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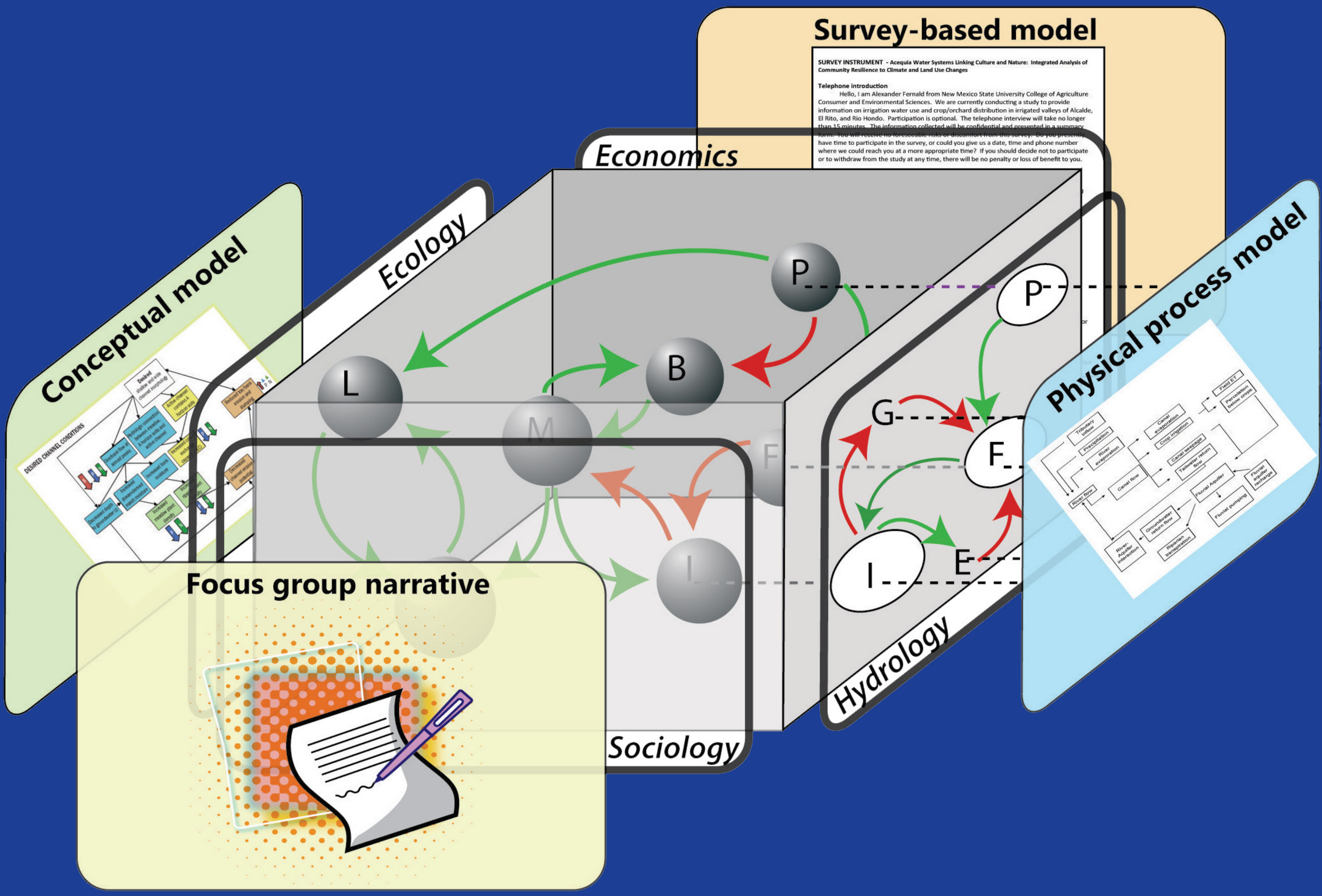

SURVEY INSTRUMENT - Acequia Water Systems Linking Culture and Nature: Integrated Analysis of Community Resilience to Climate and Land Use Changes

Telephone introduction

Hello, I am Alexander Fernald from New Mexico State University College of Agriculture Consumer and Environmental Sciences. We are currently conducting a study to provide information on irrigation water use and crop/orchard distribution in irrigated valleys of Alcalde, El Rito, and Rio Hondo. Participation is optional. The telephone interview will take no longer than 15 minutes. The information collected will be confidential and presented in a summary form. You will receive no foreseeable risks or discomfort from this survey. Do you presently have time to participate in the survey, or could you give us a date, time and phone number where we could reach you at a more appropriate time? If you should decide not to participate or to withdraw from the study at any time, there will be no penalty or loss of benefit to you.

# Interdisciplinary Modeling, Research, and Education

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**JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION**

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Cover figure represents multiple disciplines integrated into cohesive system dynamics model through collaborative development of causal loop diagrams (Fernald et. al, NSF #1010516 Dynamics of Coupled Natural and Human Systems, "Acequia water systems linking culture and nature: integrated analysis of community resilience to climate and land-use changes").

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# Journal of Contemporary Water Research & Education

**Issue No. 152** **December 2013**

# Interdisciplinary Modeling, Research, and Education

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# Interdisciplinary Modeling, Research, and Education

Timothy E. Link[1], Laurel Saito[2], and Alexander G. Fernald[3]

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Contemporary natural resources and environmental science research, management, and education communities are increasingly being challenged to develop approaches to address issues related to competing water resource demands in the context of a rapidly changing climate. To meet this need, a national commitment to innovative science focused on sustainability of ecosystem goods and services is included in President Obama's *Strategy for American Innovation* and the American Recovery and Reinvestment Act. This is also directly reflected in the budget guidance Memorandum M-10-30 by the Executive Branch's Office of Management and Budget (OMB) and Office of Science and Technology Policy (OSTP) that details research funding priorities (OMB 2010). In this memorandum, climate change and competing resource demands are explicitly noted as two of six science and technology priority investment areas for the United States. Science needs in the climate change focus areas specifically address assessment of impacts and vulnerability, and development of response strategies including mitigation and adaptation. The competing resource demands focus area entails the broad suite of freshwater, land, and ocean domains, and include the production and sustainability of food, fiber, biofuels, and ecosystem services. To accomplish these objectives, the Memorandum specifically states that resources should be focused to "support research on integrated ecosystem management approaches that bring together biological, physical, chemical, and human-uses data into forecast models, assessments and decision support tools." To support these strategic national directions, innovative educational opportunities with a focus on interdisciplinary modeling are needed to train the next generation of practitioners. In particular, practitioners need to be effective members of teams tasked with developing approaches to ensure the sustainability of water and related resources in the context of a changing climate (e.g., Pinter et al., 2013; Saito et al., 2012).

In order to advance interdisciplinary water resources research, student preparation in disciplinary integration and team-based work is needed for recent graduates to be competitive for large research grants. Recent announcements of research opportunities are likewise in accordance with the budget priorities outlined in Memorandum M-10-30, and will likely continue to be in the near future, given the resource challenges associated with growing populations, changing societal values, and climate variability. For example, a recent call from the National Science Foundation's (NSF) Water, Sustainability, and Climate (WSC) Program explicitly stated, "proposals that do not broadly integrate across the biological sciences, engineering, geosciences, and social sciences may be returned without review." A recent survey of other programs administered by NSF indicates that interdisciplinary grants related to water resources and climate change have been awarded funding via Integrative Graduate Education and Research Traineeships (IGERT), Coupled Natural and Human Systems (CNH), large, statewide Research Infrastructure Improvement (RII) grants via the Experimental Program to Stimulate Competitive Research (EPSC=oR), the USDA NIFA-AFRI grant program. Interdisciplinary modeling is often a key synthesis component of many projects funded through these programs, therefore coursework in this area should be an essential component of contemporary water resources education.

To meet the need of advancing education in interdisciplinary modeling related to water resources and climate, which has been widely recognized by both the government (OMB, 2010) and academic communities (e.g., Blöschl et al., 2012; Pringle, 1999), an innovative graduate course was developed in 2005 (Saito et al., 2007) and subsequently modified and refined based on rigorous assessments to most effectively serve the needs noted above. This special issue of the Journal of Contemporary Water Resources Education provides a series of papers that both describe the course format and provide several examples of course components. The course is a distinctive, team-based educational experience that is breaking new ground in water resources education. The course integrates a disciplinarily and geographically diverse mix of faculty and students in an intensive setting that combines interdisciplinary modeling lectures, case studies, student projects, and team-building social activities. The following sections provide a series of papers describing the course in general, followed by examples of disciplinary lectures, exercises, and interdisciplinary case studies that were presented in the most recent offering of the course in 2012. Although this volume does not contain a comprehensive collection of papers detailing the course components, the ones included in this issue provide examples of the types of approaches that various instructors employed. When taken in its entirety, this volume is intended to help guide other educators who are interested in developing a similar experience to advance interdisciplinary water resources education.

The paper by Saito et al. provides a detailed description of the development and implementation of the course and lessons learned during the process. The subsequent section detailing disciplinary modeling lectures contains examples of activities that provided students with an exposure to models used in different disciplines. This section begins with an example of general mathematical modeling by Herald et al. that uses solar radiation variability and size of icecaps as an example. This is followed by a description of vadose zone (VZ) modeling by Heinse and Link as an example of how to present VZ models to non-VZ scholars. The paper by Elbakidze and Cobourn presents a framework for hydroeconomic modeling as a means for an interdisciplinary audience of students to understand impacts of policies on coupled human and biophysical systems. The final education paper by Biondi emphasizes the importance of why the past matters and how to incorporate proxy data into watershed models.

The next set of papers present case studies where interdisciplinary models were used to address complex water and climate issues. The first three papers all relate to a National Science Foundation Coupled Natural and Human Systems funded study focused on the role of acequias (traditional irrigation systems) in sustaining human and natural systems. This large study was also the basis of a workshop embedded in the 2012 course offering for students to participate in an actual interdisciplinary modeling project directly focused on water resources in a changing climate. This project was therefore used as both a case study, and as the basis for team-based interdisciplinary modeling projects that comprised the latter third of the course. The paper by Guldan et al. describes how participatory research has been used to calibrate and refine system models of acequias, followed by a description by Gonzales et al. of how visualization methodologies have been used to model social-ecological dimensions, and finally by a description of how the physical hydrological connectivity within the acequia systems was modeled by Ochoa et al. The final two papers are examples of additional case studies related to interdisciplinary modeling that were used in the course. The paper by Sridhar describes how a land surface model can be coupled to a weather model to simulate land-atmosphere feedbacks. The special issue concludes with a paper by Elias et al. that provides an example of a case study where an economic and water supply model have been integrated to estimate the value of forests for sustaining water quality.

In summary, it is our intention that readers will find the following papers detailing the graduate course on interdisciplinary modeling for water-related issues and changing climate inspiring, interesting, and useful for developing or modifying similar courses to meet an important challenge in contemporary water resources education.

