International Environmental Modelling and Software Society (iEMSs)
7th Intl. Congress on Env. Modelling and Software, San Diego, CA, USA,
Daniel P. Ames, Nigel W.T. Quinn and Andrea E. Rizzoli (Eds.)
http://www.iemss.org/society/index.php/iemss-2014-proceedings

GIS-based environmental modeling with tangible interaction and dynamic visualization

Anna Petrasova [a], **Brendan Harmon**[b], **Vaclav Petras**[a] **and Helena Mitasova**[a]

[a] *Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Campus Box 8208, Raleigh, North Carolina, USA (akratoc@ncsu.edu, vpetras@ncsu.edu, hmitaso@ncsu.edu)*

[b] *College of Design, North Carolina State University, Raleigh, North Carolina, USA (baharmon@ncsu.edu)*

Abstract: We present a new, affordable version of TanGeoMS, a tangible geospatial modeling and visualization system designed for collaboratively exploring how terrain change impacts landscape processes. It couples a physical, three-dimensional model of a landscape with geospatial modeling and analysis through a cycle of scanning and projection. Multiple users can modify the physical model by hand while it is being scanned; by sculpting the model they generate input for modeling of geophysical processes. The modeling results are then visualized by projecting images or animations back on the physical model. This feedback loop is an intuitive way to evaluate the impacts of different scenarios including anthropogenic and natural landscape change. Integration with GRASS GIS, a free and open source geographic information system, provides TanGeoMS with a variety of easily accessible geospatial analysis and modeling tools. To demonstrate the environmental modeling applications of TanGeoMS, we will demonstrate how development can be planned based on feedback from landscape processes such as hydrologic simulation and wildfire modeling with variable fuel distribution.

Keywords: tangible user interface; landscape process modeling; visualization; GRASS GIS; Kinect

1 INTRODUCTION

Landscape has a major influence on physical processes such as water flow and sediment transport. It affects, both directly and indirectly, how we make decisions about development, transportation infrastructure and agriculture. It is, therefore, crucial – not only for scientists, but also for decision-makers who may not have a strong background in the natural sciences – to understand the often unexpected impacts of changes to the landscape. Complex computational models are used to study the impact of landscape change; it can be relatively unintuitive to work with these models because we are separated from our data by multiple layers of abstraction when using a mouse, keyboard and digital display. With tangible user interfaces (TUIs), however, we can directly, haptically interact with a physical representation of digital data. By coupling representation and input, we can more directly, more intuitively interact with our data [Ishii and Ullmer, 1997]. By linking physical models with digital models, TUIs can make environmental modeling more intuitive and scientific representations more engaging. A TUI can be used, for example, to couple a physical model of terrain with its digital elevation model (DEM) [Piper et al., 2002; Kreylos, 2013].

The Tangible Geospatial Modeling System [Mitasova et al., 2006; Tateosian et al., 2010] extends the idea of a TUI that links a physical, malleable terrain model with its digital elevation model by integrating a GIS to broaden the capabilities of the system [Ratti et al., 2004]. GIS offers a set of ready-to-use tools for different types of geospatial analyses and simulations, as well as an interface for visualization. Editing a digital elevation model in a GIS or CAD (computer-aided design) program requires specialized skills and can be tedious even for experts. However, by modifying a physical model instead of its digital representation, users can experiment with different scenarios more intuitively and with much greater ease. Once the modified model is scanned and imported into GIS, and the analysis is performed, the result is projected back on the model to be evaluated. Users are encouraged to iteratively explore a variety of scenarios to reveal the impacts of modifying terrain and then decide upon the most suitable design. While data for real-world locations and the desired analyses must prepared beforehand by a GIS expert, the end users do not need to have any prior experience with GIS thanks to the simplicity of the tangible interface.

