65). Renters were selected instead of minorities because in the Town of Sackville renters were deemed to be more vulnerable. Each vulnerability measure was scaled out of 1 (by dividing by the provincial maximum value), and the sum of the 4 scaled measures was calculated to create the SVI. An SVI score of near to 0 means that communities are less vulnerable to flooding while an SVI score approaching 4 are more vulnerable.

Table 1
Anticipated information requirements.

Layer group	Data	Resolution/Scale	Source	Description
Dyke Vulnerability	Height	10 m	MTA GML[a]	Maximum height and elevation profile at each 10 m section of dyke. Derived from LiDAR.
	Susceptibility to erosion	10 m	MTA GML	Modelled from NDVI, proximity to water
Social Vulnerability	Social Vulnerability Index (SVI)	Dissemination Area (area containing ~500 persons)	http://www.statcan.gc.ca/	Social vulnerability obtained using Stats Canada Census Dissemination Areas
Infrastructure Vulnerability	Roads	1:10,000	RSC7[b] planning	Digitized from 2013 satellite imagery and SNB DPM
	Hospitals	0.05–10 m	SNB[c] real property attribute data	
	Seniors residences	0.05–10 m		
	High density residences	0.05–10 m	SNB	
	Building Footprints	1:5000	MTA GML	Digitzed from 2009 orthophotos
	Historic sites		Parks Canada	
	Waste treatment facility	0.05–10 m	SNB	
	Lift Station	0.05–10 m	SNB	
	School		SNB	
	Church	0.05–10 m	SNB	
	Storm water system	0.5–10 m	Town of Sackville/MTA GML	
	Rail Line	0.05–10 m	SNB	
Economic Vulnerability	Tax Assessment Values (Province of NB)	0.05–10 m	SNB	Privacy concerns require that individual properties can- not be displayed
Land Allocation	AgUse	1:10,000?	NB Dept. Aquaculture Agriculture and Fisheries	
	Zoning	0.05–10 m	RSC7 planning	
Adaptation Planning	Point of Concern (POC)			User-created during workshops
	Adaptation Planning Zone (APZ)			User-created during workshops

[a] Mount Allison University, Geospatial Modelling Lab.
[b] Regional Service Commission 7 (http://www.nbse.ca/home).
[c] Service New Brunswick, geographic information gateway (http://www.snb.ca/geonb1/e/index-E.asp).

3.2. Visualization layer

The visualization layer (Fig. 1) consists of a GUI developed using the Javascript API (Flanagan, 2011). The Javascript API is a good choice for developing client-side interfaces given that it is a language deployed throughout the world wide web and highly integrated with web browser objects (Power and Kaparthi, 2002). This relieves users of the burden of having to install and update custom software on their local workstations (Sugumaran and DeGroote, 2011). Projects such as the Dojo toolkit (www.dojotoolkit.org, Russell, 2008) extend the functionality and utility of Javascript, allowing the production of special graphical output, for instance. Dojo is used extensively by ESRI's Javascript API to govern interaction with the ArcGIS Server.

The main map viewer pane (Fig. 2) displays both a basemap, as well as any and all data layers activated by the user using check box controls housed within the "Layer Selection" tab of the accordian pane (Fig. 2). The "Basemaps" button on the task pane (Fig. 2) calls the `BasemapGallery` customized Dojo dijit (ESRI, 2014), allowing the selection of nine different basemap layers. Subsequent user feedback indicated that the use of an aerial imagery baselayer, while displaying land cover details, could be disorienting. Pan and zoom functionality is automatically built into the `Map` object class, and triggered by click and mouse wheel events.

Feature creation is launched by clicking on the appropriate icon in the feature-creation pane (Fig. 2). Users have a choice of two types of geometry: a point geometry feature (locations of concern, LOC; Fig. 3a) or two classes of areal geometry (adaptation planning zones, APZ; dyke improvement zone, DIZ; Fig. 3b). At any time users can access and edit the attribute information pertaining to that feature, or delete features altogether (Fig. 3). The `SessionID` field stores a session-specific identifier for that feature, ensuring that only features created during a single adaptation planning session are displayed in the map viewer pane. Data from other sessions are hidden, unless "all" is specified at the time of page loading.

Project metadata is exposed via the "Further Information" tab of the accordion pane, which presents a pulldown control with a fixed set of optional topics. `XMLHttpRequest` function calls are used to open simple `HTML` text files hosted on the Documentation Server (Fig. 1). For the CAV project, topics included information on sea-level projections, as well as the social vulnerability index.

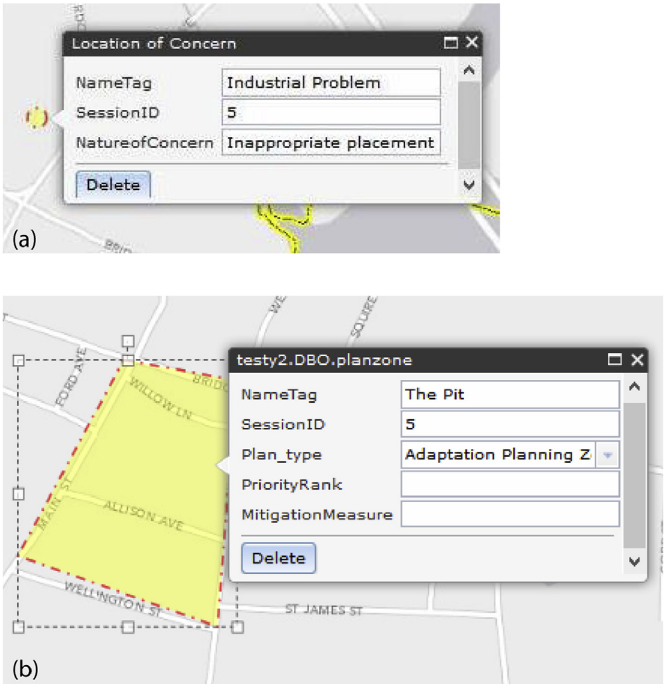
Once users have explored the map viewer and created APZ features, the "Select Planzones" button on the task pane (Fig. 2) permits the selection of one or more APZ features using an expandable window frame. "Selection" status is indicated using a broken red border and yellow shading, which corresponds to the selected geodatabase features contained within the Database server (Fig. 1). Selected features can be deselected using the "Clear Selection" button on the task pane (Fig. 2), or passed on to the Processing Layer (Fig. 1) by clicking on the "Analyze!" button (Fig. 2). Example of geoprocessing output is shown in Fig. 4. Fig. 4 (a) is a barchart widget summarizing total estimated economic vulnerability for all parcels intersecting the selected APZ features, under each of five different sea levels (Section 3.1.1.). This dijit features a mouse-over event that prints a message box of total estimated residential damages. Social vulnerability (Fig. 4b) is output simultaneously with economic vulnerability, and jointly displayed within the "Results" tab of the accordian pane (Fig. 2). At a glance, users can assess the socio-economic vulnerabilities of any set of APZ polygons.