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# Lessons Learned From an Inter-Institutional Graduate Course on Interdisciplinary Modeling for Water-Related Issues and Changing Climate

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**Abstract:** Computer modeling is a useful tool for integrating approaches from different disciplines to address complex water and climate issues, but because academic training is typically disciplinary, many scientists and practitioners are not aware of modeling techniques in other disciplines or ways that different models can be integrated to address complex questions. Since 2005, we have conducted a course on interdisciplinary modeling that provides lectures and laboratory exercises from different disciplines as well as topics related to interdisciplinary modeling such as issues of scale and uncertainty. Students work in interdisciplinary teams to integrate modeling approaches from different disciplines to address issues related to water and climate. In this paper, we provide a description of course development and implementation, results of course evaluations of course content, lessons learned, and future needs for educating students about interdisciplinary approaches. We also provide results of surveys of course participants regarding course effectiveness and sustainability.

**Keywords:** *Interdisciplinary modeling, water, climate, education*

The need for training in interdisciplinary approaches to address water and climate issues is widely recognized (Barthel et al. 2012; Blöschl et al. 2012; Daraio et al. 2010; Ewel 2001; Johnson and Weaver 2009; Pringle 1999; Saito et al. 2012). Computer modeling is a useful tool for integrating approaches from different disciplines (Nicolson et al. 2002), but because typical academic training is principally disciplinary, many scientists and practitioners are not aware of available modeling techniques in other disciplines (Saito et al. 2007). Since 2005, we have been conducting an inter-institutional course on interdisciplinary modeling for water-related issues and changing climate. The course objectives were to increase students' awareness of modeling approaches in different disciplines and provide experience in working in interdisciplinary teams. The course originated with a week-long curriculum development workshop funded by the National Science Foundation (NSF; Saito et al. 2007). A first inter-institutional course offering between the University of Nevada Reno (UNR), the Desert Research Institute (DRI), and University of California at Davis (UCD) occurred in 2008. The most recent two offerings were conducted as part of the Western Tri-State Consortium (WTC; http://westernconsortium.org), which is a collaboration between the NSF-funded Experimental Programs to Stimulate Competitive Research (EPSCoR) for Idaho, Nevada, and New Mexico to improve infrastructure for climate change and water resources research in each state. A key feature of this course has been the use of multiple instructors from different institutions to provide lectures and laboratory exercises from different disciplines and perspectives. In this paper, we present a brief description of course development and implementation, results of course evaluations, lessons learned, and future needs for educating students about interdisciplinary approaches for addressing water and climate-related issues.

## Course Development and Implementation

The initial 2005 curriculum development workshop set the stage for future courses with extensive lecture content and intensive participant interaction (Saito et al. 2007). The workshop was formatted so that most of the presentations were one-hour lectures on disciplinary models related to water resource applications, or issues relating to interdisciplinary modeling in general such as scale and uncertainty (Table 1). At the end of each day, faculty and students spent time reflecting on considerations for developing the course as a full-semester course offering. Although a few local faculty and students commuted to the course, most were housed at Granlibakken at Tahoe City, California, a resort that allows for group accommodations with meals and meeting rooms. Thus, almost all faculty and students had all meals together, which facilitated additional informal interaction beyond the lectures and discussions. Participants went on a field trip to a local watershed for a portion of one day, and students worked in interdisciplinary teams to complete a proposal for an interdisciplinary modeling project related to this watershed as one of the three course exercises. The other two activities were a conceptual modeling exercise and a demonstration of an actual model linkage framework (the Modular Modeling System (MMS; Leavesley et al. 2002). Presentations on case studies were provided during dinner sessions. Student participants took the course for one or three graduate credits. All students attended all lectures and course activities, and prepared evaluations of each lecture, while students in the three-credit option also wrote a summary of an assigned lecture for potential use in a virtual textbook. Course materials were distributed on a wiki that was provided by the NSF-funded Digital Library of Earth Systems Education (DLESE). Preliminary funding to develop the proposal to host the workshop was provided by Nevada NSF EPSCoR through the Advanced Computing in Environmental Science (ACES) Program. Funding for travel, lodging, course fees (including tuition), and logistics was provided by NSF EAR-0509599 Interdisciplinary Modeling for Aquatic Ecosystems Curriculum Development Workshop. A graduate student was funded to assist with implementation of the workshop on this grant.

**Table 1.** Summary of Content and Course Format for Interdisciplinary Modeling Course Offerings in 2005, 2008, 2010, & 2012.

| Year | Course Format |
|---|---|
| 2005 | One-week workshop; housing and meals provided; one-hour lectures; no labs; three model exercises; one field trip; case study presentations by instructors; student interdisciplinary modeling proposal assignment; one-credit and three-credit options; used course wiki provided by Digital Library of Earth Systems Education (DLESE). |
| 2008 | Three-week course; no housing; lunch provided; two-hour lectures; two-hour labs; one field trip; case study presentations by instructors; interdisciplinary modeling project; used course wiki provided by the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI). |
| 2010 | Three-week course; housing and lunch provided[a]; two-hour lectures; two-hour labs; one field trip; case study presentations by instructors; interdisciplinary modeling project; used course wiki provided by CUAHSI. |
| 2012 | Two-week course; housing and meals provided[b]; two-hour lectures[c]; two-hour labs[d]; no field trip; two-day "conference" in middle of course; case study presentations by instructors; interdisciplinary modeling project; used course wiki provided by CUAHSI. |

[a] Breakfast and dinner per diems were provided to students and faculty who traveled to Reno.
[b] Breakfast and dinner were provided at the NMSU Student Union for students and faculty who traveled to Las Cruces.
[c] Most lectures occurred during the first week of the course.
[d] Most labs occurred during the second week of the course.

The first offering of the course in a formal three-credit graduate-level format was in 2008 as an inter-institutional course between UNR, DRI, and UCD. This three-credit offering was as a regular course as opposed to the 2005 one-week curriculum development workshop, so the three-credits were for coursework rather than for preparing a synthesis of a lecture as in 2005. A Coordinating Instructor was designated for UNR and UCD who was responsible for recruiting students and faculty to participate from each institution. Co-instructors were designated who helped to develop interdisciplinary modeling projects, interacted with students during the course as they worked on their projects, and assisted with the final assessment of projects. Additional guest lecturers provided lectures and laboratory exercises on disciplinary approaches and topical matters such as issues of scale and uncertainty. The course was offered over three weeks for eight hours per day at Sierra Nevada College in Incline Village, NV, with two-hour lectures in the morning, and two-hour laboratory sessions in the afternoon during the first two weeks of the course. A few case study presentations demonstrating interdisciplinary modeling efforts were made during the last week of the course. The students worked in interdisciplinary groups on interdisciplinary modeling projects in the afternoons during the final week of the course. There was one partial-day field trip in the middle of the course that related to some of the student projects. Because DLESE did not want permanent wikis on its site, the course wiki was moved to a wiki supported by the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI; https://cuahsi.centraldesktopcomintmod) and was used throughout the course to distribute course materials. Students paid tuition for the course which included nominal stipend coverage for coordinating and co-instructors and lunches for all participants. A small grant (a few thousand dollars) was secured to cover supplies for the course, transportation to the course site, and undergraduate student wages to assist during the course.

The course was offered again at UNR in 2010 in a three-week, inter-institutional format. In 2008, the states of Idaho, Nevada, and New Mexico were each awarded five-year NSF EPSCoR Research Infrastructure Improvement (RII) grants to develop research infrastructure related to climate change and water resources. Because all three states intended to develop climate and water-related models, a team of three faculty members from Idaho, Nevada, and New Mexico submitted a proposal to WTC for funding to offer the course as an inter-institutional tri-state activity. The WTC agreed to provide funding for travel, lodging, and logistics for the course, but asked that students pay tuition for the course. The course format included lectures, labs, case study presentations, a field trip, and interdisciplinary modeling projects. The modeling projects were related to issues being addressed by the EPSCoR projects in each state. Lodging was provided at UNR for instructors and students who traveled to Reno for the course. Unfortunately, meals were unavailable through dining services on campus, so per diem was provided for breakfasts and dinners. The wiki hosted by CUAHSI was again to disseminate course materials.

The WTC provided funding again in 2012 to offer the course as another tri-state activity at New Mexico State University (NMSU), this time with an umbrella focus area for the interdisciplinary modeling projects. Because one of the coordinating instructors (Fernald) had received an NSF Coupled Natural and Human Dynamics of the Earth System (CNH) grant related to acequia management in northern New Mexico, student interdisciplinary projects were centered on this theme. Instead of the three-week course model, a condensed two-week format was implemented in which two-hour disciplinary and topical lectures were offered during the first four days of the course, followed by two days of conference related to cross-cutting topics, case study presentations, and presentations related to the CNH acequia project. The next two days consisted of mostly two-hour laboratory activities, followed by over three days of unstructured time for students to work on their team-based interdisciplinary modeling projects. The CUAHSI-hosted wiki was again used as the virtual textbook for the course. Food and lodging for faculty and student participants who traveled to Las Cruces were provided on the NMSU campus.

A selective application process was used in all years to determine student composition of the class. Part of the reason for this was due to space and budget limitations, but it also enabled the selection of an interdisciplinary group of students with the background to effectively participate in student teams. In addition, in all years, break rooms were provided with refreshments and places for informal discussions, and a final social gathering was held when the students gave their project presentations and everyone celebrated the completion of the course.

Overall numbers of student and faculty participation in the course are summarized in Table 2. The lowest student and faculty participation occurred in 2008 when funding was not available for lodging and travel. Although the course was offered to both students at UNR and UCD that year, only UNR students participated, most likely due to the longer distance to be traveled by UCD students and housing constraints in the Lake Tahoe area in the summer. Also of note is the increase in faculty participants in the course from 2008 to 2012, with a large number of faculty participants involved in subsequent years.

**Table 2.** Summary of Participants in Interdisciplinary Modeling Course in 2005, 2008, 2010, & 2012.

| | 2005 | 2008 | 2010 | 2012 |
|---|---|---|---|---|
| Faculty Participants | 22 | 17 | 26 | 31 |
| Student Participants | 23 | 8 | [a] 23 | 25 |
| Institutions for Faculty Participation | 11 | 3 | 9 | 10 |
| Institutions for Student Participation | 6 | 1 | 6 | 7 |
| Faculty Who Participated in a Previous Offering of the Course | 0 | 6 | 11 | [b] 18 |

[a] One student participant was a post-doctoral associate.

[b] One faculty participant was a student in the course in 2010.

Table 3 summarizes the disciplinary backgrounds of the students involved in the course. The goal was to have an interdisciplinary group of students. As expected for a course that has a water-related theme, the largest representation of student disciplines was hydrology and water resources. However, in some years there were a substantial number of students from engineering and ecology, and students from more diverse disciplines such as political science, planning, social sciences, and economics participated in most years.

In all but the first year (2005), the course was offered for three graduate credits. In the first year, students had the option to take the course for one credit or for three credits, as described previously. In all other years, students received three graduate credits for submitting evaluations of all lectures and exercises and participating in interdisciplinary groups to complete the modeling project. In 2008, one student took the course pass/fail, but all other students completed the course for a grade.