In this article, we present a new, improved version of TanGeoMS. Drawbacks of the first TanGeoMS prototype include the cost and weight of the equipment, the difficulties in setting up the system, and the lengthy response time. The substantial lag time between interaction and visualization detracted from the intuitive nature of the process and impacted the number of scenarios users would test. Our goal is to enhance intuition and learning, encourage and stimulate creativity and make the system more accessible. Therefore, we developed a new, more flexible, affordable version of TanGeoMS capable of real-time response and dynamic visualization. Since the feedback loop of modifying, scanning, computing and projecting is the most important feature of TanGeoMS, we focused on automating the whole process so that it could run in real-time. With an automated workflow, users would be able to change the physical model and get feedback quickly without having to manually run any processing. We hoped this fast feedback loop would encourage people to experiment more as it would be very simple to test numerous scenarios.

2 Methods

In this section we first describe the physical setup for TanGeoMS, including different types of physical models. Then we discuss the software components and the workflow for modeling with real-time response.

2.1 Physical setup

The new setup consists of 4 primary components: *(a)* a physical model that can be modified by a user, *(b)* a 3D scanning device, *(c)* a projector and *(d)* a computer with GIS software and additional software that connects all the components together. The physical model, laid on a table, is scanned by the scanning device mounted above. When the scan is imported into the GIS software and processed, the projector projects the resulting image or animation directly onto the modified physical model so that the results are put into the context of the modifications to the model.

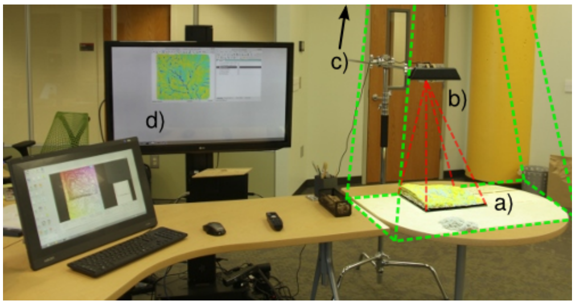
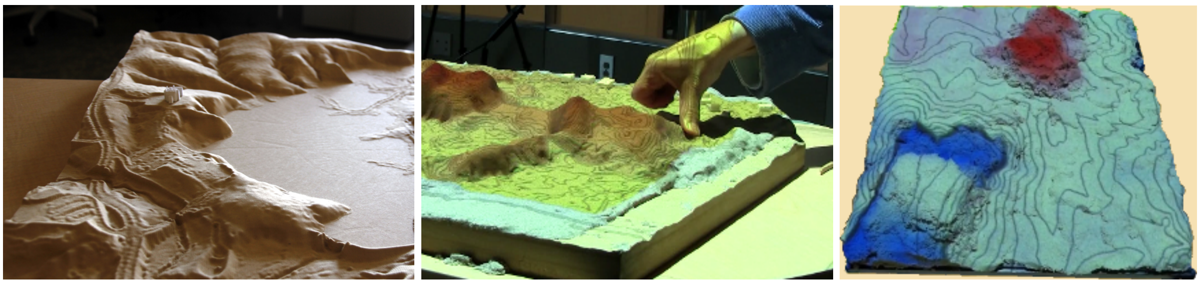


Figure 1. Physical setup: a) physical model; b) 3D scanner; c) ceiling mounted projector; d) computer with GIS software.

We use the Microsoft Kinect for Windows scanner to acquire a 3D scan of the physical model. Our new, updated TanGeoMS is now affordable since the Kinect scanner is much less expensive than the 3D laser scanner that we had previously used. Furthermore, this small, lightweight scanner is highly portable and can be easily mounted on a stand. Given the scanner's limited angular field of view – 43° vertical by 57° horizontal – the height of the scanner above the physical model depends upon the size of the model. For smaller models (∼40 cm diagonally), the scanner should be mounted ∼0.5 m above the model to get a reasonable resolution. We scan with 2 mm horizontal and vertical resolution, however the actual precision is lower due to the noise caused by the scanner. Scanning resolution deteriorates with increasing distance from the model. Therefore, the size of the physical model is limited. We have found that a model size of ∼70 cm diagonally is ideal for larger models. The Kinect scanner is connected to the computer as well as the projector. While we use a ceiling-mounted projector, the projector could also be mounted on a stand.