Two other functions provided by the main user interface include a "Search" dijit in the accordian pane, and a "Print" button in the task pane. The search dijit provides a geocoder to support address lookups, while the Print button launches an Adobe compatible portable document format (.pdf) map complete with legend, scale bar, etc.

3.3. Processing layer

A web-SDSS is not intended to be a complete geoanalytical environment, and cannot replace already established geographic information systems (GIS). Nevertheless, vendors such as ESRI have exposed geoprocessing tools as web services, allowing for the execution of complicated and sophisticated geospatial analyses. Such functionality has been incorporated into the CAV, as well as some other web-SDSS, e.g., Rao et al. (2007).

Fig. 2. Schema of the main user interface.


Location of Concern

NameTag: Industrial Problem
SessionID: 5
NatureofConcern: Inappropriate placement

NameTag: The Pit
SessionID: 5
Plan_type: Adaptation Planning Z
PriorityRank:
MitigationMeasure:

Fig. 3. Text controls for editing attribute information for user-created locations of concern (a), and adaptation planning zones (b).

In effect, ArcGIS Server geoprocessing scripts are "stored procedures" which receive data dynamically at runtime. Geoprocessing tasks can be as complicated as need be and, given that they are server-side processes, tend to be quite efficient to run. Two geoprocessing tasks were created to support vulnerability analysis within the CAV: `EconVuln` and `SocVuln` (Fig. 5). Both of these geoprocessing tasks perform a spatial overlay of user-selected APZ polygons with property parcel data (stored within the Spatial server of the Data Layer, Fig. 1), tabulate economic or social vulnerability, and return the output as a result set to be parsed and printed as text and graphical information in the Results window of the Accordian pane (Fig. 2).

3.4. *Anticipated workflow during adaptation planning sessions*

Previous experience with user–software interaction suggested that typical user sessions would consist of three phases: data exploration, feature creation and annotation, and analysis of geographic patterns of social and economic vulnerability.

1. Phase 1: unstructured (but not necessarily non-systematic) data exploration. Participants expose layers as desired, and inspect regions of the map of greatest concern. There are three dimensions or properties that are likely to affect the discrimination of important patterns or groupings in the data:
   [{visible layers}, map scale, location]
   Progression may be slow in this phase depending upon the size of the map and the number of data layers to inspect. It is expected that the "information seeking mantra" of Schniederman (1996), or "overview first, zoom and filter, and then details-on-demand" constitutes a sensible approach for consideration of different data layers, in different locations, at different scales. Users can drill-down and access details as necessary.
   Other frameworks, for instance, the approach of Flax et al. (2002), could be used to guide the process of hazard identification and analysis. Depending upon the expertise and knowledge of the participant group, there may be a decision to initiate data exploration with the most familiar aspect of community vulnerability, e.g., physical infrastructure, economic damages, or social vulnerability.
2. Phase 2: feature creation and annotation. Users identify locations of concern through the feature-creation pane (Fig. 2), and provide "expert" knowledge. Planning zones may delineated at the same time, or as part of a separate process following problem identification of LOCs.
3. Phase 3: analysis of social and economic vulnerability of LOCs and assignment of relative priority rankings. Coincident with this is the discussion of mitigation opportunities for lowering risk and increasing resiliency. It is assumed, however, that further analysis of the costs and benefits, as well as social and political feasibility, will be conducted outside of the SDSS session. Such an analysis could be conducted, for instance, by independent experts or advisory committees.

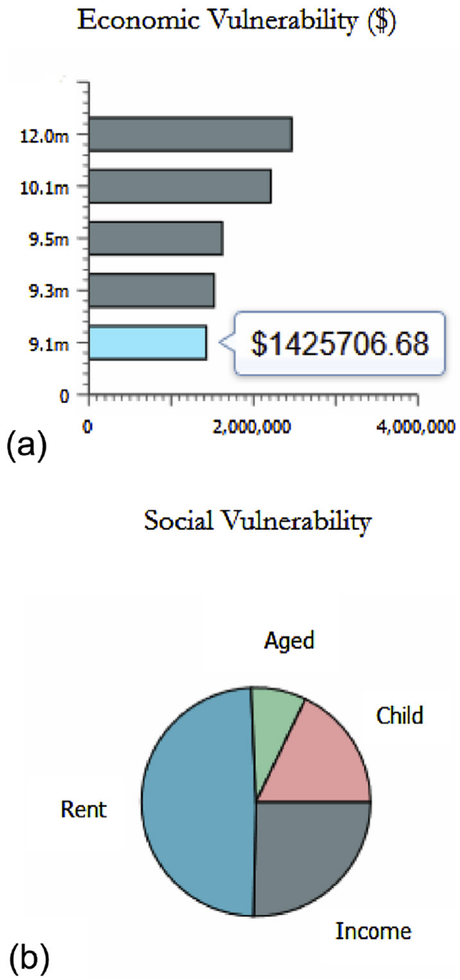


Fig. 4. Graphical output of economic (a) and social (b) vulnerability data for user-selected planing zone features.