## Course Evaluation

Course evaluation was an important aspect of each course offering because of the challenges involved in teaching to an interdisciplinary student body in an inter-institutional environment. In all years, every lecture and lab was evaluated by the students in terms of 1) how effective and thorough the lecture or exercise was in covering the material; 2) how effective the lecturer was in covering the material; 3) suggestions for improving the lecture or exercise; and 4) providing suggestions for other ways to present the topic. Evaluation forms were developed based on course syllabi. These evaluations were conducted using paper forms in all years except 2012, when an online format via www.zoomerang.com was used in which the evaluation forms were posted online and links to the forms were given to students. In 2012, evaluation results were compiled by SmartStart, Inc. (www.smartstartecs.com).

Students also evaluated the course for its overall effectiveness in meeting the course goals of 1) increasing awareness of models used in different disciplines to simulate water-related issues and climate change; 2) increasing knowledge of the challenges of applying models in an interdisciplinary context; 3) improving skills and confidence in working in interdisciplinary teams to address complex issues; 4) increasing confidence in doing interdisciplinary modeling; 5) increasing enthusiasm for working with interdisciplinary modeling approaches for addressing water-related issues and climate change; and 6) increasing interest in interdisciplinary modeling. Students completed a pre-course survey and a post-course survey to assess their gains through the course. The post-course survey also included questions regarding course logistics such as course format, location, lodging, food, and other issues related to course delivery. In

**Table 3**. Summary of Disciplinary Backgrounds of Student Participants in Interdisciplinary Modeling Course.

| | 2005 | 2008 | 2010 | 2012 |
|---|---|---|---|---|
| Animal & Range Sciences [a] | 0 | 0 | 1 | 2 |
| Atmospheric Science | 1 | 0 | 1 | 1 |
| Computer Science | 0 | 0 | 0 | 1 |
| Ecology [b] | 1 | 1 | 2 | 6 |
| Economics | 2 | 1 | 0 | 2 |
| Engineering [c] | 3 | 0 | 7 | 2 |
| Environmental Science | 1 | 1 | 2 | 1 |
| Geosciences [d] | 1 | 0 | 0 | 1 |
| Geography | 1 | 0 | 2 | 1 |
| Hydrology & Water Resources [e] | 12 | 4 | 5 | 7 |
| Mathematics | 1 | 0 | 0 | 0 |
| Planning [f] | 0 | 0 | 1 | 1 |
| Plant Science | 0 | 0 | 1 | 0 |
| Political Science | 0 | 1 | 1 | 0 |

[a] Includes forest, rangeland and fire science.
[b] Includes fish, wildlife and conservation ecology; ecology, evolution, and conservation biology; life sciences; wildlife science.
[c] Includes civil engineering; civil and environmental engineering; environmental and water resource engineering.
[d] Includes geology.
[e] Includes water resources; waters of the west; Antarctic and southern ocean studies.
[f] Includes community and regional planning.

all years except 2012, students completed these course surveys using the Student Assessment of Learning Gains (SALG) website (www.salgsite.org). In 2012, the same online format used for the lecture evaluations was used, and SmartStart, Inc. compiled the results.

In 2010 and 2012, faculty participants were also asked to provide feedback on the course in terms of its effectiveness in conveying interdisciplinary modeling issues as well as its effectiveness in stimulating interdisciplinary research and education activities among the faculty, a goal of the EPSCoR RII project that aimed to increase faculty capacity and collaboration across the Western Tri-State Consortium. In 2012, a follow-up survey was also prepared for all previous participants in the course (including those participating in 2012) to assess the course's influence over their subsequent careers. These surveys in 2012 were administered using www.zoomerang.com. In this paper, only results from the 2012 surveys are presented due to space constraints. Course evaluation results for other years were similar to 2012.

### Effectiveness of Course Content

On a scale of 1 (no help) to 5 (great help), students in the 2012 course rated the overall usefulness and quality of course components as much help. The average rating of specific class activities was much help, ranging from a high of 4.50 for working on class projects to a low of 2.88 for doing evaluations of the lectures. Evaluation of the pre-and post-survey results indicated that the students had significant ($p < 0.05$ for t-test comparisons) gains in all course goals except goal 5 (Figure 1):

- Goal 1: increase awareness of models used in different disciplines to model water-related issues and climate change.
- Goal 2: increase knowledge of the challenges of applying models in an interdisciplinary context.
- Goal 3: improve skills and confidence in working in interdisciplinary teams to address complex issues.
- Goal 4: increase confidence in doing interdisciplinary modeling.

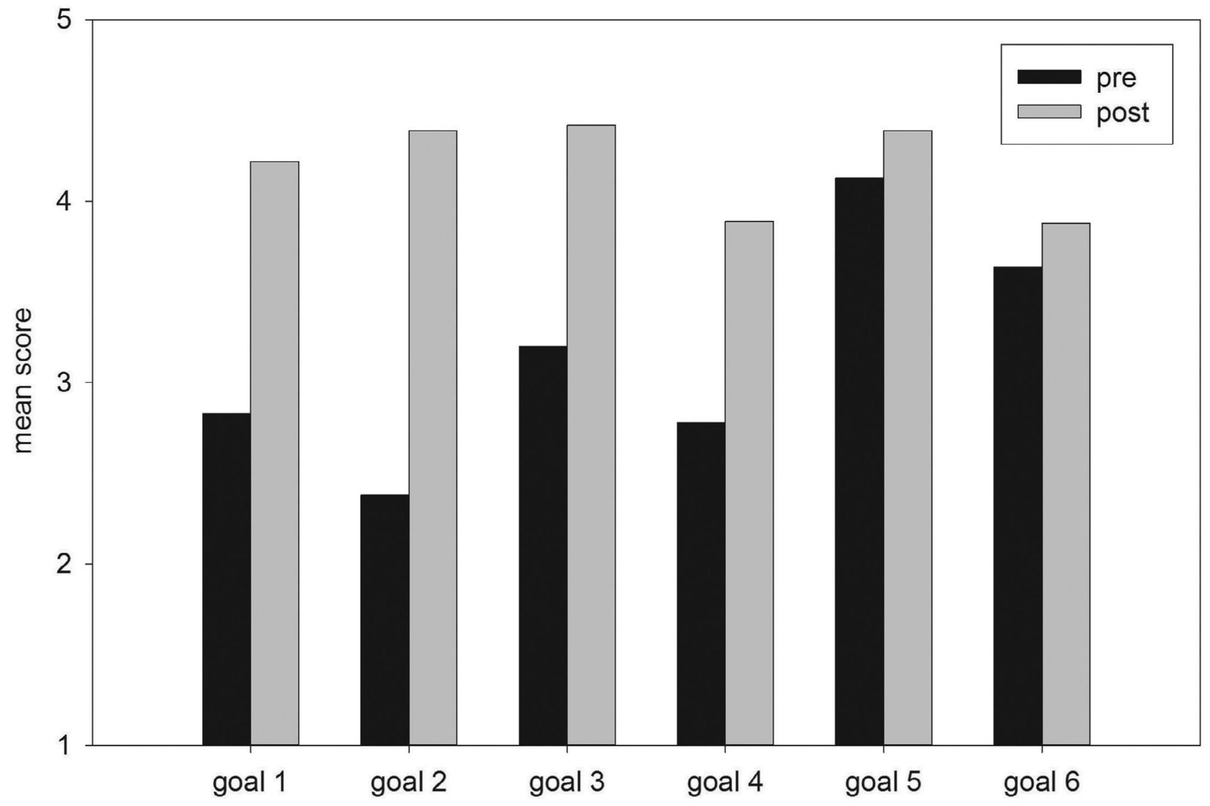

**Figure 1.** Pre- and post-interdisciplinary modeling course survey results (scale of 1 = not at all to 5 = a great deal) regarding course goals to: 1) increase awareness of models used in different disciplines; 2) increase knowledge of challenges of applying models in an interdisciplinary context; 3) improve skills and confidence in working in interdisciplinary teams to address complex issues; 4) increase confidence in doing interdisciplinary modeling; 5) increase enthusiasm for working with interdisciplinary modeling approaches; and 6) increase interest in interdisciplinary modeling.

- Goal 5: increase enthusiasm for working with interdisciplinary modeling approaches for addressing water-related issues and climate change.
- Goal 6: increase interest in interdisciplinary modeling.

The insignificant gain in Goal 5 could have been due to bias since students who chose to participate in the course may have done so because they were already interested in interdisciplinary modeling approaches as indicated by the high pre-survey mean.

### Results of Follow-Up Survey of Course Participants

The majority of student respondents to the follow-up survey provided comments about how they have been able to apply course knowledge and skills. A smaller number indicated that there had not been enough time for material to be applied, and a few reported not having applied course skills. The top activities reported by respondents as resulting from course participation included scientific research, making presentations, taking additional water/climate related courses, pursuing an advanced degree in a science-related field, and increased interest in teaching a course related to interdisciplinary modeling (Table 4). In addition, 64 percent of survey respondents indicated that they currently work in interdisciplinary teams.

### Faculty Impacts of Participation in the Course

Over half of the twenty-one faculty who responded to the follow-up survey indicated that participation in the course strengthened existing relationships (Table 5). The majority of responding

**Table 4.** Follow-Up Survey Results of Students Who Participated in a Interdisciplinary Modeling Course.

| Activity | Percent |
|---|---|
| I participated in scientific research. | 40 |
| I made presentations. | 28 |
| I took additional water/climate related courses. | 26 |
| I pursued an advanced degree in scientific-related field. | 26 |
| My interest in teaching a course related to interdisciplinary modeling increased. | 23 |
| I decided to pursue a career in science. | 21 |
| I prepared a paper for publication. | 14 |
| I submitted a grant proposal. | 9 |

n = 43
Percentages do not add up to 100 percent because respondents could select more than one answer.

**Table 5.** Follow-Up Survey Results of Faculty Who Participated in a Interdisciplinary Modeling Course.

| Impact | Percent |
|---|---|
| Ideas generated, improved, or will improve my research. | 75 |
| I collaborated, or will collaborate, on a project with another course participant. | 38 |
| I collaborated, or will collaborate, to develop a proposal with another course participant. | 29 |
| I collaborated, or will collaborate, to develop a paper with another course participant. | 29 |
| I collaborated, or will collaborate, to develop a new course with another course participant. | 8 |

n = 21

faculty also indicated that they generated ideas that have or will improve their research as a result of participating in the course. These results indicate that the course has substantial professional benefits for faculty participants that may not be present in courses that do not involve so many faculty or such a diverse group of inter-institutional faculty participants.

## Lessons Learned and Future Challenges

There have been several lessons learned as the course has been implemented several times since 2005:

- The involvement of an interdisciplinary group of faculty is a strong factor in obtaining an interdisciplinary student body. Most of the student participants heard about the class through one of the instructors in the course or through their advisor who was often one of the instructors in the course.
- The formal course application process ensured that students had the background and motivation to effectively engage in the course.
- The student team interdisciplinary modeling project was a highlight for the students (Figure 2). Having designated faculty for each group to provide thematic focus and abundant data reduced unfocused exploration and excessive data searching that could have distracted from the goal of giving the students experience in working together in interdisciplinary teams.
- Careful attention to group dynamics and explicit expectations of inclusiveness were important early in the conceptualization phase of setting up the course projects. The interdisciplinary project teams were designed by the coordinating instructors after observing students during several days of class interactions and examination of application forms in which students described their research interests and skills.
- The choice of models to present is important. In all years except 2005, Stella (www.isee.com) and Excel were the primary software packages used by faculty to do laboratory exercises, and a training session on Stella was included in the curriculum. Students were allowed to use any model they were familiar with for their modeling project, including Stella and Excel. In general, the faculty were encouraged to avoid using complex models in laboratory exercises to maximize efficient use of limited time.