Initially, we built models by stacking layers of foam board cut along projected contours and then covered them with a layer of modeling clay [Mitasova et al., 2006; Tateosian et al., 2010]. Since this method required a lot of manual work, we experimented with different approaches and materials. When building models manually, we now use a sand enriched with a polymer since it is easy to sculpt, sticks together and holds its form and is unaffected by humidity. We can also build models using automated processes such as computer numerical control (CNC) routing (Fig. 2a), laser cutting, and 3D printing. Since a model created from a solid material (such as a CNC routed model made of medium density fiberboard) is not malleable, we build a second model that is an inverse of the first and then mold a layer of sand between the two models, casting a precise yet malleable surface (Fig. 2b). This way we benefit from the precision of computer-aided manufacturing and the flexibility of sand.

We typically work with models that represent real, geographic places. When manually building a model of a real place from polymeric sand, we overlay and project various raster and vector layers of the place – such as the DEM, slope, and contours – as a guide. In addition to projecting the contours and elevation of the real area, we can continuously scan the model and then compute and project the difference between the DEM and the scanned elevation, thus highlighting places where we need to add or remove sand in order to match the DEM (Fig. 2c). This way we can always rebuild or reset the model after modifying it. When building a model, we usually apply vertical exaggeration greater than 1 depending on the horizontal scale of the model and local topography. Since the scanned DEM is scaled to real-world dimensions, the GIS analyses are not affected by the vertical exaggeration.



(a) (b) (c)

Figure 2. Different methods of creating models: (a) a model carved with a CNC router; (b) a carved model combined with a layer of molded sand; (c) a sand model sculpted manually using projected contours and a color map representing the difference between the current and desired states. Blue shows that sand should be added; whereas, red indicates that sand should be removed.

2.2 Software tools

There are several different software components that we use with TanGeoMS: the Kinect for Windows SDK for scanning, GRASS GIS for processing scans, and our custom library that automates the entire process.

We wrote a simple application in C++ with the Kinect SDK to continuously scan the model and output a file with the point cloud. To connect TanGeoMS's components, we developed a small library and a set of scripts in Python which are able to process the scan and interface with GRASS GIS. The library contains methods for handling different types of input data (e.g. georeferenced versus ungeoreferenced inputs and models with different shapes).

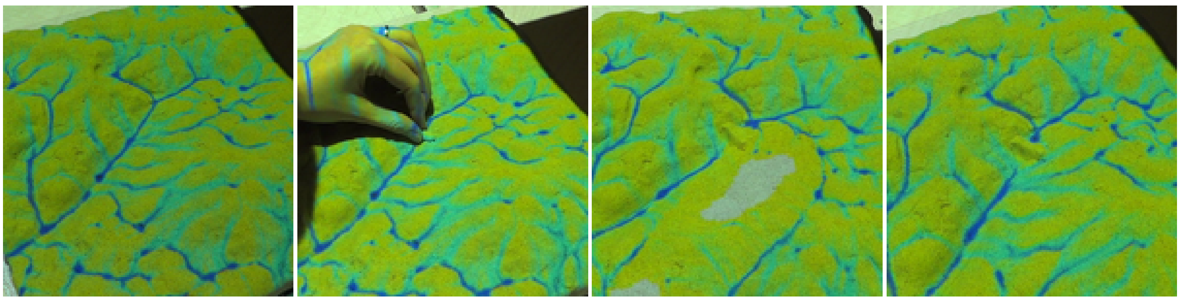
GIS is a crucial component of TanGeoMS as it is used to create a DEM from scanned data, to run analyses or simulations, and to visualize data. GRASS GIS [Neteler et al., 2012], a free and open source GIS, offers a variety of tools for topographic analysis, hydrologic and erosion modeling, or wildfire simulation. Moreover, many highly specialized algorithms are implemented and accessible through the add-on repository. It is very simple to combine different tools in a script using its Python API. While the previous version of TanGeoMS used GRASS GIS, we have now fully integrated this GIS with TanGeoMS in order to easily automate the process and connect all of TanGeoMS's components, thus enabling a more effective workflow.

2.3 Workflow

The TanGeoMS workflow is an interactive process in which users modify a physical model that is then scanned, the scan is imported into GIS software, analysis is performed on the modified input, and then the result is projected back on the model, allowing the users to revise their modifications.

