Software for Scientists facing Wicked Problems
Lessons from the VISTAS Project

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ABSTRACT
The Visualization for Terrestrial and Aquatic Systems project (VISTAS) aims to help scientists produce effective environmental science visualizations for their own use and for use in presenting their work to a wide range of stakeholders (including other scientists, decision makers, and the public). The need for better visualization tools for environmental science is well-documented, but little prior work has been done to determine what kinds of visualizations work and with whom. The VISTAS research and development project has applied social science methods to this question, and has identified issues relevant to visualization software development, particularly where the application area involves wicked problems such as climate change. This paper presents visualization problems of scientists whose presentations of scientific results might be enhanced if they and software developers were consciously aware of the nature of so-called wicked problems and the considerations of non-scientist secondary users. While VISTAS focuses on visualization software, we believe results are generalizable to software in general. The primary lesson learned from our work is that extending the scope of the domain context will likely provide scientists with software that is more effective and relevant to non-scientist stakeholders, but that doing so can be time consuming and more costly unless the nature of the underlying science problem is recognized and characterized early in the product cycle.

Categories and Subject Descriptors

General Terms
Design, Human Factors, Management.

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Scientific Visualization, Visual Analytics, Wicked Problems, Climate Change, Post-Normal Science, Software Development.

1. INTRODUCTION
Current ecological problems such as environmental change drive researchers to look outside their normal, discipline-oriented boundaries to understand how their particular model, process or system might interact with other models and systems. Technical innovations developed by computer science and engineering research provide not only the hardware (sensor tools, processing capability of computers), but also the software, for dealing with ecological problems [19]. Using such new technologies researchers learn, observe, and might come to conclusions differently than they had before. New practices usually emerge with technical innovation, and the relatively new “deluge” of data now available for analysis is no exception. Some observers have suggested the “data deluge” might lead to the “end of theory”, where data mining will be just as important as experimental hypothesis testing [3]. Whether that will come to pass or not, the amount of data collected by sensors and models is clearly outpacing the ability of scientists to process and analyze the data and many scientists ask how they can increase their understanding and use of that data and whether these innovations will lead to new insights into contemporary problems. While it is clear that the nearly overwhelming amount of data currently available to scientists necessitate that they look outside their own disciplinary boundaries to work with other scientists, it is less clear that the data deluge alone calls for the interaction between scientists and non-scientists to solve pressing ecological and environmental problems.

In 2011, computer scientists, social scientists and environmental scientists at The Evergreen State College, Oregon State University and Willamette University, the Environmental Protection Agency, and the Conservation Biology Institute, launched the Visualization for Terrestrial and Aquatic Systems project (VISTAS). Project objectives were to conduct ecology informatics and computing research that would enable the visual analytics of environmental science model data and sensed data—both of which produce large data volumes that, without visualization and advanced analytics, are increasingly difficult to use effectively. To these ends, computer scientists and programmers are working with three environmental scientist collaborators to design and implement a tool that the scientists can use to visualize their own research data. Social scientists are evaluating the environmental scientists’ use of VISTAS as well as the VISTAS’ co-development process. The team as a whole is also evaluating the tool’s and the visualizations’ extensibility to other applications.
We initially expected the following three outcomes from the project:

1) a visualization tool that would be used by our collaborators and visualization research transferable to other efforts,
2) visualizations to explore complex and coupled ecosystems problems (including climate change), and published environmental science research that used those visualizations, and
3) increased understanding of which visual analytics work, for whom, and why; best practices for engineering complex scientific systems; a determination of prerequisite knowledge and skills for co-developers; and a process for studying co-development of scientific visualizations and software.

VISTAS’s software development process has employed traditional software specification or software acquisition methods which first involve interviews with primary users and the development of use cases. Next, iterative, incremental, and agile development techniques all emphasize putting nascent software into the hands of key collaborators early in the development cycle [5,25]. We have generally adopted these accepted iterative development methods, adapting them for a small team (three part-time programmers, each assigned to one scientist). Luckily for us, this “release early, release often” philosophy unearthed relatively early in the process a lack of understanding about how the software would ultimately be used.

During the course of development, we discovered that two of our collaborators needed to create visualizations using our software in ways we had not anticipated, i.e., they wanted different, and often heavily annotated, visualizations to present findings to non-scientists, rather than showing visualizations they had used in their own analysis. Further, rather than these visualizations being standalone explanations of the physical phenomena, the visualizations were being used by the scientists to tell a story, to explain their results. The non-scientists with whom the scientists were interacting were typically local, state, or national government decision makers who were involved in defining policy for the environmental science problems. As a result, during the course of development the fact that our science collaborators presented different kinds of visualizations to non-scientists prodded us to modify both software specifications and development priorities. While specification changes are generally expected in an agile development process, this involved involved rather extensive review and revision of the underlying problem domain that even altered some underlying technical assumptions we had made about how to design or render visualizations.