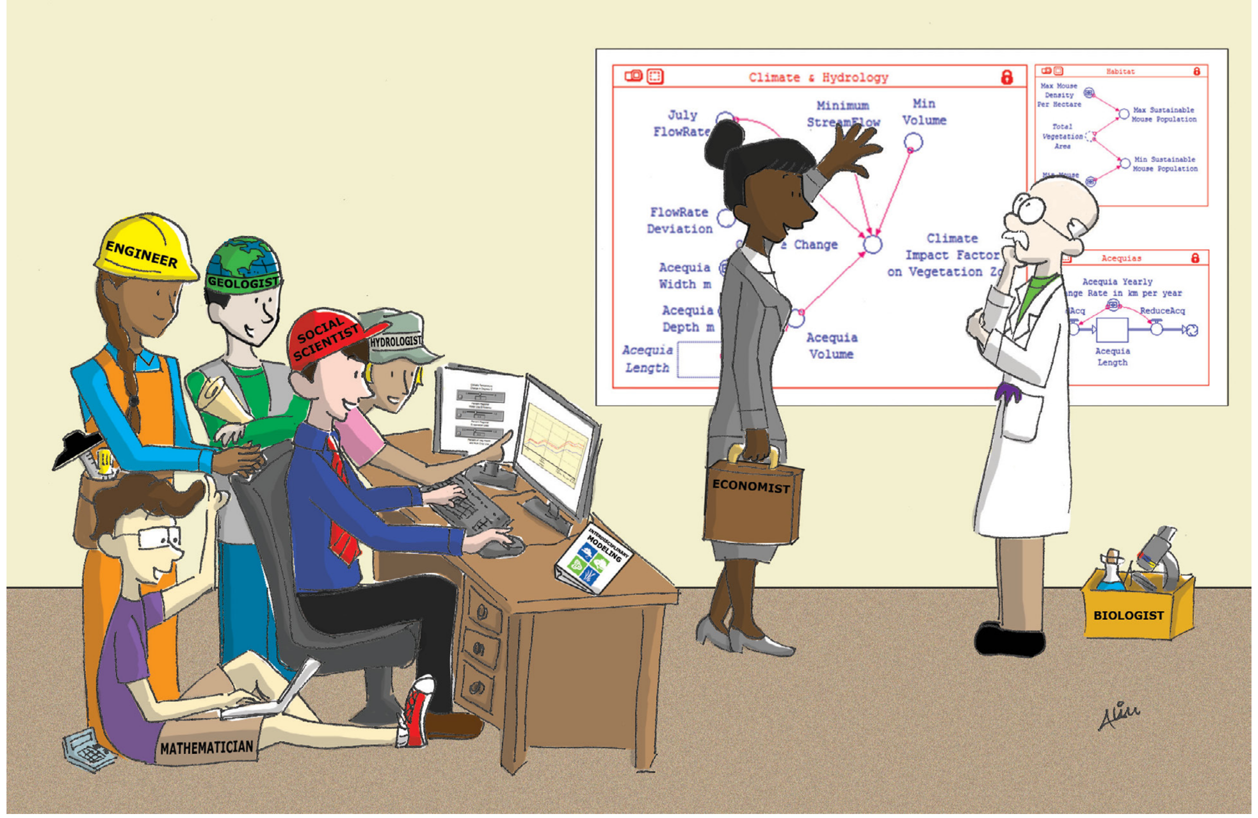

**Figure 2.** Illustration of the interaction among students on the interdisciplinary modeling project.

- The use of an online virtual textbook via a "wiki" has worked well for the course. The authors have been fortunate to use the DLESE and CUAHSI wikis which have not required a cost. However, such cost-free sites do run the risk of not being continually supported, which can then require that another site or service be found.
- Student-faculty interaction was greatly enhanced in 2012 when course participants were able to have all meals together rather than just lunches.
- The course should not be offered with a pass/fail option. Because the primary interdisciplinary activity for the students is the group project, having students involved who are not receiving a letter grade can influence attitudes towards group participation.
- Student team-building, productivity, and course satisfaction were enhanced by various informal activities (e.g., visiting local attractions, group dinners out, sports activities, etc.) in addition to the formal academic activities (Figure 3).

Overall, the results of course evaluations indicate that the course was very successful in achieving the stated goals. In addition, the follow-up survey indicates the course had a positive impact on both faculty and students in their academic and professional careers. However, the sustainability of the current model of an inter-institutional course with multiple instructors is questionable because of the costs involved in bringing students and faculty together from different locations. The majority of faculty (71 percent) and students (88 percent) who participated in the 2012 course would not have participated in the course if they had to pay for travel and lodging. In 2005, 2010, and 2012, travel and lodging were covered by grants. The low enrollment in 2008 was likely

**Figure 3.** Students and faculty from the 2012 course at White Sands, New Mexico.

due to the lack of funds to cover travel and lodging for UCD students (no UCD students enrolled in the course that year even though UCD faculty participated).

There are a few options for reducing travel and lodging costs. The duration of the course could be reduced, and the 2012 offering occurred over 12 days rather than 19 days as in 2008 and 2010. Both students and faculty from the 2012 offering preferred the shorter course duration and the shorter duration did not appear to affect the effectiveness of the course. However, the cost for travel and lodging was still substantial and further ways to reduce costs are needed.

Another option may be to offer the course either fully or partially via online or distance learning technologies to reduce or eliminate travel costs. Participants in the 2012 course were asked if the course should continue as a face-to-face course or if parts should be offered online. The majority of faculty (52 percent) and students (63 percent prefer that the course should be offered completely face-to-face as it has been thus far. Forty-three percent of faculty and 38 percent of students would like to see the course offered partially online and partially face-to-face. No students and only one faculty member preferred to have the course completely online. Thus, it appears that a partially online course might be a way of further reducing travel costs.

Survey results indicate the benefits of an inter-institutional course with face-to-face interaction appear to be very strong for both students and faculty. While such courses require planning at least a year in advance and strong coordination between institutions, the virtual textbook has been developed in hopes that others may be able to implement a similar course and build on materials produced by this course. It is hoped that budgetary coordination between institutions might enable these types of inter-institutional courses to continue to be offered so that more students and faculty can gain from interdisciplinary educational experiences.

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# Simple Climate Models to Illustrate How Bifurcations Can Alter Equilibria and Stability

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**Abstract:** Climate change is, by its nature, a truly interdisciplinary topic. While college level science classes now frequently include exposure to climate change issues, not all science majors, math majors and future math K-12 teachers are likely to see climate issues in the course of their studies. Here we present one self-contained topic that can be presented to those students without requiring too much additional explanation about climate change issues. This case study also can serve to illustrate the rather sophisticated concept of a "tipping point" to a diverse science audience without advanced training in dynamical systems. We consider the effect of solar radiation on the size of ice caps, and show that small changes in solar radiation can cause major irreversible changes in the size of ice caps. We present two sets of exercises that students can be asked to work on their own, after the overall conceptual model has been presented during the class. This material was inspired by the experience gained by one of the authors in teaching Interdisciplinary Modeling: Water-Related Issues and Climate Change course in summer 2012. It was used by the authors in a Math 420/620 Mathematical Modeling class at the University of Nevada, Reno in Fall 2012.

**Keywords:** *Tipping point, climate change, ice caps, bifurcation, mathematical modeling*

Climate change has recently become one of the most pressing scientific challenges facing society, as changes in various ecosystems, ocean systems, and atmospheric systems have been observed and documented (Weart 2008). In 1988, the Intergovernmental Panel on Climate Change (IPCC) was formed by two UN organizations to gather scientific information on the effect of human activity on climate and its potential impact on the environment and society. The Norwegian Nobel Committee highlighted the importance of understanding man-made climate change in its announcement (Nobel Peace Prize 2007) that the 2007 Nobel Peace Prize would be shared by the IPCC and Al Gore, stating that "Extensive climate changes may alter and threaten the living conditions of much of mankind. They may induce large-scale migration and lead to greater competition for the earth's resources. . . . Action is necessary now, before climate change moves beyond man's control."

Some of man's effects on the climate are gradual, but many models point to the possibility of abrupt changes in the near future (National Research Council 2002), which could be far more devastating for society and the environment, because there could be far less time to adapt. Our goal is to present the topic of climate change, particularly the subtle but crucial concept of a tipping point, to students with limited background in this area. By tipping point, we mean the phenomenon wherein small changes in circumstance in a dynamical system cause dramatic changes in its behavior.

In interdisciplinary modeling, researchers and students with diverse backgrounds, training, and perspectives combine their expertise in order to analyze one complex problem, but taking multiple effects simultaneously into account. Often in such situations, mathematics is treated as a black box that provides solutions to a system of differential equations. The system is usually highly complex and nonlinear, making it necessary to rely on the results of the numerical simulations. Typically, the parameter values are usually not known precisely, and there is uncertainty about the form of the functional expression of many processes. Thus results of numerical simulations should be viewed cautiously, and additional analysis is required.

One of the authors has had first-hand experience participating in an interdisciplinary modeling course, Interdisciplinary Modeling: Water-Related Issues and Climate Change, in summer 2012. At the end of the course, the students from many varied backgrounds completed projects modeling multiple phenomena. Often they used the Stella software to simplify the mathematical solution of the differential equations, with little appreciation of the dangers of blindly trusting results from numerical simulation. We want to emphasize that results of black box calculations should be evaluated critically.

In this paper we consider one mathematical phenomenon, of which people doing interdisciplinary modeling must be aware – bifurcation and tipping points. In linear systems, our intuition that small changes in parameters will result in small changes in the outcome is valid. For nonlinear systems, this may not be so; it is often the case that solutions are highly sensitive to small changes in parameters.

We present a case study with two sets of exercises developed for an interdisciplinary modeling class. We used it in teaching the mathematical modeling class at the University of Nevada, Reno. The course is geared towards STEM majors and future high school mathematics teachers. These new exercises do not require extensive background in climate change models or sophisticated techniques to analyze complicated dynamics. Thus, we hope to bring some of the compelling questions of climate change to a broader audience of students.

With a little tailoring, these exercise sets may be equally valuable in bringing calculus-literate science and engineering majors into a fruitful exploration of the relevant dynamical system behavior as well. Depending upon the mathematical backgrounds of the students in an interdisciplinary course on climate change, the dynamical models explored here could be approached using qualitative theory of differential equations, graphical methods, or ready-made packages for solving differential equations. After investigating this toy model of a tipping point, there is room to have broader discussions of other feedback loops that make up components of the complicated earth climate system, such as permafrost melting, methane hydrates, and cloud cover.