Before we start scanning, we first calibrate TanGeoMS to geometrically correct for any inaccuracy in the angle or direction of the scanner. This is needed because the scanner is very difficult to align precisely perpendicularly to the model and uncorrected misalignments would result in a tilted scan. Next, we georeference the point cloud. Since we know the geographic extent of the area represented by the model and the model orientation is aligned with the scanner, we only need to translate and scale the point cloud. Then, we import the scan as 3D points into the GIS and create a DEM, either by binning or by interpolation. Once we have the DEM, we can run the desired GIS analyses and project the results as color maps back onto the physical model. Then we can evaluate the impact of the changes from the previous run, modify the physical model and repeat the entire process again, except for the calibration process.

We automated this feedback loop so that the impact of changes to the physical model can be projected back onto the model in real-time. Immediate feedback facilitates the testing of different scenarios, potentially resulting in better designs. The time between the updates is usually a few seconds, depending on the size of the model and, most importantly, the analyses run on the scanned DEM. Since interpolating the DEM would slow down each run significantly, we use binning (the per cell point average of z-values) combined with smoothing to create the DEM. This way we can compute standard topographic analyses including slope, aspect, and flow accumulation relatively quickly. Approximate solutions can be used for more complex analyses and computationally intensive models to produce results that are less accurate, but still reasonable and relevant.



(a) **(b)** **(c)** **(d)**

Figure 3. Real-time water flow modeling: (a) initial state; (b) adding a check dam; (c) water flow when hand was captured by scanner; (d) check dam filling with water.

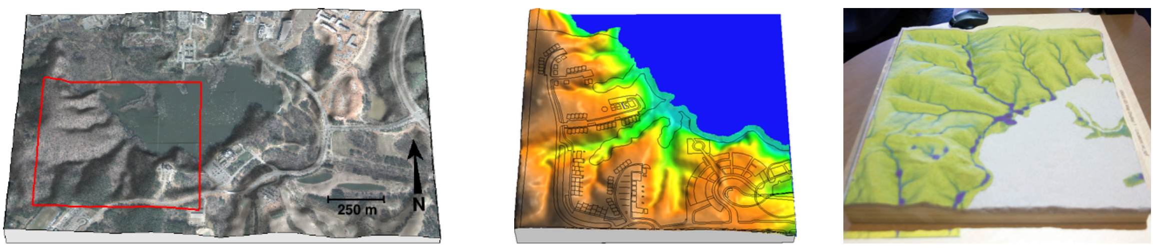
To demonstrate a design process with real-time response we modeled overland water flow [Mitasova et al., 2005] using a sand model based on a DEM of an existing study site. We have tried to capture storm water and reduce runoff by building a small check dam on the model. Fig. 3 shows several snapshots which include Fig. 3a, the initial state, Fig. 3b, a user adding sand and shaping the check dam and Fig. 3d, the change in the water flow filling the dam. In Fig. 3c we see water flow computed on a scan captured when the user's hand was still modifying the model. This happens because we scan continuously; therefore we always have to wait a few seconds after a change has been made to get a clean scan before we can evaluate the modifications.

3 APPLICATIONS

The value of TanGeoMS is that it enables a dynamic, experimentation-based learning process that combines creative exploration with geospatial analysis. This may lead to highly creative yet scientifically grounded solutions. TanGeoMS can encourage interdisciplinary collaboration and exchange since users from different disciplines such as land managers, landscape architects, engineers, and scientists can simulatenously interact with the model. TanGeoMS has been used for a broad range of applications supported by the extensive set of geospatial analysis and modeling tools available in GRASS GIS. TanGeoMS can be used at a wide range of spatial scales depending upon the application and the scale of the intended real-world terrain modifications. It can be used for example at a fine scale to plan building massings, at a coarser scale to study watersheds, and at an even coarser, regional scale to study a mountain range. We have explored how dune breaches affect the extent of coastal flooding, the impact of different building configurations on viewsheds, cast shadows and solar energy potential, and the effectiveness of various landscape designs for controlling runoff and erosion [Tateosian et al., 2010]. Here we present two new applications. We evaluated the environmental impact of a development scenario and then designed and tested alternatives. We also modeled the spread of a fire and then designed and tested fire-control measures.