This paper focuses on the special issues we found when we discovered that our collaborators use VISTAS visualizations when presenting to non-scientist stakeholders scientific results relating to climate change, and relates to the third outcome above. Initially, we had assumed that the visualizations would primarily be viewed interactively from the software by primary users to enhance that user’s understanding of the scientific phenomenon being studied [9]. Now, we understand that our scientist users are presenting visualizations not only to other scientists, but to non-scientist stakeholders, and we have come to recognize that using the visualizations for presentation to non-scientists, is different in kind than we had anticipated. We therefore suggest that developers (or those involved in visualization software selection) carefully consider non-scientist secondary users who experience the visualizations independently of direct interaction with the software. We present evidence for this contention and some suggestions for how to achieve it.

We believe our results are relevant to the digital government community as they develop or select software to study complex scientific problems in which the public holds considerable interest in resolution or adaptation. The primary contribution of this paper lays in the fact that an understanding of so called wicked problems is critical to software developers in general, and to those developing or procuring software that conveys scientific results to decision makers and the public at large. This is a relatively new conception of the role of software engineers. While the Association for Computing Machinery (ACM) software engineering code of ethics contends that “…software engineers …[should] consider broadly who is affected by their work,” they have traditionally been taught to eschew policy matters [3,12]. Recent social science research suggests that technology inevitably has policy implications [23], despite the past best efforts of scientists and engineers to divorce themselves from policy decisions [24]. We have come to believe that it is better for the engineer and scientist to recognize the role that their artifacts play in decision making.

Further, recent studies of both public policy and the philosophy of science tell us that public policy and government decision making are not greatly influenced by scientific research results and, conversely, that nonscientists rarely influence the formulation of science problems [23]. However, given the global-scale nature of current issues, and the likely failure of straightforward technological solutions to solve those problems [14,15], it seems critical to explicitly extend the scientists’ and software engineers’ role to understand both the primary and secondary users of the science and technology they create. We do not advocate that scientists and engineers practice normative science, only that they be more aware of the information, technology, or science needs of those who set policy and make decisions.

The crux of the story we relate here is that our initial software specifications and discussions with collaborators indicated that our scientists were primarily interested in using the software to enhance their own and other scientists’ understanding of the physical phenomena being studied. While they suggested they might also use visualizations in presentations to non-scientists, we all believed that visualizations shown to non-scientist “secondary users” would not differ significantly from those developed for secondary users who were scientists. However, we now realize that secondary users must be considered by both the visualization designer (the scientist) and the software tool developer, and perhaps even directly engaged during the development process.

In examining these newly expressed needs for visualizations that could be used to communicate results to both science and non-science audiences, we began to understand the challenge of creating software to tackle scientific problems classified as “wicked”. This led us to think about how wicked problems differ from the scientific problems we had expected our users to design visualizations for.

2. WICKED PROBLEMS AND POST-NORMAL SCIENCE – CHANGING ROLES FOR SCIENCE

The late 20th century brought a host of grand challenges to the discipline of ecology, including the concept of coupled human and natural systems (e.g., Liu et al [26]), which present as complex, dynamic and adaptive systems. When managers or policy makers deal with problems in these complex systems, they often exhibit...
features of what have come to be known as wicked problems (Table 1). Wicked problems are characterized as difficult or impossible to resolve because of the fluid and often contradictory requirements for any effective or acceptable solution. For example, the complex interdependencies of the issues usually result in the creation of new problems even as we think we’re making progress with the original problem [32]. For the most part, traditional “normal science” [21] is unprepared to answer questions posed by policy makers responsible for managing these complex systems that generate wicked problems. New approaches, what have come to be known as post-normal science, are emerging as ways to generate the information needed to make intentional and collective choices to resolve wicked problems.

Table 1: An overview of wicked problems (adapted from Bruce Shindler [35], after Rittel and Webber [33]).

<table>
<thead>
<tr>
<th>Scientific/technical solution?</th>
<th>Consensus or general agreement about the problem?</th>
<th>YES</th>
<th>NO</th>
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<tbody>
<tr>
<td></td>
<td>Tame problem</td>
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<td></td>
<td>problem is isolated</td>
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<tr>
<td></td>
<td>agreement on solution</td>
<td></td>
<td></td>
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<td></td>
<td>Examples: fire suppression, municipal trash collection</td>
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<tr>
<td></td>
<td>Mess or complex problem</td>
<td></td>
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<td></td>
<td>science provides solution</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>no agreement how to proceed</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Examples: population control, traffic congestion</td>
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<td></td>
<td>Puzzle or mystery</td>
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<td></td>
<td>agreement on solution</td>
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<td></td>
<td>lack technical/scientific capability for solution</td>
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<td>Examples: disease treatments, flood control</td>
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<td></td>
<td>Wicked problem</td>
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<td></td>
<td>no agreement on solution</td>
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<tr>
<td></td>
<td>lack technical/scientific capability for full solution</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Examples: climate change, Middle East war, nuclear power, waste cleanup</td>
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</table>