There are many great challenges in modeling climate change and its effects, largely because the earth's climate involves so many interconnected factors. Some of the most important current debates have to do with the most fundamental properties of climate behavior and how changes in the amount of greenhouse gases in the atmosphere, ice cap size, etc., will affect the climate. For example, might relatively small changes in these conditions alter the climate so that it is no longer in (or near) a stable equilibrium? We now investigate this question with a very simple model, with minimal prerequisite background.

It has been documented that temperatures have been rising in recent decades, and it is clear that ice packs and glaciers in various parts of the world are receding, very likely as a result of the increased temperatures. Current climate trends are expected to lead to continued melting of the ice caps, resulting in an 18 to 59 cm increase in sea levels over the next century (Intergovernmental Panel on Climate Change AR4, SYR 2007). These projections do not take into account all possible feedback loops between ice sheet melting and climate change (Jarvis 2013). Such rises in ocean levels can logically be expected to cause dramatic flooding in many coastal areas, virtual destruction of certain low-lying island nations, and radical changes in many ecological and climate systems around the globe.

Let's leave aside the questions of whether the human race has the technology, political will, political structures, and determination necessary to radically cut our $CO_2$ emissions, or even take bold steps such as wider implementation of carbon sequestration to draw significant amounts of existing $CO_2$ out of the atmosphere. At best, implementing such changes would take time. What changes are needed to avert disaster, and by what deadline? Is it conceivable that, after the current disturbances in greenhouse gas levels, the climate will change dramatically, even if we manage to return the $CO_2$ levels to the old values?

Climate change discussions often refer to a tipping point, a point at which the dynamical system governing the climate is altered, causing the equilibria to change dramatically. Even though the system remained for a long time in an equilibrium or oscillatory pattern, the behavior after passing the tipping point can be very different. Read, for example, Hansen (2008).

The expected, familiar behavior of physical phenomena governed by dynamical systems is that there are equilibria, perhaps some stable and others unstable. Because of occasional disturbances to the system from outside influences, we don't expect to find a natural process resting in an unstable equilibrium, for example, like a bowling ball perched on a pointed mountain peak. Over time, if outside factors change gradually, we tend to expect the equilibria in a system to change gradually. But in some cases, a small change in a parameter in the system can cause a bifurcation, that is, a change in the set of equilibria; and the result can be a transition to a very different equilibrium.

In this study, we will explore two fairly simple models of certain aspects of the climate system to illustrate that the presumption that gradual change in parameters leads to gradual change in equilibria can be incorrect. We illustrate instances where a gradual change in outside factors (which are parameters in our dynamical system) can give rise to sudden dramatic shifts in the behavior of the dynamical system. Furthermore, we will explore whether resetting a parameter value back to its old value necessarily leads the system to return to its old stable equilibrium. For example, if gradual change in certain climactic parameters like greenhouse gas levels reach a point where some dramatic change begins to happen, will backing off those parameters save the system from catastrophic change?

## Modeling Ice Cap Size as a Function of Solar Radiation

Let us consider the effects of solar radiation level on ice cap size. Roughly speaking, solar radiation affects temperatures (by different amounts at different latitudes), and those temperatures affect the formation or melting of polar ice caps. But, in addition, the existence or nonexistence of ice caps in certain regions affects the absorption and reflection of solar radiation. This is what is known as a feedback loop. (Similar feedback loops occur when temperature alters the amount of water vapor or cloud cover in the atmosphere, which then affects radiation absorption and cooling of the planet).

We consider solar radiation level not because changes in solar radiation are thought to be a primary driver of the global warming being observed, but as a proxy for other forms of warming, without the complications of multiple feedback loops in our model. We start with some comments on a differential equation to illustrate how small changes in a coefficient can have a profound effect on the behavior of solutions.

### Preliminary Remarks on ODEs

We start with a brief discussion of some properties of differential equations. The parameters in a differential equation can affect how many equilibria there are, and what stability properties they have. Behavior of nonlinear equations, which often appear in applications, are more complex than that of linear equations. Consider, for example, the differential equation:

$$\frac{dx}{dt} = -(x-a)(x-b)(x-c) \text{ when } a < b < c.$$

Since $f(x) = -(x-a)(x-b)(x-c)$ is positive on $(-\infty,a)$ and $(b,c)$ and negative on $(a,b)$ and $(c,\infty)$, we see that there are three equilibria: $x = a$ and $x = c$ are stable, but $x = b$ is unstable.

Next, consider the same differential equation, but with $a = b < c$. Then $f(x)$ is positive on $(-\infty,b)$ and on $(b,c)$, but negative on $(c,\infty)$ so $x = c$ is stable but $x = b$ is semistable.

Finally, consider the differential equation:

$$\frac{dx}{dt} = -((x-b)^2+\epsilon)(x-c).$$

When $\epsilon = 0$, this agrees with the previous case, but as soon as $\epsilon > 0$, there is only one equilibrium, $x = c$, and it is stable. This illustrates that varying a parameter can cause bifurcations, sudden changes in the number and/or stability properties of equilibria. In climate-related applications, it is an illustration of the tipping point concept.

### North's Ice Cap Model

Gerald North has studied a model for average sea-level temperature $T$ as a function of $x$ = sin(latitude) and time $t$, which takes into account warming from solar radiation at different latitudes, diffusion of heat from warm areas to cold areas, and the albedo (reflectiveness) of ice cap and ice-free regions (North 1984).

The evolution over time of the sea-level temperature may be modeled by a partial differential equation:

$$\frac{\partial T}{\partial t} = D\frac{\partial}{\partial x}\left((1-x^2)\frac{\partial T}{\partial x}\right) -A - BT+QS(x)a(T).$$

In this formula, $Q$ is the solar constant divided by 4, measured in $W/m^2$, $D$, $A$, $B$ are empirical constants,

$$a(t) = \begin{cases} 0.38 \text{ for } T < -10°\text{C} \\ 0.38 \text{ for } T < -10°\text{C}' \end{cases}$$

represents the co-albedo (so a higher $a(T)$ value represents lower reflectivity and greater heating through absorption of sunlight), and $S(x)$ is the mean annual sunlight distribution.

The methods required to solve this partial differential equation go beyond the scope of the present analysis, but we will derive from this equation a simpler model for the size of the ice cap, and how it evolves over time.

We can obtain an ordinary differential equation (ODE) describing the temperature in the steady state regime by setting $\delta T/\delta t$, namely:

$$-D\frac{d}{dx}\left((1-x^2)\frac{dT}{dx}\right) +A + BT = QS(x)a(T).$$

This model contains the following feedback loop: the co-albedo in a region is determined by whether it is covered with ice, and this is determined by whether or not $T(x) < -10°$, but this co-albedo affects the solar heating.

Solutions to the ODE for the Northern Hemisphere satisfying appropriate boundary conditions ($dT/dx = 0$ at $x = 0$ and $x = 1$, in order to extend to symmetric solutions on the sphere) are potential steady-state temperature distributions. For each such temperature distribution, the lowest value of $x$ above which $T(x) < -10°$ is an equilibrium ice cap size.

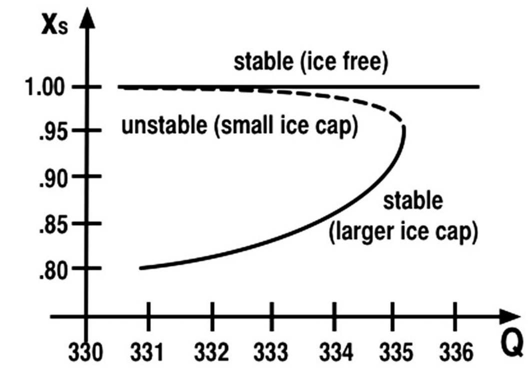

**Figure 1.** Ice cap size versus solar constant. Line $x_s = 1$ corresponds to the stable solution with no ice cap present; dotted curve corresponds to an unstable small ice cap; solid curve corresponds to a stable ice cap of larger size.

Even solving this nonlinear ODE with boundary conditions requires techniques beyond the scope of many Mathematical Modeling courses, so we will rely on the numerical work done in (North 1984), and focus our attention on the equilibrium ice cap sizes, determined by $Q$, the average amount of solar energy received by a square meter of the earth's upper atmosphere at the equator. We normally think of $Q$ as constant, but it might change with a deformation of the earth's orbit, or with changes in the power released by the sun. In terms of global warming considerations, we can view an increase in the value of $Q$ as a proxy for an increase in greenhouse gas levels, which increases the absorption or retention of solar energy.

North's analysis leads to the surprising conclusion (Figure 1) that the equilibrium ice cap size is not uniquely determined by $Q$. Figure 1 qualitatively matches the results of his numerical simulations. Namely, for a certain range of values of the $Q$ parameter in the model, there are three different steady state ice cap sizes. In this diagram, $x_s$ denotes sine of the latitude of the ice cap boundary. Note also that the middle equilibrium, in the range of $Q$ values where there are three, is unstable; the other two are stable. For example, when $Q = 332$, there are three steady state $x_s$ values. One is $x_s = 1$, meaning that there is no ice cap all the way up to latitude 90°; this one is stable, in that if there was a very small ice cap around the pole, it would melt away. The second $x_s$ equilibrium is slightly smaller, around 0.99 (meaning a small, but nonempty ice cap), but this is unstable; if the ice cap is a little smaller, it shrinks to nothing, and if it is larger, it grows. Finally, there is a third stable equilibrium $x_s \approx 0.8$, corresponding to latitude ≈

55°. As $Q$ increases toward 335, the two lower $x_s$ equilibrium values get closer together, and they ultimately meet and disappear around $Q = 335$.

### A Cubic Model for Ice Cap Size

We now shift our attention to a simpler dynamical model, where the ice cap size, measured by $x_s$ = sin(latitude of boundary), satisfies a differential equation involving the parameter $Q$, and has three similar equilibria for $332 < Q < 335$ (with the middle one unstable, the others, stable), and around $Q = 335$, the lower equilibria come together and disappear, leaving only the stable equilibrium at $x_s = 1$. The primary simplification is that we treat the ice cap size as one quantity whose rate of change depends on its current value and $Q$, rather than having the ice cap size and the entire temperature distribution $T(x)$ interdependent on one another.

This model is given by:

$$\frac{dx_s}{dt} = (1-x_s)\left(Q-355 + 3 \cdot \left(\frac{x_s-0.89}{0.09}\right)^2\right)$$

Assume here that $t$ measures time in centuries. We next present a sample set of student exercises pertaining to this cubic model.

1. Figure 2 shows an implicit plot of the equilibrium $x_s$ values for a range of $Q$ values, created using a computer algebra system without attention to using sufficiently fine resolution. Compare this with the conclusions you reach using algebra. How should the correct figure look? What qualitative differences are there between the behavior of the equilibria in this model and the equlibria approaching each other asymptotically in Figure 1?
2. Assume $Q = 333$. Verify by simulating with a few initial values that there is a stable equilibrium near $x_s = 0.82$.
3. Still assuming that $Q = 333$, what sort of simulation scheme would allow you to find the unstable equilibrium near 0.99? (Hint: think about running time backward.) Carry this process out.
4. Assume that $Q$ has remained around 333 for a long time and $x_s$ has settled into the stable equilibrium found in Part 2, but then external factors suddenly cause $Q$ to jump up to 336. Assuming it stays up this high from then on, what happens to $x_s$, and what does this imply about the ice caps?