3.1 Scenario planning with hydrology and sediment transport modeling

TanGeoMS can be used to iteratively design and test scenarios. We used the system to study the environmental impact of building a residential development in Lake Raleigh Woods on North Carolina State University's Centennial Campus, a site that has been experiencing rapid urban development. Our study area is approximately 750 m in both dimensions. The mostly forested terrain is hilly with steep slopes, especially near the lake (Fig. 4a). We began by carving a medium-sized base model (50 by 50 cm) of the current landscape with a vertical exaggeration of 2. Then we carved an inverted model of landscape that we used to mold a 2 cm thick layer of sand on top of the base model. We modeled overland hydrologic flow, erosion and deposition using a particle sampling method [Mitasova et al., 2005] for the current state (Fig. 4c). By manually modifying the sand layer and adding 'buildings' on top, we modeled the impact of a development scenario based on the southwest part of a 1999 masterplan for Centennial Campus (Fig. 4b) that would require extensive excavation and grading. This development



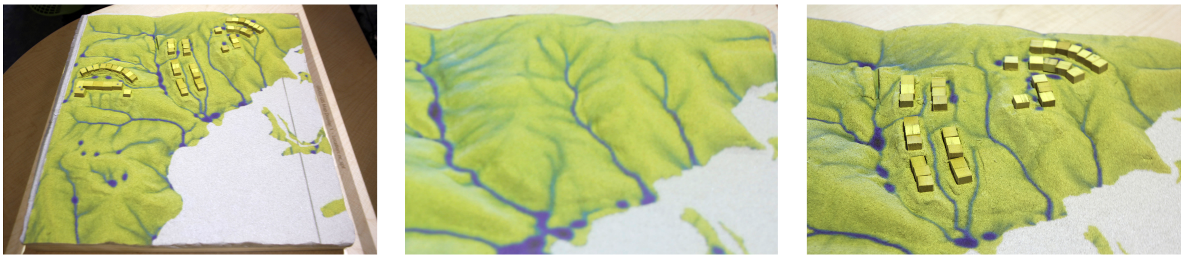
(a) (b) (c)

Figure 4. The current condition of Lake Raleigh Woods: (a) orthophoto with highlighted study area; (b); DEM with overlaid masterplan (looking north) (c) overland hydrologic flow (looking west).

scenario changed the local hydrologic conditions significantly (Fig. 5b, c). To design a more sustainable development, we sculpted drainage and retention ponds (Fig. 6). Next we designed a second, alternative development scenario in which we attempted to minimize excavation and grading by building in low slope areas (Fig. 7a-c). Again, we studied the modeled impacts of the scenario and sculpted drainage and retention ponds to reduce erosion (Fig. 7d-f). The erosion modeling part was based on scanned DEM but was computed separately since it requires additional spatially variable inputs and is more process-intensive as well. Through this iterative process of experimentation and modeling, we were able to test and evaluate the impacts of our designs.

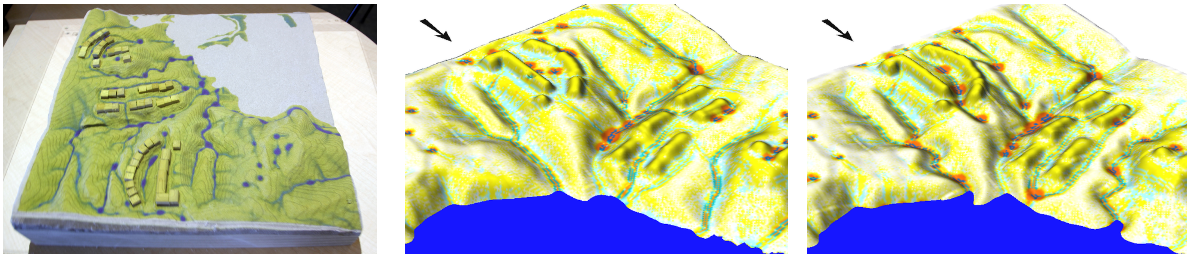
3.2 Wildfire modeling

TanGeoMS can also be used to model wildfire spread. Here the physical model represents the terrain with the tree canopy. The tree canopy surface was acquired by lidar mapping and the sand layer of the physical model was molded using the inverted carved model of canopy. The simulated spread of wildfire is determined by the wind, the topography, and spatially variable fuel availability which is represented here by the tree canopy. Thus by removing sand representing the canopy from a certain area, we can easily create firebreaks. As we can intuitively create new scenarios, we can rapidly test how different



(a) (b) (c)

Figure 5. First development scenario (a) and comparison of overland hydrologic flow before (b) and after development (c), looking west. Note that new stream channels draining developed areas were created.