There are three key, interconnected, components of the post-normal science model that make it different from other approaches and more appropriate for dealing with wicked problems: (1) Uncertainty is considered more than a technical or methodological issue; uncertainty is accepted as the state of affairs within which decisions must be made. (2) Different approaches are recognized and leveraged rather than assuming a scientific or policy consensus can be found. (3) The group of individuals considered capable of assessing the quality of the results is extended beyond the normal peer community to a wider range of experts and knowledge; this new group is then better able to consider the array of risks, benefits, and implications for multiple stakeholders [13].

This relatively new approach to developing science, especially in the face of wicked problems, is in contrast to normal science. In normal science, peer communities are typically limited to those experts who can judge the quality of the science; for the most part, these are disciplinarily-trained peers (e.g., environmental scientists, biologists, physicists, geologists). When uncertainty and decision stakes increase, the post-normal approach suggests that the peer community can and should be extended to non-disciplinary experts, those with experiential, context, or local knowledge. This is because a single scientific discipline and strictly scientific knowledge are, by definition, incapable of capturing the full complexity of such problem settings. In post-normal approaches, the peer community is extended to include not only producers of information but potential users as well. Non-experts can contribute to knowledge production in a variety of ways including co-framing problems, providing non-scientific information or data, acting as critical reviewers of the output, helping interpret data in the local context, and acting as critical reviewers of the output.

Multiple approaches have been created to bring non-experts into both the production and evaluation of knowledge including consensus conferences, which have been used to bring together competing perspectives and values around topics like bioremediation of hazardous wastes [22]; citizen juries, which have been organized to assess the quality of biomedical research [29]; or the introduction of uncertainty guidance to the Netherlands Environmental Assessment Agency that includes ways to consider both quantitative and qualitative metrics of uncertainty in risk assessments [31]. Another approach is creation or use of a knowledge to action network (KTAN) [7] that brings together a dynamically evolving group of participants who work together to pose and answer questions collaboratively and iteratively, with the goal of creating usable information (or knowledge).

One highly visible and credible example that integrates the idea of an extended peer community is the Intergovernmental Panel on Climate Change (IPPC) [17], which can best be described as an interdisciplinary assessment of scientific research to integrate available knowledge for use by policy makers [20]. This extended peer group is not only an interdisciplinary group of scientists studying the problem, but an interdisciplinary group of scientists and policy experts working together to interpret and understand the consequences of the data.

Two of our collaborators work with non-scientist decision makers on wicked problems related to the impact of climate change on local and regional landscapes. In these cases, even as the decision stakes rise for policy makers and citizens due to climate impacts, the level of uncertainty increases as global models are downscaled to regional areas and as forecasts are stretched into an unknowable future. This combination of high systems uncertainty and high decision stakes suggests the situations these teams find themselves in have evolved such that a new problem solving strategy grounded in post-normal science may be appropriate for developing the information needed to move forward on local and regional decisions. What makes these cases unique is that the collaborators—and subsequently the VISTAS team—are part of a larger team that includes non-scientists working together to co-develop a sophisticated model in order to explore together the impact of climate change in the local context. Not only was the choice of technology co-selected, but the scientists and the community also co-developed the inputs and assumptions of the model, working together as a knowledge to action network. VISTAS developers were brought in to develop the software tools and help the team create visualizations to explain results generated by the complicated model to answer questions about the impact of climate change.

Projects like these leave the software development team with the responsibility for creating software that enables their collaborating scientists to create visualizations that help explain not only the scientific results of their model to scientists and non-scientists, but also to incorporate and visualize assumptions and variables identified by the non-scientist users into the model.

We now ask whether our software development process or specifications would have been different had we known earlier what we know now. To what extent (if any) do visualizations
presented to non-science stakeholders differ from visualizations a
scientist might use in understanding or refining the model’s
science, or in presenting its results to other scientists? What is our
responsibility as researchers and developers for helping our
collaborators create visualizations for a wider audience? Should
software that creates those visualizations for non-scientists differ
from visualization software for scientists?