4. Adaptation focus groups and software assessment

Six, small-group adaptation focus groups were conducted between January 20 and February 3, 2014. These sessions gathered $n = 31$ expert stakeholders from the Town of Sackville, New Brunswick, and included members of Town council, engineers and emergency measures personnel, town planners, dyke managers,

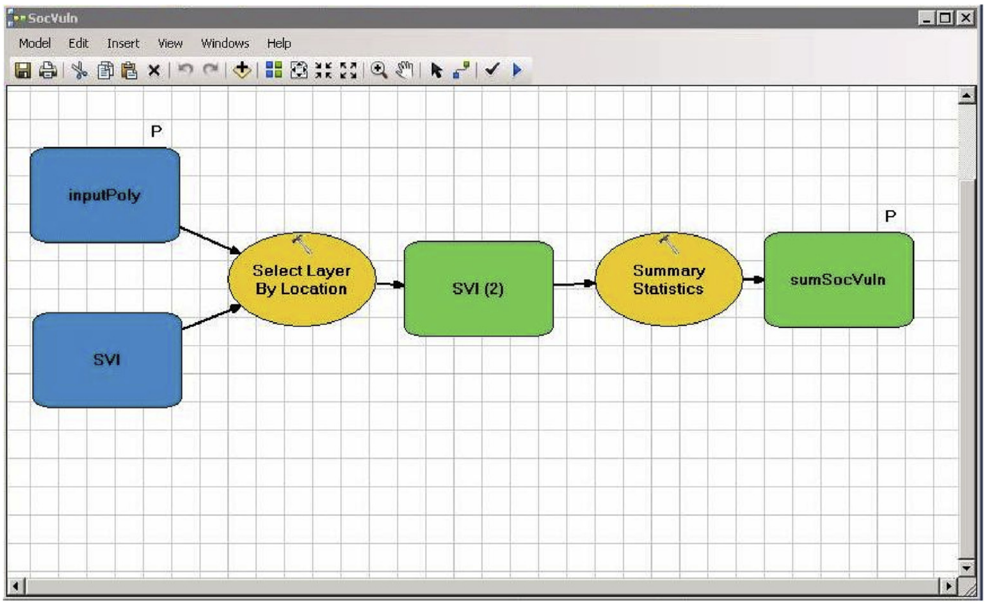


Fig. 5. Model outlining the functionality of the geoprocessing service `SocVuln`, which provides a mean summary of the social vulnerability components for land parcels intersecting the user-selected adaptation planning zone(s).

representatives from non-governmental agencies, and community service providers. Small group sessions were adopted in order to: (1) foster knowledge exchange between participants, recognizing that knowledge is, in part, socially constructed (Ramsey, 2009); (2) counterract the tendency for self-censorship in larger group settings (see Hopfer and MacEachren, 2007); and (3) gather participant feedback on the CAV software.

To expedite the three-hour sessions, the principal investigator acted as the software "chauffeur" (sensu Aggett and McColl, 2006; Jankowski et al., 2006), interacting with the toolkit as directed by participants who used laser pointers to identify locations displayed on a projector screen. This has the advantage of shielding users from the technical details of using the software, and allowed them to focus attention on aspects of community vulnerability. Initially, overviews of all data layers was provided, followed by identification of locations of concern (LOCs), delineation of special adaptation planning zones (APZs), and analysis of the associated economic and social vulnerabilities. Later sessions commenced using the data layers most familiar or interesting to participants, which served as a more effective "ice breaker" and improved the willingness of participants to volunteer information.

Groups identified common as well as unique locations, and discussed different implications for each (Fig. 6). Features included vulnerable sections of dykes and aboiteaux; need for maintenance of drainage ditches; agricultural impacts; commercial and industrial impacts; interruption to community and emergency services; flooded neighbourhoods and neighbourhoods temporarily isolated as a result of road flooding; concerns about land use decisions; questions about the resilience of lift stations and the sewage network; vulnerable historic sites; and, vulnerable populations such as children and elderly. Focus groups identified five main adaptation planning zones, with a total economic exposure of $6,470,000 (CDN) under the current 10% chance per year, 8.9 m flood scenario. While much attention was payed to the 8.9 m flood risk, more severe scenarios and the associated economic damage costs were also examined (see Fig. 4a). For instance, under a 10.1 m flood depth (4% chance per year by 2100), economic damage costs for the five APZs rose to $13,475,000 (CDN). The current tax assessed value of the parcels in the APZs was about $21.6 million (CDN).

A second phase of consultation took the form of a single plenary session on February 18, 2014. The chief findings included an assessment of the CAV toolkit (Fig. 7, $n = 28$ respondents), new information about flood-risk tolerance, and a set of key recommendations for lowering community vulnerability. Focus group particpants reported high levels of satisfaction with aesthetic (Fig. 7b) and navigational aspects of the CAV (Fig. 7d), and evaluated it to be both easy to learn (Fig. 7c) and easy to understand (Fig. 7a). Fewer focus group participants reported the menu to be "friendly" to understand (Fig. 7e), and there were aspects of the flood risk problem that some participants felt were not addressed (Fig. 7f): provisioning of information about inland flooding areas, locations of wetlands, finer topographical information, more information about the sewage collection system, support for photographs, and information about flood depths.

With regards to flood-risk tolerance, a survey administered at the end of the plenary session ($n = 16$ respondents) indicated that even a moderate 1% chance (1-in-100 year) flood event deters slightly over an estimated 70% of respondents. By the time one considers flood events of 1-in-50 years return frequency (2% chance per year), approximately 90% of respondents indicated a willingness to relocate. This suggests that 1-in-10 year flood maps under represent people's true sensitivity to risk.

5. Discussion

5.1. *SDSS as a means to explore climate change risk*

Given the potential severity of future climate change impacts (IPCC report WGII 2014) there is clearly a pressing need for proactive, systematic, community-level assessment of climate change vulnerability (Flax et al., 2002). According to Flax et al. (2002), recognition of the importance of this process led FEMA to tie disaster-relief funding to state-level submission of risk mitigation plans. Examples such as the CAV, the Tyndall Coastal Simulator (Mokrech et al., 2011), the IAMM model (Haasnoot et al., 2014), and the EverVIEW Data Viewer (Romañach et al., 2014) illustrate how SDSS software tools can "fast track" the preparation of such plans by aiding visualization, knowledge generation, and analysis of vulnerability, and