(a) (b) (c)

Figure 6. Modified first development scenario (a) and comparison of erosion/deposition before (b) and after (c) applying best management practices. Results suggest that stream banks should be protected more by planting grass or trees.

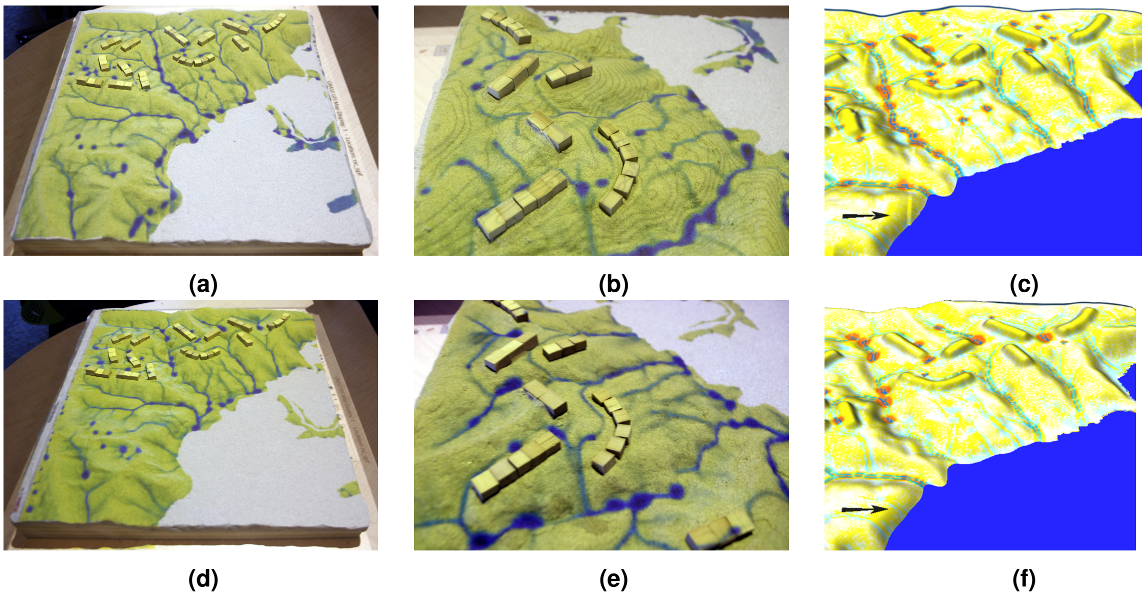


Figure 7. Second development scenario before (upper row) and after (bottom row) applying best management practices: (a) and (d) overland hydrologic flow (looking west); (b) and (e) detail of the western part (looking north); (c) and (f) erosion/deposition (looking west). Retention ponds successfully reduced downstream erosion.

sizes, shapes, and placements of firebreaks affect the spread of a fire. The wildfire simulation itself is computed using GRASS GIS's wildfire modeling tools [Xu, 1994] and the result is projected as an animation on the model. As an example, we have simulated the spread of a fire across our study area and observed that fire reached the Chancellor's House quickly due the abundance of fuel and the prevailing south-east wind direction (Fig. 8). We attempted to protect the house by building a fire line, perpendicular to the wind direction, that stretched from the lake to the road. However, the fire eventually spread beyond our fire line due to the presence of low lying vegetation beside the road. Nevertheless the firebreak slowed the spread of the fire significantly, potentially giving firefighters more time to act.

(a) **(b)** **(c)**

Figure 8. (a) Tree canopy in detail; (b) and (c) wildfire simulation before and after adding a firebreak.