3. CASE STUDY METHODS FOR DESIGN
AND ANALYSIS

To answer these questions, we used a single case study approach
[42] for studying the VISTAS research collaboration which
consisted of four subunits, each working on distinct projects. Each
key informant—seven ecologists and computer scientists—was
formally interviewed at least once. In addition to the transcripts
from these interviews, data were produced via follow-up emails and
informal conversations about the project with members of the
group, which were tracked through memos written during or after
the event. Data were also collected from participants of the
VISTAS case study at all-hands and development meetings that
were organized and run by project leads. All of the data from interviews, conversations, meetings, and
memos were transcribed for an analysis that used themes built
from the project’s propositions, interviews with the key
informants, and models and frameworks for understanding the
many facets of the VISTAS case study. Data analysis from the
case study provides insight into both the visualization software
design process and the greater, ongoing conversation about how
visualization contributes to problem solving in an era of wicked
problems and “big data.”

4. VISTAS AND ITS VISUALIZATIONS

During the VISTAS software design process, which was tracked
and analyzed as the case study described above, domain scientists
with real data, dealing with real scientific problems, determined
the direction of development. We thus assert that the VISTAS co-
development process fits the description of a “problem-driven”
design project. Software developers considered the types of
visualization that VISTAS science collaborators were requesting.
Over the course of the first three years of the project, VISTAS
collaborators communicated ways they would want to visualize
results with different non-science audiences. These problem-
driven design considerations required developers to re-design to
multiple specifications within the VISTAS software tool.

The first and primary visualization design objective for VISTAS
involved moving the collaborators’ visualizations of physical
terrain from “flat” 2D to incorporate topography. While scientists
have always suspected that the ecology of a particular region
varies with topography, only recently have innovations in
environmental science data acquisition enabled scientists to
collect data, conduct experiments, and validate models in areas
with complex topography. Our collaborators came to us with an
overarching problem: with their current visualization tools, they
could not “see” the topographic difference in landscape that drove
the physical processes under study. Thus they all wanted to
enhance their current 2-dimensional visualizations with digital
elevation models so that the landscape’s topography would stand
out in 3-dimensions. They were convinced (and this has been
confirmed) that this third dimension would allow them to intuit
more readily where environmental response variables change as
drivers and assumptions change. Thus the primary visualization
problem that we aimed to address was (and remains): visualize
changes in landscape where topography likely plays a role in
effecting those changes.

We found during the course of the VISTAS project, however, that
topography seems to serve a different purpose for non-scientist
audiences. This theme emerged over the course of the project in
both the interview and meeting data when VISTAS scientists
highlighted the distinction between the different audiences to
whom they present visualizations, and described how they would
design output with a particular audience, such as non-scientists, in
mind. Rather than help with the science problem of determining
the effect of topography on ecological response variables,
topography helps non-scientists recognize and relate to familiar
landscapes. So, we discovered that the third dimension also allows
secondary users not familiar with the topography to more easily
recognize features on the landscape.

Other primary needs were to produce animations, i.e., include in
visualizations a fourth dimension (time) and display changes in
landscape via fly-throughs that highlight particular areas. A third
initial goal, not yet accomplished, was to be able to view data at
different geographic extents (spatial scales) in the same window.

To make the new system tractable, we decided to focus on three
environmental science research projects, each of which would
benefit from being able to view data topographically but each of
which focuses at different spatial scales. They all also wanted to
use animation to visualize space displacement or the 4th
dimension time, and to view their data simultaneously with another’s data.
The following three sections describe those three projects and how they used the VISTAS visualizations they created.

4.1 Alternative Land Use Scenarios

VISTAS collaborator John Bolte and his team at Oregon State
University have worked with VISTAS developers to embed
VISTAS into ENVISION, his open-source GIS-based multi-agent
model for scenario-based community and regional integrated
planning and environmental assessments [6]. ENVISION
integrates spatially explicit models of landscape change processes
and production for alternative futures analyses. It currently
produces 2D maps (as shape files) that illustrate changes over
time of modelled attributes such as species habitat, ecosystem
type, and disturbance. Bolte believes that 3D maps and animations
(shown either as the model runs in real time or post-simulation),
will help both scientists and stakeholders better understand
alternative futures. He also wants to view side by side “camera-
position-coordinated” fly-throughs at specific points in time for
different attributes or scenarios. Bolte’s group previously
produced fly-through visualizations, but these had typically taken
weeks or months to produce.

To exercise the most recent implementation of ENVISTAS
(ENVISION with the VISTAS visualization engine as a back-end
plug-in), Bolte’s team generated fly-throughs for the Central
Oregon Alternative Futures Project (Forest, People, and Fire).
This project focuses on better understanding how biophysical
systems, management actions and socio-economic influences
interact to affect sustainability in fire-prone landscapes under
climate change, and aims to improve wildland fire policies in the
U.S. Figure 1 shows a VISTAS animation created to demonstrate
the tool. The visualization is designed to show how land use
affects vegetative cover—which in turn will determine fire
hazards. To see a fly-through animation of this visualization,
well as VELMA animations (described in Section 4.2 below), see http://vimeo.com/103346160.