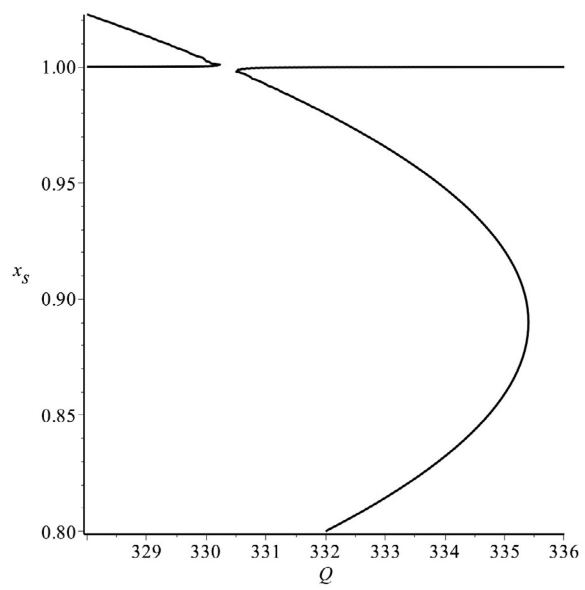

**Figure 2.** Ice cap size versus Q (implicit plot from cubic model).

5. Assume that $Q$ has been 333 and $x_s$ has been at the stable equilibrium from Part 2, but $Q$ then increases to 336 for a finite time interval of M years, after which it decreased to $Q = 333$. Use simulation to determine what happens if M = 50, M = 100, M = 200. Explain in English what your conclusions are for these scenarios.

This model was developed by approximating the $x_s < 1$ equilibria (Figure 1) by a parabola passing through xs = 0.80 and $x_s = 0.98$ for $Q = 332$ and having a vertex at $Q = 335$. The factor $(x_s - 1)$ adds another equilibrium at $x_s = 1$, independent of $Q$.

Parts 1 through 5 of the problem provide opportunities for students to explore with numerical techniques what the stability means for the different equilibria in this dynamical system, which has $Q$ as a parameter. Parts 4 and 5 get at the heart of the question of whether small parameter changes can cause catastrophic climate change. We note that students can do the numerical simulations with Euler's method or other standard techniques.

### A Second Model for Ice Cap Size

The cubic model in the previous section does an adequate job fitting North's model when $332 \le Q$, but this model also had the property that the upper and middle equilibria crossed when $Q$ dropped below a certain level. We next discuss a slight modification of this differential equation which displays some different features as $Q$ is varied:

$$\frac{dx_s}{dt} = -0.003+(1-x_s)\left(Q-355 + 3 \cdot \left(\frac{x_s-0.89}{0.09}\right)^2\right)$$

In the ranges $332 < Q < 335$, this model again provides a pair of equilibria similar to the two branches of a parabola, as well as a third equilibrium near $x_s \approx 1$. But in this model, the $x_s \approx 1$ and the unstable equilibrium cancel each other out and disappear when $Q < 331.5$. The set of equilibria for a range of $Q$ values is illustrated in Figure 3. In this model, assume that time $t$ is again measured in centuries.

Here, again, we present a series of student exercises pertaining to this model.

1. Assuming $Q = 334$, locate the three equilibria using numerical solvers. Linearize to determine the stability of each.
2. Use a computer algebra system to reproduce the same graph as Figure 3.
3. In the region illustrated in Figure 3, where is $dx_s/dt$ positive and where is it negative? Figure 1 indicates the stability or instability of the equilibria corresponding to different parts of the curves. On your copy of Figure 3, identify which parts of the curve correspond to stable equilibria and which correspond to unstable equilibria.
4. If the solar constant has been $Q = 333$ for some time, and the ice cap size is at the lower $x_s$ equilibrium, but then $Q$ is raised suddenly to 336 for 200 years, and then it is returned to 333, what will happen to the ice caps?
5. Suppose that the solar constant has been $Q = 333$ for some time, and the ice caps have been at the lower $x_s$ equilibrium, but then $Q$ is raised suddenly to 336 for 135 years. At this point, suppose that through massive technical advances, the human race develops the ability to decrease $Q$. How far would we have to decrease $Q$, at least on a temporary basis, in order to restore the ice caps to their historical size? Explain and illustrate with diagrams of some kind.

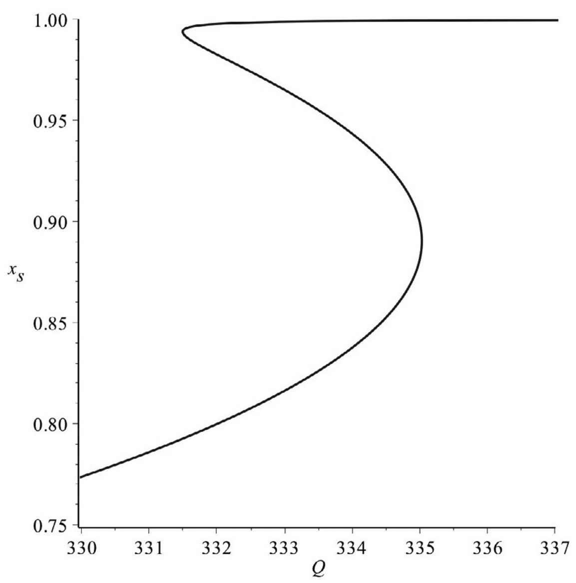

**Figure 3.** A second nonlinear model of ice cap size versus solar constant.

## Conclusion and Discussion

Our goal with these two sample problem sets is to increase the awareness of climate change issues among students who may not have any other exposure to climate change in their coursework. In order to be successful in conveying the main ideas, we ask students to read the paper by North (1984) beforehand; it is often the case that math and math education students do not read a single scientific research paper during their undergraduate studies. Reading an actual research paper allows them to see that important information is presented not only in textbooks but also in research publications, and that with their mathematical background, they are in a position to understand some of the research literature. During the class dedicated to climate change we explain in detail the key equations of North's paper and our further set of simplifying assumptions.

With these climate projects we try to convey the point that, in a nonlinear system, small changes in parameters can lead to major changes in the behavior and, moreover, changes can be irreversible. The climate on Earth is highly a nonlinear system. We presented a simple model that uses a nonlinear ordinary differential equation with a bifurcation point; for multiple examples of such systems see Strogatz (1994). Similar in spirit to our model is a conceptual model describing circulation in Atlantic Ocean saltwater versus freshwater input (Figure 8.4 in Broecker 2010). Again, under certain conditions, the system may be close enough to a bifurcation point that even a small change in the amount of incoming freshwater to the ocean can completely alter the circulation pattern.

We note that similar energy climate models were considered in various papers. We refer to just a few of them (Cahalan and North 1979; Drazin and Griffel 1977; North 1990). In general, the modern energy climate models were developed independently by Budyko and Sellers, and the current model is also an example of an energy balance climate model. While it would be great to present more of Budyko's original work to the students, the time constraints in our modeling class required a more restricted focus. More comprehensive treatment of climate energy models likely will fit better into the curriculum in atmospheric sciences or various interdisciplinary programs. We have at least succeeded in conveying to students outside these disciplinary areas that even small changes can have extreme effects on the climate.

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# Vadose Zone Processes: A Compendium for Teaching Interdisciplinary Modeling

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**Abstract:** We describe one approach of teaching vadose zone (VZ) processes to non-vadose zone (NVZ) scholars interested in the water and climate change nexus. Our objective is to introduce key models and input parameters, briefly explain the mechanics of solving the problem using the Richards equation approach, and to point out alternative and scale-dependent approaches and solutions. Our goal is to provide enough information such that students gain some familiarity with key terms, have a rudimentary mechanistic understanding, and most importantly, know where to look for more information. We recognize that in some situations a significant amount of complexity is embedded within problem solutions, and we have not attempted to broaden the scope to include every interaction. Rather, we focus on the defining principles of soil-water physics to introduce the VZ to NVZ scholars. We propose the use of water as a lens to allow for an accessible categorization of VZ processes. This in turn will form the foundation for the impact of those models on student learning, experiences and attitudes towards VZ modeling.

**Keywords:** *vadose zone, soil water, soil physics, hydrology*

The vadose zone (VZ) refers to the shallow (from latin: *vadosus*) zone of unsaturated porous media roughly between the land surface and the groundwater (Figure 1). Having varying thickness from a few centimeters in wetlands to several hundreds of meters in arid climates, the VZ is characterized by porous media (soil or fractured bedrock) partially saturated with a wetting fluid (e.g., water). The dynamics of water in this zone are intrinsically linked to the hydrologic cycle via partioning of water at the land surface and regulating the movement to and from the groundwater, thereby effectively governing interrelationships between precipitation, surface runoff, infiltration, groundwater recharge and evapotranspiration. As such, the VZ takes a central role in the critical zone describing the most heterogeneous and complex region for life on Earth that encompasses the region between the top of the vegetation canopy to the bottom of the groundwater aquifer (Lin 2009) in which rock, soil, water, air and living organisms regulate the natural habitat (National Research Council 2001). As one central theme, water fundamentally frames environmental, hydrologic, socio-economic, and agricultural problems in this zone. Through the lens of water flow and distribution, the disciplines of soil physics and hydrology study the VZ.

## Outline

In this compendium, we summarize and extend on a two hour VZ lecture plus modeling exercise given to interdisciplinary students engaged in water resources research. While developing this paper we aim to address two main questions: (1) what role does the VZ play in interacting and intersecting spheres explored through the lens of water, and (2) what are the modeling approaches for VZ water? We begin with the following pillars:

1. There is no panacea for VZ modeling approaches for all scales and interactions.
2. Water regulates much of the interactions with life in the VZ. Its status determines hydration of organisms, access to nutrients, exchange of metabolic products, as well as critically influences thermal and chemical properties of soils contributing to habitat formation.