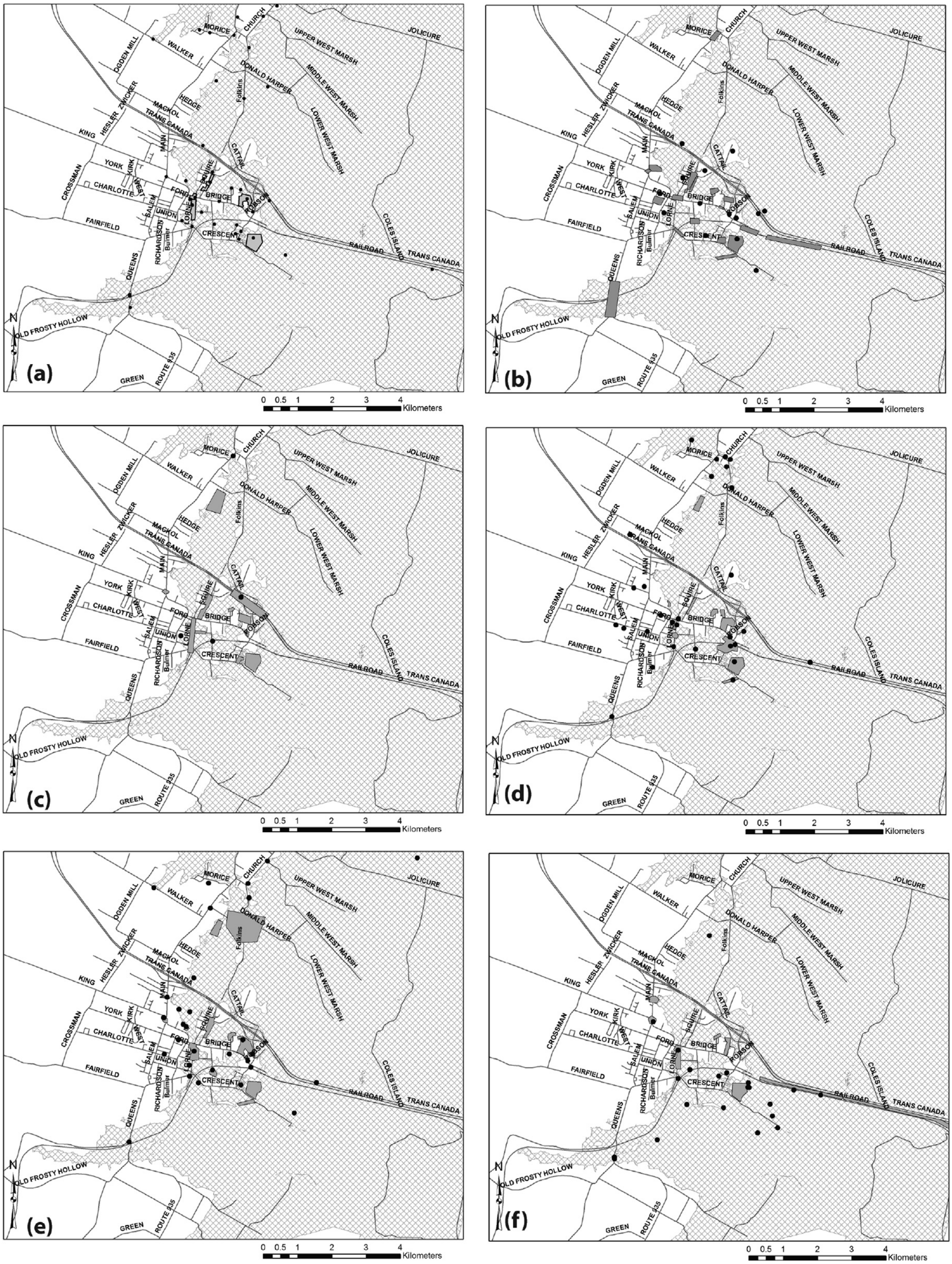


Fig. 6. Locations of concern (LOCs, filled circles) and adaptation planning zones (APZs, shaded polygons) identified during six adaptation planning sessions (a–e). Also indicated is the possible extent of an 8.9 m flood (CGVD28 vertical datum, hatched area).

can work within other pre-existing frameworks. Empirical studies confirm that map-based data reduces the cognitive load on users and leads to faster, more efficient decision making (Crossland et al., 1995; Keenan, 2006). In general, the more risk-data available the greater the opportunity to pinpoint high-risk areas (Flax et al., 2002).

SDSS software can facilitate adaptation planning in other ways. As elaborated by Moss et al. (2013), when decision makers confront adaptation challenges, they tend to be bound by considerations of cost, feasibility, social acceptance, tradition, and other factors. This immediately inhibits creative problem solving.