Figure 1. Alternative land use futures scenario - Central Oregon alternative futures: Left: vegetative cover (giant trees to seedling, shrub, meadow, barren, developed). Right: land use (homeowner, tribal, private or public industrial, state or federal).

Bolte was coincidentally tasked with climate change impact modeling for the Big Wood Basin Project in south central Idaho. This project, funded through NOAA, is an example of an effort where a group of community members and potential information users are engaged with scientists and computer modelers. Initial meetings included state and federal agencies, non-governmental organizations, local and county, university extension, canal companies, and residents interested in thinking about the future of the region. Climate change emerged unsolicited during the initial sessions as a primary reason for involvement, in spite of the fact that local informants had warned against asking explicitly about this “hot-button” topic. Back casting was used to start people thinking about the future and characterizing conditions that might lead to desired futures [16]; these were later clarified with the development of a concept map by the group as a whole (See Figure 2). A stock-flow diagram (systems dynamics model) [28] of climate change causes and impacts in the region was also constructed, but the group found that model too static to be of use.

The above activities deepened all participants’ knowledge of relationships among natural and human systems, and others’ perspectives and values around those systems. The concept map exercise moved the group forward in identifying variables they wanted to consider, data they would need to support those variables, and what probably could not be included in the model due to limitations in data or research methods, and brought about two impacts critical to the VISTAS visualization effort. 1) Non-scientist participants realized that a complex science-based “black box” model was critical to understanding and mitigating the problem, and 2) Scientist participants tasked with developing that model were provided with assumptions and variables that the community viewed as important and that would drive the model. In other words, the process identified gaps in knowledge for both non-scientists and scientists.

As a result of this exercise, Bolte and his team were tasked with co-developing a complex model that would allow the joint exploration of the impact of climate change in the local context. In this case, not only the choice of technology but the inputs to and assumptions of the model were co-developed by scientists and the community, working together as a knowledge to action network. VISTAS developers were then tasked to help Bolte (and by extrapolation the Big Wood Basin team) create visualizations that could help explain the results generated by the complicated model to answer questions about the impact of climate change in this western basin. Thus visualization challenges not anticipated for VISTAS/ENVISION’s use with non-scientist stakeholders was expanded to showing model assumptions and levels of uncertainty and aggregating variable types to simplify visualizations, as well as how to increasing audience attentiveness with 3D maps, animations, and flythroughs.

Figure 2. Big Wood Basin stakeholder problem solving and concept mapping.

4.2 Hydrological-Biogeochemical Processes

VISTAS collaborators Bob McKane and Allen Brookes of the U.S. Environmental Protection Agency (EPA) use VISTAS to demonstrate results from their hydrological model VELMA [1]. Given a set of drivers (e.g., temperature, precipitation) and disturbance (e.g., fire, harvest, fertilization), VELMA models the interaction of stream flow and biogeochemical processes, and carbon and nitrogen dynamics in plants and soils. Running on a daily time step across thousands of pixels, VELMA generates multiple gigabytes of output for multi-century simulations of large landscapes. VELMA results are difficult to tune, interpret and communicate without visualization.

The EPA currently studies nitrogen deposits—a critical problem near croplands and in wetlands because agricultural pollutants and eutrophication are critical water quality problems, and many bays, estuaries, and tributaries exhibit high nitrate levels. VELMA was run to investigate the feasibility of using an ecohydrological model to help bound uncertainties in difficult-to-measure nitrogen fluxes. VISTAS visualizations (Figure 3) were generated from VELMA by McKane for an EPA webinar in July 2014.

Unanticipated (by both McKane and the VISTAS team) specifications for VELMA arose as McKane presented the results of VELMA visualizations to his non-scientist stakeholders. For example, McKane found it easy when refining his science model to view one image with land use (Figure 4, Left) then to imagine in his mind’s eye the land use boundaries on VISTAS visualizations of nitrate flux (Figure 3), but his new audience wanted to see the land use boundaries explicitly. This issue was critical enough for McKane that he reprioritized his wish list for enhanced visual analytics within VISTAS and put as top priority the overlay of land use boundaries. While this seems like a simple change in the visualization, for technical reasons it required significant re-thinking about how to render the overlay in VISTAS. See Figure 4 (right) for an initial effort at this visualization; achieving this feature will involve a re-implementation of the underlying graphical rendering technique, a non-trivial undertaking.
4.3 Airflows in Mountain Valleys

VISTAS collaborator Christoph Thomas, University of Bayreuth, Germany, is interested in how heat, humidity, and carbon dioxide communicate across landscapes; to that end he takes spatially distributed point-measurements of wind speed and direction to characterize the airflow, which transports these quantities [38]. To scale up to the watershed level, he needs to develop new models, and wants to draw on insights from viewing his data in topographical context. He also would like visualizations that provide more intuitive understanding than what he currently uses for scientist colleagues and to superimpose his visualizations with those of McKane’s.