4 Discussion

There were two major challenges in developing TanGeoMS: the accuracy of representation and the speed of real-time response. The inaccuracy arises as the physical model is a simplification of reality which is further modified manually and then scanned. We are trying to address these issues by using computer aided manufacturing to generate more precise physical models. However, we consider TanGeoMS to be primarily a 3D sketching tool, which enables users to rapidly explore different scenarios. To save time and effort, we only need to compute precise models for the most promising of scenarios. Modeling with real-time response is limited by the current scanning technology, modeling algorithms and process automation. While the Kinect scanner enables fast scanning, certain TanGeoMS applications would benefit from higher precision scanning. It is necessary therefore to continue exploring the potential of other scanning technologies. The speed of real-time response is obviously limited by the processing time of the analyses selected. The automation of the process is complicated by usage of different types and shapes of models and variations in physical setup. However, due to the benefits of the fast feedback loop, we think it is worth trying to overcome these obstacles. Being able to see the impact of a change immediately highlights the cause and effect relationship. Moreover, users are able to test more scenarios in a shorter time.

5 Conclusion

We have presented an enhanced, affordable version of the Tangible Geospatial Modeling System capable of modeling and visualization with both real-time and near real-time response. The updated TanGeoMS has an automated real-time feedback loop that transforms changes to a physical model into a digital form, computes analyses, and projects the results back onto the model. This automated real-time feedback loop is a powerful method for testing multiple landscape-altering scenarios without having to interact directly with a GIS. By using the inexpensive Kinect scanner and GRASS GIS, a free, open source GIS, we made TanGeoMS financially affordable. Furthermore, we have made TanGeoMS even more intuitive to use by creating easily malleable models built with innovative technologies and materials. By linking intuitive phyiscal modeling with geospatial analysis, TanGeoMS enables collaborative, interdisciplinary, and creative problem solving that is grounded in science. The design process becomes a cycle of physical experimental, computational analysis, critical reflection, and creative re-imagination or refinement. We have demonstrated how TanGeoMS can be used for urban planning and fire crisis management. These examples represent just a few of TanGeoMS's many potential applications.

References

Ishii, H. and Ullmer, B. (1997). Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '97*, pages 234–241, New York, New York, USA. ACM Press.

Kreylos, O. (2013). Augmented Reality Sandbox.

Mitasova, H., Mitas, L., Ratti, C., Ishii, H., Alonso, J., and Harmon, R. (2006). Real-time landscape model interaction using a tangible geospatial modeling environment. *IEEE Computer Graphics and Applications*, 26(4):55–63.

Mitasova, H., Thaxton, C., Hofierka, J., McLaughlin, R., Moore, A., and Mitas, L. (2005). Path sampling method for modeling overland water flow, sediment transport, and short term terrain evolution in Open Source GIS. In Miller, C., Farthing, M., Gray, V., and Pinder, G., editors, *Proc., XVth International Conf. on Computational Methods in Water Resources (CMWR XV)*, pages 1479–1490. Elsevier.

Neteler, M., Bowman, M., Landa, M., and Metz, M. (2012). GRASS GIS: a multi-purpose Open Source GIS. *Environmental Modelling & Software*, 31:124130.

Piper, B., Ratti, C., and Ishii, H. (2002). Illuminating clay: a 3-D tangible interface for landscape analysis. In *Proceedings of the SIGCHI conference on Human factors in computing systems Changing our world, changing ourselves - CHI '02*, page 355, New York, New York, USA. ACM Press.

Ratti, C., Wang, Y., Ishii, H., Piper, B., and Frenchman, D. (2004). Tangible user interfaces (tuis): a novel paradigm for gis. *Transactions in GIS*, 8(4):407–421.

Tateosian, L., Mitasova, H., Harmon, B. A., Fogleman, B., Weaver, K., and Harmon, R. S. (2010). TanGeoMS: tangible geospatial modeling system. *IEEE transactions on visualization and computer graphics*, 16(6):1605–12.

Xu, J. (1994). *Simulating the Spread of Wildfires Using a Geographic Information System and Remote Sensing*. PhD thesis, New Brunswick, NJ, USA.