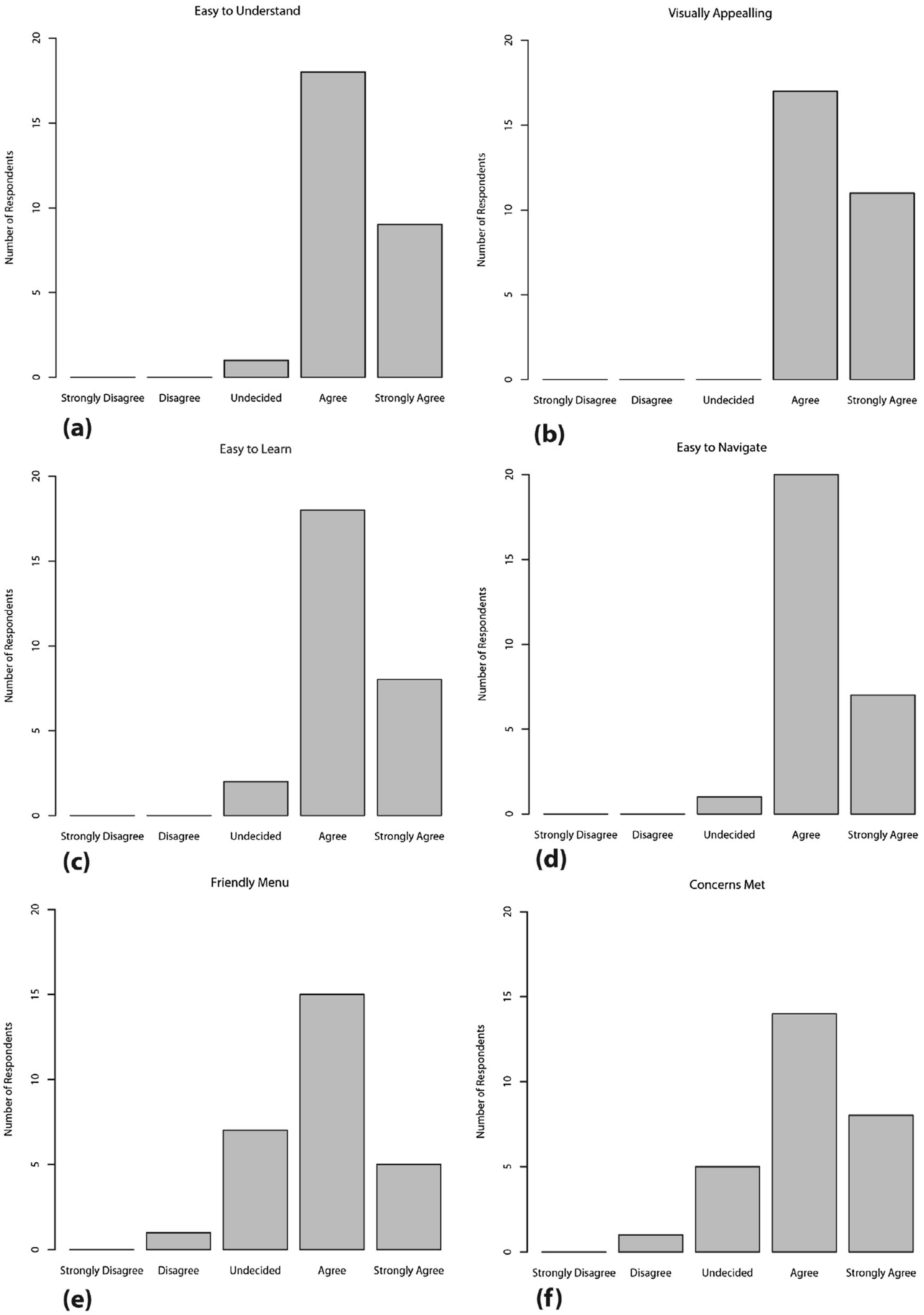


Fig. 7. Assessment of CAV software by focus group participants ($n = 28$ responses).

Can SDSS help to close the “usability gap” of scientific information and help decision makers whose primary concerns are fixated on other matters? Before answering that question we need to consider the processes an exploratory software tool can support.

Koua and Kraak (2004) consider there to be three key exploratory tasks for knowledge construction. The first set of tasks involves categorization and classification, such that attention is drawn to clusters or trends. Perception of these patterns may be facilitated by different perspectives, e.g., 2D and 3D layers, animations. The CAV case study, along with examples such as Rosenzweig et al. (2011) illustrates that interactive visualization of vulnerable infrastructure, with risk layers superimposed on the same map, aids spatial reasoning and is a rapid and efficient way to identify vulnerable locations. In the case of the CAV, focus group participants consistently identified some of the vulnerabilities (Fig. 6). For example, the sewage lagoon and sections of highway potentially inundated under an 8.9 m flood event were uniformly flagged by participants. Group consensus may naturally emerge under these conditions.

In addition to supporting user-driven queries about which buildings or features lie within the flood risk zone, users could upload their own knowledge. A unique functionality of the CAV is its use of two levels of annotation (LOCs and APZs), allowing users to either "pin" specific locations of concern or classify entire areas by delineating them as APZ polygons. For instance, participants who were personally familiar with eroded sections of dyke identified those locations on the map, leading to their digitization and, hence, their documentation. Participants benefited from the knowledge exchange, which deepened overall flood-risk awareness of the group.

Koua and Kraak's (2004) second exploratory task ("comparison") was facilitated through the social and economic vulnerability output provided by the Processing Layer (Fig. 1). CAV participants gained immediate feedback on which APZ polygons were most at-risk, thereby ensuring that subsequent discussion was informed by a rational appraisal of the evidence. The CAV project demonstrates how the use of "stored procedures" and pre-processed data can support rapid assessment of complex, multi-dimensional information. From a usability perspective, it is important for an SDSS to show high responsivity – sufficiently so that it can act as the motivation for development work in the first place. For example, Haasnoot et al. (2014) built an integrative assessment model largely to produce a more decision "friendly" version of a more complex model.

The "reflective" aspect of exploratory visualization (evaluation, integration, generalization) occurs naturally when general statements about vulnerability can be made. For the CAV, most locations of concern could either be classified as vulnerable to flooding or vulnerable to isolation.

To render SDSS tools effective in collaborative settings, Ramsey (2009) recommends making SDSS tools as flexible as possible. This constitutes an important departure from the knowledge-DSS (see Power and Kaparthi, 2002) applications of Best et al., 2007 and Rao et al., 2007, where design goals focused on delivering outputs from complex, custom-designed algorithms applied to well-structured problems. Many aspects of environmental management are qualitative, not quantitative, and involve discursive elements surrounding social and political factors which may, at first blush, appear to be external to the problem domain. Map visualization should be pursued for those aspects of the problem amenable to spatialization; when they cannot, other media (e.g., annotations, text) should be used to capture and represent that knowledge (Ramsey, 2009). This philosophy was pursued during CAV development, though emphasis was placed on two-dimensional, map-based representation. Previous work (Lieske et al., 2014) identified other forms of visualization (e.g., 3D animations) to be important vehicles for risk communication, but given the high level of problem familiarity of the participants in this project these tools were not deemed worth the time to develop. Nevertheless, depending upon the intended audience, other modes of representation may be effective for communicating particular aspects of the problem domain (though see Lieske, 2012 for a caveat regarding the limitations associated with presenting complex visualizations to "casual users").

5.2. Advantages of the CAV

Key advantages of the CAV include its ease of use, its open-ended feature creation capacity, and its support for rapid assessment of economic and social vulnerability. It's ease of use was facilitated through the provision of a centralized, web-based user interface, eliminating the need for client-side software installation. Updates to the CAV can be made by developers without the need to ship updates. The open-ended and qualitative nature of the assessment of many climate change risks was suitably addressed through two levels of feature creation: locations of concern, and candidate adaptation zones. As the software was designed with multiple groups of stakeholders in mind, all users are free to identify locations and areas of concern to them. In the Tantramar case study, locations and areas were combined across different stakeholder groups to form "concensus" summaries.