A prototype VISTAS WebGL application was implemented for Thomas to depict measurements of wind speed and direction, here observed by a pair of ground-based acoustic remote sounders located at H. J. Andrews Long Term Ecological Research Forest in Oregon (Figure 5). Measurements were taken at two stations in adjoining valleys with a horizontal separation distance of approx. 6 km. Variables were continuously sampled and subsequently averaged over 5 min. for a period of 3 months and organized into daily files. Wind speed and direction were computed for 10m height increments extending from 15m to 395m above ground. The visualization shows one 5-min. vector given by wind magnitude and direction for each height interval.

Visualizing wind measurements in the context of topography was critical to identify and interpret flow patterns, which are strongly influenced by the position in the deeply incised, narrow valleys. Displaying and playing back observations as animations from both stations in the same visualization provided non-quantitative, but intuitive information about spatiotemporal correlation between the two stations, which Christopf says will be instrumental in diagnosing the connectivity through atmospheric transport in the adjoining valleys and thus the ‘breathing’ of the mountainous landscape.

While we computer scientists can suggest technological enhancements to this visualization design, not all of which are trivial to implement, we have not yet faced design problems similar to those described above for the Bolte or McKane visualizations. We attribute this to the fact that the audience for Thomas’ visualizations is scientists only.

4.4 VISTAS Implementation Note

VISTAS grew out of prior scientific visualization work implemented in Java and the Visualization Toolkit VTK; expertise gained there was applied to a modular, scalable design implemented in C++ and OpenGL. Our intention was to create a scalable and extensible visualization tool for environmental scientists that allowed them to view landscapes in 3D and to animate those landscapes over time. Our intention was that adding new data and visualization types would become straightforward, as would embedding the visualization engine in other scientific application software such as ENVISION [8]. Thomas’ prototype was generated with WebGL in a JavaScript API and a digital elevation map (DEM) created from LiDAR data provided by HJA. VISTAS is freely available (http://blogs.evergreen.edu/vistas).

4.5 Designing Visualizations with VISTAS

To some extent, the benefits and limitations of visualization in helping solve VISTAS collaborators’ problems depend on software design and development. Throughout the software design process, we have employed traditional methods that emphasize close collaboration with users and designing a tool that would (as a necessary condition) solve their primary problem. We interpreted this problem, generally, as viewing data in the context of topographically complex terrain. Thus, the VISTAS project can be termed a “problem-driven design study” structured to exploit the power of visualization for scientific users. While the domain problem has been a primary consideration for us in this project, in settings such as the Big Wood Basin study, based on case study data we see that the domain problem is considerably more complex than originally anticipated. Computer scientists and scientists involved in design and implementation of both visualization tools and visualizations for wicked problems must take particular care to fully characterize the domain problem early in the design process, and throughout the subsequent implementation, deployment and maintenance—in other words throughout the product life cycle. In this case study of scientific visualization, we found that the product life cycle requires both developers and scientist users to recognize wicked problems and to better understand how to characterize them and design visualizations for them.

In traditional scientific visualization projects, computer scientists often suggest and prototype technological innovations to enhance the scientific content of the visualization. However, few computer scientists are trained in which scientific visualizations work for non-scientists in a post-normal science world, so we were at a loss to suggest enhancements. Social and environmental science research conducted by the VISTAS team found that even the scientists themselves don’t always know how to design visualizations accessible to non-science audiences. These findings are consistent with the literature, which highlights the difficulty of...
matching the best visualization technique with the way the data is abstracted [32].

We do know that visualization can help non-scientists better understand complex scientific results (and the scientists specified this as a use for visualization). Our collaborators want to visualize their results simultaneously to problem solving (analysis) sessions with stakeholders. Our science collaborators ask us to suggest ways to enhance the visual interest of the images, e.g., improving the aesthetics or providing animation, but it turns out that neither the computer scientist nor the environmental scientist has mastered the best ways to create visualizations most accessible to secondary non-scientist users [40].

Next, we describe a design model and our additions to it that recognizes and characterizes wicked problems in visualization software design and development.

5. USING A DESIGN MODEL
A problem-driven design study can be summarized by the nested blocks and guidelines model, which is a popular template for conceptualizing design and evaluation criteria in visualization design research, because it aligns design to need [30].

![Nested Model Diagram]

Figure 6: Munzner’s Nested Model [30].