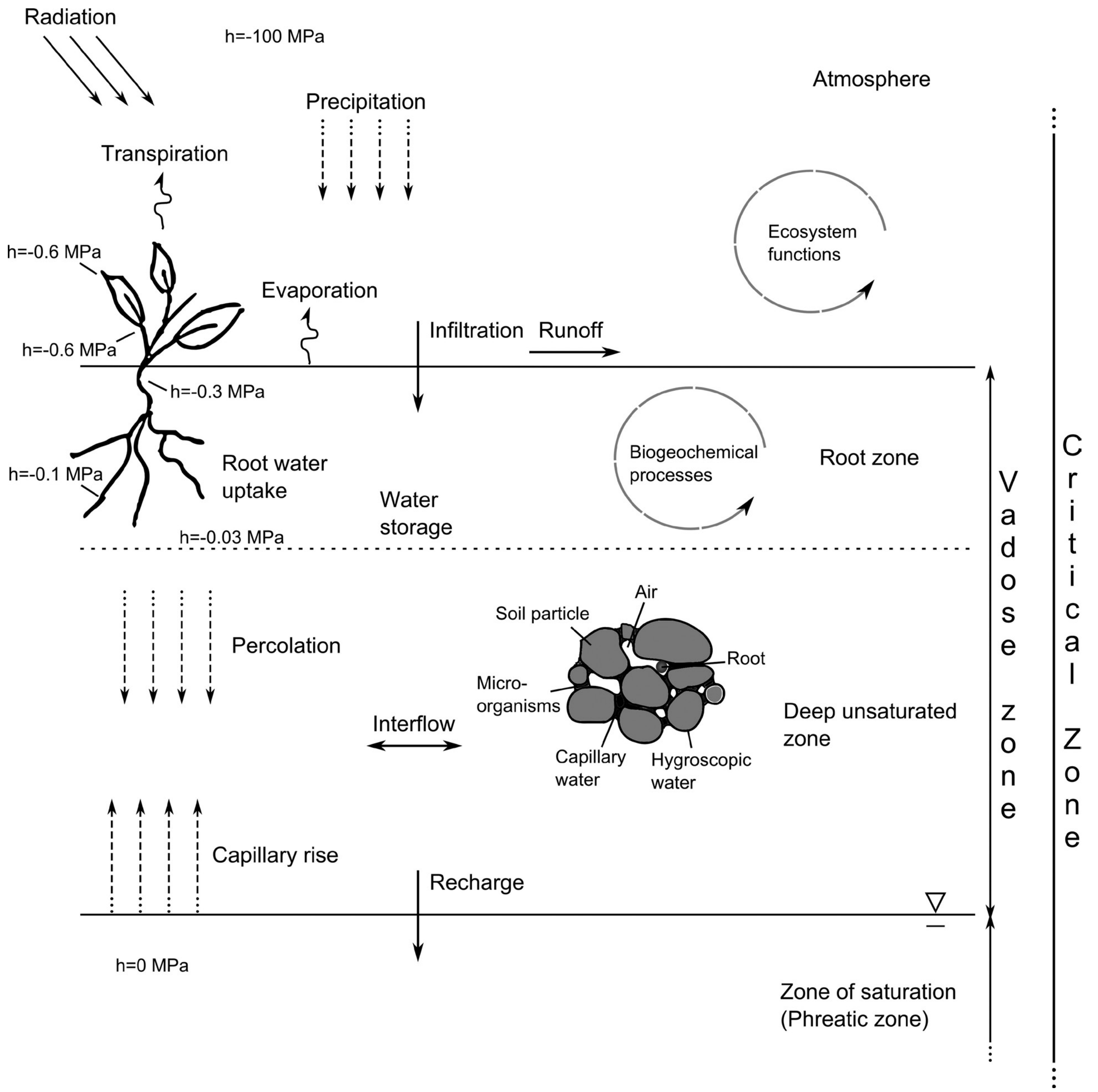

**Figure 1.** Fate and distribution of water in the vadose zone. Characterized by porous media along with water and air which distribute according to energy potentials closely tied to pore sizes and shapes, various constituents and participants benefit from, and modify the VZ environment. For example, plants compete with the porous media for capillary water held in the pore space and remove water from the root zone driven by a gradient of soil-water potentials h which become increasingly more negative. With decreasing water contents in the VZ, the connectivity for gas-filled pathways that facilitate aeration increases. Similarly, thermal, chemical, pedological and biological processes are critically affected by water contents and fluxes. To facilitate optimal biogeochemical processes and support resilient ecosystem functions in the critical zone, some optimal balance (i.e., a critical window) of soil water, gas exchange and nutrient availability must be maintained in the VZ.

3. The VZ is a thin layer constituting a natural resource that contributes to the resilience of ecosystems by acting as a low-pass filter for variability in weather, resource availability and toxicity (e.g., contaminants and solutes).
4. The Richards equation is the most common modeling approach for VZ water from the sample to the field scale.
5. Pore- and watershed-scale models utilize alternative modeling approaches with up- and down-scaling bridging the scale gap or addressing a parameterization problem.

Using these five pillars we aim to make VZ processes and modeling accessible to non-VZ students with a strong bias towards water resources. Necessarily, we cannot provide a complete treatment of VZ processes and interactions nor a complete treatment of modeling approaches. Rather, the goal of this paper is to provide an overview and compendium of resources that enable a big-picture understanding and sufficient opportunities for further reading. To facilitate a dialogue between disciplines, we have tried to reduce technical jargon and mathematic rigor in trying to explain what VZ modelers are doing.

## Why VZ Processes are Inherently Interdisciplinary

The study of the VZ has long been central to agronomic, hydrologic, ecologic, and engineering sciences. Yet the VZ is a complex and dynamic system driven by natural processes and affected by human activities that defy disciplinary borders and place the VZ in a larger interdisciplinary context as the seminal crucible of terrestrial life (Hillel 2007).

The VZ is a diverse system composed of "constituents" (i.e., solids, liquids, solutes and gases) and "participants" (i.e., microbes, animals and plants) whose development and function is shaped by climate, parent material, topography, humans and time. Despite its relative thinness compared to the atmosphere, the lithosphere and even the phreatic zone (saturated aquifer), the VZ plays a central role in the terrestrial hydrologic cycle with its capacity to absorb, store, and transmit water among these spheres. The VZ also acts as a filter and buffer for dissolved or suspended compounds, thereby determining fate and transport in biogeochemical cycling closely linked to the hydrologic functions. These coupled processes in the VZ are central to mutual interactions involving water, air, soil, rock, organisms, and humans that regulate the natural habitat (Lin et al. 2011).

The partioning of energy and mass at the land surface as well as the distribution and fluxes within the VZ are determined by interactions of porous-media solids with fluids (i.e., water and gases), microbial and vertebral participants, as well as plant roots. Water, because of its tendency to wet solid surface (i.e., forming liquid films, bridges and curved interfaces), largely controls the connectivity and tortuosity of pathways for the flow of water and gases, thereby mediating biogeochemical reactions dependent on some balance and composition of these phases. Therefore textural and structural porous-media properties fundamentally determine whether incoming precipitation will generate overland flow, infiltrate, be made available to plant roots, or contribute to groundwater recharge. On the other hand, solar radiation absorbed by the land surface and plants drives evaporation, condensation, transpiration and biochemical reactions that exchange heat, water and gases between the VZ and the atmosphere.

Being at the nexus of water and energy fluxes, VZ processes are essential for water and ecosystem health (e.g., Robinson et al. 2012) where soil functions depend on a small degree of multitude soil organisms. This biodiversity and ecological functions are interrelated (Ekschmitt and Griffiths 1998; Wardle et al. 2004) at local, regional and global scales. VZ resource pools and organism interactions alter dynamics of water and nutrient resource availability such that they alter the functional stability and ecological resilience. VZ water in particular constrains the resources for biota, which in turn control the spatial and temporal patterns of vegetation (D'Odorico et al. 2010; Porporato and Rodriguez-Iturbe 2002). Feedback loops such as these highlight the mutual impacts of VZ processes on the climate (Seneviratne et al. 2010). Plants, above all, play a central role in theses feedbacks acting as the chief connector between atmosphere, below ground strata, and organisms in the exchange of greenhouse gases (i.e., water vapor, carbon dioxide, methane, and nitrous oxide). Carbon dioxide synthesized with VZ water and nutrients then forms the largest terrestrial organic carbon stock (second in size only to the oceans) which interacts strongly with the atmosphere, climate and land-use change to mediate the global greenhouse effect (Jobbagy and Jackson, 2000).

The complexity of interactions within and between VZ constituents and participants necessitate interdisciplinary study and modeling approaches. Consequently, many VZ models address fluxes, distribution and exchange of energy and mass at the boundaries and within the VZ, its interactions with plant roots and organisms as well as interactions, exclusions and accelerated transport of chemicals and colloids. However, because the study of the VZ has historically been disciplinary, simulation models tend to express linkages between constituents and participants explicitly (Šimůnek and Bradford, 2008). There is also a disjuncture between characteristic scales for these processes: whereas soil science deals with phenomena on the scale of a vertical profile or a restricted field, hydrology typically operates on a watershed level. Future advances in VZ models will benefit from advances in our understanding of fundamental physical, chemical and biological processes and interactions, but maybe even more so from synergistic applications from users outside of the traditional VZ sciences.

## Metrics of VZ Water Status: How Much is There and How Easy is It to Extract

Many important functions in the VZ such as heat and solute transport, biological processes, water supply to plants, evapotranspiration, groundwater recharge, and runoff generation are controlled by the state of water in the VZ. One of the tenants of VZ water is to describe its availability in addition to the amount (e.g., Nimmo, 2006). The availability of water recognizes that interactions with solids in the presence of solutes alter the energy required to forcibly move water in the VZ and determine the flow of water within the VZ. The availability is described as a specific energy potential *H*. It is recognized that water moves within the VZ according to gradients in this energy potential.

The water content most often provided as a volumetric water content $\theta_v$[L$^3$ L$^{-3}$] describes the volume fraction of water with respect to the bulk soil as $\theta_v = V_{water}/V_{soil}$. A wide variety of methods and sensors exist that make $\theta_v$ the most easily obtained VZ water status property. Nevertheless, given the immense variability in the VZ, the lack of spatially and temporally exhaustive water-content data remains one of the biggest limitations for furthering our understanding of this complex zone to date (Vereecken et al. 2008; Robinson et al. 2008).

The water content $\theta_v$ alone is insufficient to characterize soil-water status. Like all other forms of matter, water flows from locations with high potential energy to locations of lower potential *H* energy in pursuit of an equilibrium state (e.g., Nimmo and Landa 2005). The specific energy potential *H* (i.e., a potential per unit quantity of water) used to describe the energy potential of water in porous media is a measure relative to some reference state (free water at a standard atmosphere). *H* may be partitioned into multiple summative components: matric *h* (describing forces of interaction between solid and liquid), gravity $h_z$ (position in a gravity field), osmotic (presence of solutes which tend to increase the surface tension), and pressure (height of free water above a point of interest, or pore water pressure due to restrictive horizons). To simplify, the total hydraulic potential is often considered to consist of only matric *h* and gravitational potential $h_z$. The following expression for the 1-dimensional vertical gradient in potentials at steady state can be written when potentials are expressed as energy per unit of weight (i.e., resulting in units of length [L]):

$$\left(\frac{dH}{dx}\right) = \left(\frac{dh}{dx_i} + \frac{dh_z}{dx_z}\right) = \left(\frac{dh}{dx_i} + 1\right) \qquad (1)$$

For horizontal flow, the gradient $dh_z/dz = 0$. Bittelli (2010) provides a recent review of measurement methods. The value of *h* ranges from zero, when the soil is water-saturated, to very low negative numbers when the soil is very dry (i.e., we need to invest work to retrieve water).