The open-ended nature of the system, i.e., support for user-contributed information parallel to visualization of quantitative spatial data (along with associated supporting "metadata"), and an easy-to-use and intuitive interface, lent flexibility to the software and allowed it to be applied in new ways. For instance, project participants suggested a wide range of novel applications for the CAV, such as: identification of areas that could be used as flood buffers for water retention, as a teaching tool for schools, or as a means to map vulnerable members of the community (Table 2). Given the fact that SDSS failures tend to stem from sociological rather than technological causes (Rivington et al., 2007), the healthy range of potential applications for the CAV suggests that it possesses a requisite level of sophistication, flexibility and ease-of-use to ensure relevance for a range of potential users.

5.3. Disadvantages of the CAV

Key disadvantages of the CAV are a lack of support for multi-criteria decision making, and a reliance on pre-processed risk, social, and economic damages information. While the CAV supported simple priority ranking, e.g., attribution of an integer rank to adaptation planning zones (Fig. 3b), participants in the case study were hesitant to volunteer values. This suggests that a different prioritization process was necessary to support this activity. Provision of an "analytical hierarchical process" (e.g., Jankowski et al., 1997; Karnatak et al., 2007) may facilitate prioritization, with individual APZs being compared in a pair-wise manner to help assign relative importance. The work of Giupponi et al. (2013) illustrates the application of a number of techniques for risk ranking, though it should be noted that development of these weights can be demanding and require extensive interaction with stakeholders. More simply, provisioning of an anonymous voting system may also have encouraged participation. However, given the complexity of multi-stakeholder, multi-dimensional problems such as community vulnerability to climate change, there may be no simple approach to setting priorities (Ramsey, 2009).

As the CAV is built on a thin-client architecture, wide deployment of the CAV requires an institutional commitment to host the necessary web services. The Tantramar case study made extensive use of the high-quality topographic, flood-risk, and other information made available as part of an earlier infrastructure investment by Natural Resources Canada and the Canadian provinces. While this ensured that the highest quality data was incorporated within the CAV, it also limited the geographic generalizability of the software: analysis can only proceed where risk and vulnerability layers are available, and when they have been pre-processed and hosted on a map server. As a future development goal, preparatory data processing tools could be created to perform some of this analysis in advance.

Table 2
Potential applications of the CAV SDSS software, as suggested by project participants.

- ♣ Use by private citizens to check when Town Council wants to approve a project; the tool could allow citizens to be more aware of Town decisions and enable them to lobby for by-law changes.
- ♣ To identify areas that could be rehabilitated into flood buffers.
- ♣ Use by NGOs to look at vulnerable areas and focus work on outreach with vulnerable community members.
- ♣ The tool could be used as a promotional and awareness tool for communities and therefore, as an educational resource.
- ♣ To see where flood boundaries are and what will be affected.
- ♣ For future program planning.
- ♣ For emergency planning, e.g., evacuation or [placement of] reception centre.
- ♣ For land use planning and development.
- ♣ To lead discussions and to stimulate conversation.
- ♣ To help when buying or selling land or houses.
- ♣ To help make elected officials aware of potential flooding.
- ♣ To help municipal councils and planning commissions in creating adaptation plans.
- ♣ When constructing infrastructure and determining where to invest in infrastructure repairs or upgrades.
- ♣ To evaluate roadway systems.
- ♣ To evaluate how many homes and businesses may be affected during an event.
- ♣ For public presentations and meetings.
- ♣ For calculating risk.
- ♣ To introduce flood issues to new communities beyond Sackville.
- ♣ As a teaching tool
- ♣ For advance warnings during major weather events, such as storm surges, rainfall, high winds, and high tides.
- ♣ To plot people in the community that use home care.
- ♣ To understand the risks involved with flooding in a particular area of town or on [Mount Allison University] campus.

5.4. *General barriers to community adaptation*

Successful identification and prioritization of candidate adaptation measures may not, in itself, lead to implementation. Individual communities may not have access to the resources necessary to carry out significant adaptation measures, i.e., those with greatest chance of lowering community vulnerability. In the case study, relocation of the core of vulnerable residences via land acquisition was estimated to exceed $21 million (CDN). Participants concluded that even if such an initiative could be enacted, other system components would remain vulnerable, e.g., the travel corridor comprised of the Trans-Canada Highway and CN railway, and local agricultural activity. Recognition of these linkages led to the conclusion that the existing dyke system, with a relatively modest investment of approximately $2.5 million (CDN), was an efficient option for counter-acting sea level rise in the short term and protecting the range of community assets. Over the long-term (approximately 40 years), limitations in the capacity to raise the height of the dykes without major re-engineering would likely nullify their capacity to withstand future sea levels. As a consequence of these findings, participants quickly identified pro-active emergency response and land use planning as vital to limiting and lowering community vulnerability in the interim.

While the case study involved expert stakeholders, i.e., those whose professional responsibilities or areas of knowledge directly pertained to coastal flood risk reduction, the CAV could just as easily been used as an outreach and information gathering tool and addressed a wider cross-section of the general public. In fact, it has been argued that fostering multi-stakeholder, iterative, consultative discussions are a good remedy for preventing decision making processes becoming unmanageable or contentious (Jankowski et al., 2006; Nyerges et al., 2006). GIS and the Web hold great potential for public use (Kingston et al., 2000). Rather than attempt to force top-down, “winner vs. loser” models, SDSS has the potential to involve everyone in risk appraisal visualization, possibly resulting in more equitable, consensus-based sets of recommendations endorsed by most or all stakeholders (Flax et al., 2002; Nyerges et al., 2006).

6. Conclusions

Recent SDSS research, of which this project is a part, demonstrates how integrative assessments of climate-change related risks and vulnerabilities can provide valuable insights to decision makers. In reviewing the challenges and best practises of environmental decision support systems, McIntosh et al. (2011) single out failure to adopt as a key challenge, but also suggest that development of these tools should proceed as part of a participatory process. In the case of the CAV, development was only partially user-centred, but was supported by input from stakeholders before the project even began. This provided critical insight into the information gaps identified by the users, for example, the ability to assess the economic damage costs and social vulnerability for different areas within the town, and helped set the high-level development goals for the project. Ease of use is also a quality of a successful SDSS, which the CAV achieved by adopting a responsive, attractive interface with all functionality accessible from a central web page.