The nested design model defines four levels for consideration in visualization design and evaluation. In the nested model, assumptions about the various types of problems found in the highest level of the model cascade to affect design criteria at the lower levels, ideally aligning the design of task abstractions to interaction techniques to algorithms with the problems in a particular domain (Figure 6). For example, in order to solve a problem in a certain domain, scientists might rely on certain datasets, which they analyze using statistics; or, they might create data through building a simulation or model. These datasets would constitute the data or task abstraction block. In this stage of the visualization process, researchers choose what phenomena to measure—or how to operationalize a process [27]. Once scientists collect datasets and perform the necessary manipulations and transformations, or model a problem, a technique for visualizing the data or model would be chosen. The primary lesson to be taken from the nested model is that domain problem characterization should affect the design decisions about the resulting visualization—such as how best to encode or interact with that data.

In a 2014 position paper on problem-driven design, we created a conceptual model for characterizing the outermost level of the nested model—the domain problem—and described the associated challenges, which are mainly due to the nature of contemporary inquiries. We postulated that in the case of wicked problems, the domain problem is dynamic and difficult to problematize [41]. Problem-driven design studies are not new in software design (see Evans [11] for a description of domain theory and domain-driven software design), and in the field of visualization other problem-driven design studies have been conducted. The findings from these studies range in their reference to specific users and situations, such as the intelligence community in Kang & Stasko [18] to casual users in Sprague & Tory [36]. Our study, however, is unique in seeking to understand how visualization might be used in a public policy and decision making setting where scientists are presenting their data and models to stakeholders.

Users find that certain visualizations are better than others for certain tasks; however, pinning down the variables that matter into a conceptual model and measuring “effectiveness” are still challenging to visualization researchers and designers. Two major guidelines for software design are related to the wicked problem conceptual model: the essential human in the decision making process and the wicked problems that may be encountered, which by nature are difficult to problematize.

5.1 Design for Wicked Problems
The end users of the VISTAS visualization tool are scientists and stakeholders trying to understand the short- and long-term effects on the landscape of their decisions. In this way, the problems vary in size and complexity from solvable puzzles to wicked problems. The wicked problems paradigm applies to the VISTAS study, where the environmental domain problem is tightly coupled with the sociological and political domains [41]. Wicked problems, such as what to do about climate change, move beyond the ability of science to determine clear causal relationships, to predict the future, to control or overcome the unpredictable outcomes, or to establish exactly what is the best outcome [4], which makes them both challenging to solve, but also controversial.

In the VISTAS project, scientists distinguish among activities they use to address research problems—they intend to use visualizations for exploring their science problems and communicating their findings. However, they do not necessarily frame their research activities by referring to them as wicked problems, nor do they talk about the distinction between complicated problems and simpler puzzles when they make models or analyze data. Even so, understanding that scientists will be conducting science within the context of wicked problems could help characterize and design software for their future visualization use. This context includes not only technically challenging problems, but also problems where there might be low consensus and skepticism within the extended community. Prior to presenting design considerations and recommendations for visualization development based on the VISTAS case study, we discuss (below) how users of visualization might vary.

5.2 Design for Various Users
In our position paper on visualization software design and development, we recommended distinguishing between types of users of scientific visualizations. We observed that individuals will experience the same visualization differently, and that the same individual’s visualization experiences vary over time. We also described the importance of a user’s motivation, attentiveness, and agency when using visualization. Additionally, we distinguished among visualization users who range from viewing results to conducting complex visual analytics [41].

All users, from those who simply view research results to those who conduct analytics, are governed by rules of low-level or pre-attentive vision. According to studies in gestalt principles and cognitive science, viewers are relatively consistent in their low-level perception of what is communicated visually [34]. Consider: a single red dot in a sea of blue dots will stand out. Similarly, 50 arrows pointing in the same direction would cue the viewer to perceive significance. The concept of pre-attentive vision implies that low-level visual systems help viewers rapidly identify basic
visual properties, and works with other design principles such as gestalt and color choice. Low-level vision unites viewers to the extent that they sense something and come to some conclusion, without necessarily being aware that they have done so.

Researchers such as Tufte and Graves-Morris [39] show how design effectiveness contributes to clearly communicating an idea. Sometimes meaning emerges from seemingly meaningless or unrelated components. Design principles and concepts lead to more or less effective visualization experiences. Scientists, computer scientists, and programmers are not usually trained to consider these basic design principles in ways that might reveal insight in their audience when they communicate research results or choose parameters for setting up a model or for viewing data.

5.3 Design for Exploration and Communication

The VISTAS research group began the project with the proposition that data visualization tools could help scientists better understand and communicate their own data, as well as increase their ability to integrate their research with others and overcome challenges associated with big data, as mentioned in the literature [37]. VISTAS science collaborators had used visualization prior to the project, but their processes, tools, and output varied. They also vary in their workday tasks, not only because of the ecological processes they study, the scale at which they study, or the part of the visualization process they work on, but because they use technology and modeling in different ways, and produce results for different audiences. In our reporting of the distinction between exploring and communicating among scientists, we highlighted how visualization use might change depending on the audience and the purpose (i.e., whether the visualization being used was for exploration in a scientific setting or communication in a broader decision-making process) [41].