While the case study reported here was for a small municipality, the CAV software can be applied at any scale, for any hazard for which spatial information is available. The CAV was demonstrated to be a rich environment for spatial analysis, allowing submission of geographically-specific knowledge as well as rapid assessment of social and economic vulnerability at particular locations. Such a process supports objective and rational risk appraisal and stands to better inform stakeholders. Given the pressing nature of climate change, and the long time frame required to fulfil some adaptation plans, it is crucial that communities utilize all tools at their disposal to immediately develop and initiate adaptation strategies.

Acknowledgements

The author acknowledges the financial support of the New Brunswick Environmental Trust Fund (ETF Grant 130278) and the Social Sciences and Humanities Research Council (SSHRC) Small Universities Grant (Grant 681-2011-0003). The author acknowledges the data management provided by J. Bornemann, and facilitation of community focus groups by L.A. Roness and E.A. Phillips. The author is grateful to A. Hamilton–Wright and two anonymous reviewers for kindly reviewing an earlier draft of the manuscript The author also thanks the participants who generously donated their time to evaluate the CAV, while also providing important flood adaptation recommendations for the Sackville community. Lastly, the author acknowledges the many software developers who have contributed the free and open-source software libraries used in this project.

References

Aggett, G., McColl, C., 2006. Evaluating decision support systems for PPGIS applications. Cartogr. Geogr. Inf. Sci. 33, 77–92.

Andrienko, N., Andrienko, G., 2006. Exploratory Analysis of Spatial and Temporal Data: a Systematic Approach. Springer, New York.

Andrienko, G., Andrienko, N., Jankowski, P., Keim, D., Kraak, M.-J., MacEachren, A., Wrobel, S., 2007. Geovisual analytics for spatial decision support: setting the research agenda. Int. J. Geogr. Inf. Sci. 21, 839–857.

Bhargava, H.K., Power, D.J., Sun, D., 2007. Progress in web-based decision support technologies. Decis. Support Syst. 43, 1083–1095.

Best, B.D., Halpin, P.N., Fukioka, E., Read, A.J., Qian, S.S., Hazen, L.J., Schick, R.S., 2007. Geospatial web services within a scientific workflow: predicting marine mammal habitats in a dynamic environment. Ecol. Inf. 2, 210–223.

Chen, C., 2005. Top ten unsolved information visualization problems. IEEE Comput. Graph. Appl. 12–16. July/August.

Chen, M., Liou, Y., Wang, C.-W., Fan, Y.-W., Chi, Y.-P.J., 2007. TeamSpirit: design, implementation, and evaluation of a web-based group decision support system. Decis. Support Syst. 43, 1186–1202.

Crossland, M.D., Wynne, B.E., Perkins, W.C., 1995. Spatial decision support systems: an overview of technology and a test of efficacy. Decis. Support Syst. 14, 219–235.

Cutter, S.L., Mitchell, J.T., Scott, M.S., 2000. Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina. Annu. Assoc. Am. Geogr. 90, 713–737.

Eppler, M.J., Aeschimann, M., 2009. A systematic framework for risk visualization in risk management and communication. Risk Manag. 11, 67–89.

ESRI, 2014. ArcGIS Server. http://www.esri.com/software/arcgis/arcgisserver (Downloaded May 2014).

Flanagan, D., 2011. Javascript: the Definitive Guide. O'Reilly, Sebastopol, California.

Flax, L., Jackson, R., Stein, D., 2002. Community vulnerability assessment tool methodology. Nat. Hazards Rev. 3, 163–176.

Füssel, H.-M., 2007. Vulnerability: a generally applicable conceptual framework for climate change research. Glob. Environ. Change 17, 155–167.

Giupponi, C., Giove, S., Giannini, V., 2013. A dynamic assessment tool for exploring and communicating vulnerability to floods and climate change. Environ. Model. Softw. 44, 136–147.

Gulliksen, J., Bengt, G., Boivie, I., Blomkvist, S., Perrson, J., Cajander, Å., 2003. Key principles for user-centrered systems design. Behav. Inf. Technol. 22, 397–409.

Haasnoot, M., van Deursen, W.P.A., Guillaume, J.H.A., Kwakkel, J.H., van Beek, E., Middelkoop, H., 2014. Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways. Environ. Model. Softw. 60, 99–120.

Hebb, A., Mortsch, L., 2007. Floods: Mapping Vulnerability in the Upper Thames Watershed under a Changing Climate. http://zerofootprint.uwaterloo.ca/research/aird/aird_pub/Upper_Thames_Vulnerability_Mapping_Final_Report.pdf (Downloaded Jan 16, 2014).

Hopfer, S., MacEachren, A.M., 2007. Leveraging the potential of geospatial annotations for collaboration: a communication theory perspective. Int. J. Geogr. Inf. Sci. 21, 921–934.

IPCC WGII AR5, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Summary for Policymaker. http://ipcc-wg2.gov/AR5/images/uploads/IPCC_WG2AR5_SPM_Approved.pdf (Downloaded May, 2014).

Jankowski, P., Nyerges, T.L., Smith, A., Morre, T.J., Horvath, E., 1997. Spatial group choice: a tool for collaborative spatial decision-making. Int. J. Geogr. Inf. Sci. 11, 577–602.

Jankowski, P., Nyerges, T., Robischon, S., Ramsey, K., Tuthill, D., 2006. Design considerations and evaluation of a collaborative, spatio-temporal decision support system. Trans. GIS 10, 335–354.

Karnatak, H.C., Saran, S., Bhatia, K., Roy, P.S., 2007. Multicriteria spatial decision analysis in web GIS environment. Geoinformatica 11, 407–429.

Keenan, P.B., 2006. Spatial decision support systems: a coming of age. Control Cybern. 35 (1).

King, D., MacGregor, C., 2000. Using social indicators to measure community vulnerability to natural hazards. Aust. J. Emerg. Manag. 15 (3), 52–57.

Kingston, R., Carver, S., Evans, A., Turton, I., 2000. Web-based public participation geographical information systems: an aid to local environmental decision-making. Comput. Environ. Urban Syst. 24, 109–125.

Koua, E.L., Kraak, M.-J., 2004. A useability framework for the design and evaluation of an exploratory geovisualization environment. In: Proceedings of the Eighth International Conference on Information Visualization (IV'04). http://www.geovista.psu.edu/publications/2004/IEEEpaperUsability_Koua.pdf (Downloaded May, 2014).