We devised a conceptual model to summarize the experiences of VISTAS scientists with respect to the settings in which they might be using visualization, based on case study data. In this model, we consider visualization design differently depending on the problem context, i.e., the technical complexity of the problem (and degree to which the audience would understand the scientific reporting on that problem) and the level of consensus within the audience as to the problem solution. We also distinguish types of users who might encounter visualization; users vary by both level of attentiveness and level of agency. A user can be highly attentive during an analysis process and have a high level of agency, such as in the case of a scientist who is validating a model; whereas, a user who sees a presentation of the model but has little interest or stake in the problem, for example, would likely have lower levels of agency and attentiveness.

We provided two hypothetical examples of visualization use: one with a focus on building consensus among visualization users with varying levels of expertise, and one with a focus on creating an exploration space for users within the scientific institution. In the first example, we described the importance of considering cultural values and making visualization intuitive. In the second example, we described the importance of a technically sophisticated tool that might be able to overcome certain technical challenges associated with big data. To be sure, VISTAS scientists are finding themselves considering their visualization practices in both hypothetical situations.

The visualizations created by VISTAS scientists become artifacts viewed by secondary users. Proof of this came up during interviews and field observations as part of the case study, where VISTAS scientists described the need both for a flexible visualization tool, and for training in using the tool. The increase of the extended peer community as in the post-normal science paradigm, often requires the scientist to design good visual output as a key to others’ understanding. Key to designing both the tool and the visualization is the realization that the scientist is most likely to use the visualization in telling a story about the results of his or her scientific research. Consider the dialogue between a VISTAS computer scientist and a VISTAS scientist at a development meeting in April, 2013:

Project Lead: I guess the one question: Does [the scientist] ever see his role diminishing as the boundary object? Could someone naive understand without him being the boundary object?

Computer Scientist: Look at this as a tool as part of the set of tools to make an end product that someone views. The Public is not going to sit down and use these tools...these are all tools that scientists use to produce a final product...final material is accompanied by metadata or the person who explains...

Based on the VISTAS experience, the scientists are characterized as primary users of the visualization tool, and the non-scientist stakeholder the secondary viewer, as demonstrated in the dialogue. One implication of this characterization is that, even if a scientist has a good visualization tool, understanding how to present data visually in a way others will understand is not obvious. How one views, experiences, and transposes the data—how one designs visualization—affects understanding the data. This problem is not widely addressed by the visualization research community, and as Desnoyers points out, “Most scientists were scarcely exposed to formal training in the use of visuals and it is our experience that students resort to learning by doing and imitating what they read and see, for better or for worse” [10]. He goes on to describe the need for more systematic training in visualization creation and use, especially due to the problem of polysemy, or the diversity of perceived meanings. In addition to training scientists, software design and development might take into account the context in which visualization might be used and characteristics of the various types of visualization users [41].

Findings from the VISTAS project distinguish those (scientists) who create data stories or narratives through visualization, and the audiences of these data stories. VISTAS problem-driven design method highlights the importance of creating software that serves both the primary users—the scientists who create models and visualize their output, and secondary non-scientist users—the stakeholders and decision makers who experience the data stories told by the scientists.

6. CONCLUSIONS AND FUTURE WORK

The primary lesson thus far from our experience working with scientists who present research results exploring wicked problems to non-scientist stakeholders is that the problem domain affecting the design of the visualization is likely much broader than originally conceived. Additionally, developers and scientists should be prepared to recognize when they are working with wicked problems and be cognizant of the range of audiences interacting with visualizations produced via a software tool. Finally, while these considerations will help improve design decisions made at the beginning of the project, it is unlikely that all decisions will be the right ones, and it might become necessary to revisit software design decisions as they arise. Developers and users need to be prepared for the time and cost of revising
assumptions that drove initial technology decisions. The lessons learned over the course of the VISTAS project apply to other similar software design and development projects where scientific data is to be visualized and used in decision-making processes and public policy settings.

Future research for the VISTAS project includes testing the visualization output of the VISTAS tool with various audiences in different settings. Additionally, researchers might track and measure the role of visualization in a problem-solving process, especially the extent to which the audience can use the visualization to provide insight into a problem, and where visualization might fall short of that goal.

More generally, research on group interaction with visualization, rather than single-user interaction, would provide insight into the contribution of visualization to the process of communicating results, or of telling a “data story.” And, finally research into how to create visualizations for non-scientists—which visualizations work (or don’t) and why (or why not)—is needed. We also need to train both computer scientists and scientists on designing such visualizations for diverse audiences.

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8. REFERENCES