Lieske, D.J., 2012. Towards a framework for designing spatial and non-spatial visualizations for communicating climate change risks. Geomatica 66, 255–265.

Lieske, D.J., Wade, T., Roness, L.A., 2014. Climate change awareness and strategies for communicating the risk of coastal flooding: a Canadian Maritime case example. Estuar. Coast. Shelf Sci. 140, 83–94.

Maguire, M., 2001. Methods to support human-centred design. Int. J. Hum. Comput. Stud. 55, 587–634.

McIntosh, B.S., Ascough II, J.C., Twery, M., Chew, J., Elmahdi, A., Haase, D., Harou, J.J., Hepting, D., Cuddy, S., Jakeman, A.J., Chen, S., Kassahun, A., Lautenbach, S., Matthews, K., Merritt, W., Quinn, N.W.T., Rodriguez-Roda, I., Sieber, S., Stavenga, M., Sulis, A., Ticehurst, J., Volk, M., Wrobel, M., van Delden, H., El-Sawah, S., Rizzoli, A., Voinov, A., 2011. Environmental decision support systems (EDSS) development – challenges and best practices. Environ. Model. Softw. 26, 1389–1402.

Mennis, J., Peuquet, D.J., 2003. The role of knowledge representation in geographic knowledge discovery: a case study. Trans. GIS 7, 371–391.

Mokrech, M., Hanson, S., Nicholls, R.J., Wolf, J., Walkden, M., Fontaine, C.M., Nicholson-Cole, S., Jude, S.R., Leake, J., Stansby, P., Watkinson, A.R., Rounsevell, M.D.A., Lowe, J.A., Hall, J.W., 2011. The Tyndall coastal simulator. J. Coast. Conserv. 15, 325–335.

Moss, et al., 2013. Hell and high water: practice-relevant adaptation science. Science 342, 696–698.

National Research Council, 2006. Facing Hazards and Disasters: Understanding the Human Dimensions. National Academies Press, Washington, D.C.

Nyerges, T., Jankowski, P., Tuthill, D., Ramsey, K., 2006. Collaborative water resource decision support: results of a field experiment. Ann. Am. Assoc. Geogr. 96, 699–725.

Padgham, L., Hunter, S., Singh, S., 2013. Exploring the Adaptive Capacity of Emergency Management Using Agent Based Modelling. National Climate Change Adaptation Research Facility, Gold Coast, Australia.

Peuquet, D.J., Kraak, M.-J., 2002. Geobrowsing: creative thinking and knowledge discovery using geographic visualization. Inf. Vis. 1, 80–91.

Power, D.J., Kaparthi, S., 2002. Building web-based decision support systems. Stud. Inf. Control 11, 291–302.

Ramsey, K., 2009. GIS, modeling, and politics: on the tensions of collaborative decision support. J. Environ. Manag. 90, 1972–1980.

Rao, M., Fan, G., Thomas, J., Cherian, G., Chudiwale, V., Awawdeh, M., 2007. A web-based GIS decision support system for managing and planning USDA's Conservation Reserve Program (CRP). Environ. Model. Softw. 22, 1270–1280.

Rinner, C., 2003. Web-based spatial decision support: status and research directions. J. Geogr. Inf. Decis. Anal. 7, 14–31.

Risbey, J., Kandlikar, M., Dowlatabadi, H., Graetz, D., 1999. Scale, context, and decision making in agricultural adaptation to climate variability and change. Mitig. Adapt. Strateg. Glob. Change 4, 137–165.

Rivington, M., Matthews, K.B., Bellocchi, G., Buchan, K., Stöckle, C.O., Donatelli, M., 2007. An integrated assessment approach to conduct analyses of climate change impacts on whole-farm systems. Environ. Model. Softw. 27, 202–210.

Romañach, S.S., McKelvy, M., Conzelmann, C., Suir, K., 2014. A visualization tool to support decision making in environmental and biological planning. Environ. Model. Softw. 62, 221–229.

Roness, L.A., 2013. New Brunswick climate Change Communication Needs Assessment: Expanding the Tantramar Map Viewer. http://arcgis.mta.ca/docs/Tantramar%20Viewer%20Project%20-%20Report%20-%20FINAL.pdf [downloaded 24 April 2014].

Rosenzweig, C., Solecki, W.D., Blake, R., Bowman, M., Faris, C., Gornitz, V., Horton, R., Jacob, K., LeBlanc, A., Leichenko, R., Linkin, M., Major, D., O'Grady, M., Patrick, L., Sussman, E., Yohe, G., Zimmerman, R., 2011. Clim. Change 106, 93–127.

Russell, M.A., 2008. Dojo: the Definitive Guide. O'Reilly, Sebastopol, California.

Schniederman, B., 1996. The eyes have it: a task by data type taxonomy for information visualization. In: Proceedings of Visual Languages 96.

Strasser, U., Vilsmaier, U., Prettenhaler, F., Marke, T., Steiger, R., Damm, A., Hanzer, F., Wilcke, R.A.I., Stötter, J., 2014. Coupled component modelling for inter- and transdisciplinary climate change impact research: dimensions of integration and examples of interface design. Environ. Model. Softw. 60, 180–187.

Sugumaran, R., DeGroote, J., 2011. Spatial Decision Support Systems: Principles and Practices. CRC Press.

Wan, Z., Hong, Y., Khan, S., Gourley, J., Flamig, Z., Kirschbaum, D., Tang, G., 2014. A cloud-based global flood disaster community cyber-infrastructure: development and demonstration. Environ. Model. Softw. 58, 86–94.

Wilby, R.L., Keenan, R., 2012. Adapting to flood risk under climate change. Prog. Phys. Geogr. 36, 348–378.

Wilson, J., Trenholm, R., Bornemann, J., Lieske, D., 2012. Forecasting Economic Damages from Storm Surge Flooding: a Case Study in the Tantramar Region of New Brunswick. http://arcgis.mta.ca/docs/ForecastingEconomicDamagesfromTantramarStormSurgeFlooding.pdf (Downloaded May, 2014).

Wu, S.-Y., Yarnal, B., Fisher, A., 2002. Vulnerability of coastal communities to sea-level rise: a case study of Cape May County, New Jersey, USA. Clim. Res. 22, 255–270.