## A Word on Models in General

In vadose zone physics, and science in general, we frequently wish to make inferences about physical parameters from measured data. The aim is to reconstruct the "real world" from a set of measurements. We call this the inverse problem. In the ideal case, an exact theory is known that describes how the data (describing state variables) should be transformed in order to reproduce the "real world." In reality, the theory is incomplete and not exact; we therefore have to make do with an approximating theory to the "real world." We call this the model.The true theory would be the model that describes reality. Models are always a simplified representation of the real world. However, we can use the model to simulate the measured data. This is called the forward problem. In many cases, the model is a continuous function of space and time variables, and has infinite degrees of freedom. But measured data are finite. Therefore, the data do not contain enough information to uniquely reconstruct the model (remember that the model may also not be a good representation of the "real world"). In addition, the measured data are averages over space and time, and worse, the data also contain some amount of noise. Forward and inverse problems are therefore plagued with two fundamental issues: non-uniqueness and error propagation.

## A Strong Tradition of Using the Richards Equation to Model VZ Water

The fundamental law for steady-state water flow in porous media is named after Henry Darcy whose seminal work described the flux density $j_w$ [L$^3$ L$^{-2}$ T$^{-1}$] as the volumetric flow per cross sectional area due to a gradient in hydraulic potential (see Equation 1) mediated by the saturated hydraulic conductivity $K_s$ [L T$^{-1}$] as the factor of proportionality:

$$j_w = -K_s\left(\frac{dH}{dx}\right) \tag{2}$$

$K_s$ lumps together attributes determining the ease of water movement in saturated soils like pore-size, pore-shape and the tortuosity of water-filled pathways, as well as viscous properties. Equation 2 also encapsulates that water will flow from locations of high potential to locations of low potential.

At unsaturated conditions, which define the VZ, Darcy's law remains applicable when introducing a hydraulic conductivity term $K(h)$ [L T$^{-1}$]:

$$j_w = -K(h)\left(\frac{dH}{dx}\right) \tag{3}$$

Equation 3 is referred to as the Buckingham-Darcy law. In it, the factor of proportionality, $K(h)$, is reduced compared to the saturated case and is a highly non-linear function of soil-water content and potential. The reduction can be thought of as a reduction in participating water volumes to the flow with increasing air-filled pore spaces. This reduction is highly non-linear, because of the increasing tortuosity with desaturation of the remaining water-filled connected pathways.

The general case of unsteady and unsaturated flow is a highly dynamic phenomenon which may be represented by combining Equation 3 with continuity:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial j_{wi}}{\partial x_i} - S \tag{4}$$

to yield the Richards (1931) equation:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial}{\partial x_i}\left(K(h)\frac{\partial}{\partial x_i}(x_i+z)\right) - S \tag{5}$$

where $S$ [L$^0$ T$^{-1}$] is a sink/source term (e.g., plant water uptake). Equation 5 is a non-linear second-order partial differential equation (PDE) that describes the general flow of water in variably-saturated.

A major drawback of Equation 5 is the dependence on both $\theta$ and $h$. Obtaining solutions to this equation therefore requires constitutive relations to describe the interdependence of $h(\theta)$, or to eliminate either $\theta$ or $h$ from Equation 5. Like all other second-order PDEs, solutions to Equation 5 require the specification of two additional pieces of information that take the form of initial and boundary conditions. Initial conditions are specified as a complete description of the system in terms of parameters such as $\theta$ or $h$ at some initial time (i.e., $t = 0$). Boundary conditions are specified as environmental conditions at the boundaries of the system. For example, a 1-dimensional vertical model describing infiltration of water into a soil profile may be set up by specifying environmental conditions at the soil surface and some depth $z$ in terms of water content θ (Dirichlet condition), water content gradient $\delta\theta/\delta z$ (Neumann condition) or a linear combination of the two (Cauchy condition). The boundary conditions may change with time to describe effects such as changes in rate of precipitation or a fluctuating water table.

Analytical solutions to Equation 5 are available only for a limited number of applications and are often obtained by making simplifying assumptions, and using approximate parameterizations, as well as initial and boundary conditions (see for example Gardner 1958; Green and Ampt 1911). With today's computing power, numerical solutions using finite-element or -difference methods provide convenient brute force methods (e.g., Feddes et al. 1988, 2004). In addition, often one is interested in coupled flow and transport in soils which commonly involves setting up several general flow models and solving them iteratively. Luckily, several modeling packages are available to numerically solve these kinds of problems including, for example, Hydrus (Šimůnek et al. 2008), TOUGH (Finsterle et al. 2008), MODFLOW (Niswonger and Prudic 2004), SWAP (van Dam et al. 2008) as well as domain spreading models such as SHAW (Link et al. 2001) and more general PDE solvers like COMSOL Multiphysics. However, a solution will only be as good as the input parameterizations (Durner and Lipsius 2006) as well as assumptions and limitations inherent in the models. Common assumptions of VZ models include steady-state, equilibrium conditions, homogeneity, ergodicity and isotropy.

## Consitutive Relations Needed for Parameterizing the Richards Equation

Describing and predicting VZ-water is key to understanding interdisciplinary interactions. The movement and distribution of water depends on the hydraulic properties of the soil-water-air continuum, its intricate pore space, arrangement, surface area, and phase distribution. Together, these effects can be described through the soil-water retention characteristic, and the hydraulic conductivity functions.

### Soil-Water Retention Characteristic

$\theta(h)$ is primarily determined by the pore-size distribution and the pore shapes - it is thus a unique fingerprint for complex soils. Soils with wide pore-size distributions (e.g., loam) tend to retain more water at more negative potentials than soils with narrow pore-size distributions (i.e., sand) which tend to drain more rapidly. For a review on the theory see for example Bachmann and van der Ploeg (2002). A common conceptual model for matric potentials and $\theta(h)$ in soils is capillary rise and the simplification of soil-pore space into a bundle of capillaries. The capillary rise model predicts the matric potential (as energy per unit weight) as a function of apparent pore radii:

$$h = \frac{2\sigma\cos\gamma}{\rho_w g r} \tag{6}$$

where σ [M L$^0$ T$^{-2}$] is the surface tension, γ[-] is the contact angle, $\rho_w$ [M L$^{-3}$] is the density of water, $g$ [L T$^{-2}$] the acceleration due to gravity, and $r$ [L] the apparent pore radius. Capillary rise is higher in soils with small pores because of a more negative matric potential. One can use capillary rise to visualize $\theta(h)$ by observing the height of rise against gravity and determining the average water content of the soil at different elevations. Close to the water surface, large and small pores are water-filled, but the higher up (i.e., at lower potentials) one looks, only smaller pores remain water-filled.

For modeling and analysis it is beneficial to represent the $\theta(h)$ as a continuous parametric function. Commonly used parametric models are the van Genuchten (1980) and Brooks and Corey (1964) relationships. The van Genuchten (1980) model is given as:

$$\Theta(\mathrm{h}) = \frac{\theta_\upsilon - \theta_r}{\theta_s - \theta_r} = \begin{cases} [1+(\alpha|h|)^n]^{-m} & \text{for } h < 0 \\ 1 & \text{for } h \geq 0 \end{cases} \tag{7}$$

where α [L$^{-1}$], $n$ [-] and $m$ [-] are empirical fitting parameters. Θ [-] is the degree of saturation, $\theta_r$ and $\theta_s$ [L$^3$ L$^{-3}$] are the residual and saturated water contents, respectively. These unknown parameters can be obtained by fitting the model to measured data pairs of volumetric water content $\theta_v$ and matric potential $h$ using, for example, freely accessible RETC software (van Genuchten et al. 1992). Multiple effects related to advancing and receding water in porous media result in $\theta(h)$ being hysteretic, i.e., drying and wetting processes have distinct characteristics. This hysteretic nature adds complexity to VZ modeling efforts. To further complicate matters, $\theta(h)$ may also be dynamic (e.g., in shrink swell soils, with root advance).

### Unsaturated Hydraulic Conductivity Function

In saturated soils, $K(h = 0)$ equals the saturated hydraulic conductivity $K_s$ which constitutes the largest value for maximally conductive pathways with complete water-saturation. $K(h)$ then describes the reduction in hydraulic conductivity with decreasing water content (reduction in cross sectional area for flow and participating flow pathways; increasing solid-liquid interactions and tortuosity). Because unsaturated conductivities are more difficult to measure, $K(h)$ is most frequently modeled using a known $K_s$ and some correlated soil properties to predict the shape of the decay function. One example is to use the $\theta(h)$ shape parameters to predict the shape of the $K(h)$ function as suggested by Mualem (1976).

Current direct determinations in the laboratory or field for $\theta(h)$ are described in Klute and Page (1982) and Rawls et al. (1982), and for $K(h)$ in Dane et al. (2002). Alternatively, one may use parameter optimization to indirectly estimate $\theta(h)$ and $K(h)$ from transient flow data by modeling the flow process and minimizing some objective function describing the differences between the measured and predicted flow variables (van Dam et al. 1994; Vrugt et al. 2008). However, both direct and indirect approaches to parameter estimation are often difficult and time-consuming, resulting in a general lack of information to properly parameterize the spatial and temporal variability in the VZ. Methods to partially overcome this limitation are the use of hydraulic-parameter databases (Carsel and Parrish 1988; Nemes et al. 2001) or pedotransfer functions that predict hydraulic parameters based on other more easily measured porous-media properties (Schaap et al. 2001; Wösten et al. 2001).

## Scale Issues in VZ Modeling

Water flow in the VZ occurs at different spatial scales ranging from the interface of solids and fluids, clusters of pores, pedon, to the field and watershed scale with variations in the dominant hydrologic flow processes. This extremely large spread in scales, coupled with the inherent complexity and non-linearity of flow in heterogeneous soils with high spatial variability (often the vertical variability is much higher than the horizontal—this anisotropy is often exploited when we use 1-dimensional models) complicates VZ modeling. A rough categorization of modeling approaches with scale may be given as:

1. At the pore scale, interface shapes and energy potentials as determined by pore size, shape and fluid are recognized as modeling approaches using the Hagen–Poiseuille or Navier–Stokes equations. These approaches are based largely on energy conservation. Another approach is the use of percolation theory (Berkowitz and Ewing 1998; Hunt 2001).
2. At the pedon and field scale, VZ processes are often modeled using the Richards (1931) equation based on energy and mass conservation requiring the formulation and quantification of constitutive relations.
3. At the regional scale, VZ processes are recognized for controlling both short-term dynamics in watershed hydrology and long-term water balances of hydrologic basins (Harter and Hopmans 2004). This approach, primarily motivated by mass conservation, is advantageous because relationships linking mass to energy states are difficult to obtain at this scale.

The boundaries between the scales are rather fluid, and processes at large scales may be predicted using small scale models and vice versa. With advances in computing power, soil physicists are increasingly upscaling their models to yield predictions of flow processes based on small-scale parameters that capture large-scale behaviour of heterogeneous VZs in an average sense (Vereecken et al. 2007), while hydrologists are downscaling in an attempt to predict small-scale processes based on averaged large-scale parameters (Pachepsky et al. 2006). Several review papers, including Blöschl and Sivapalan (1995), Hopmans et al. (2002), and Corwin et al. (2006), address the current state-of-the-art for up- and -downscaling in VZ modeling.

Other issues of scale are phenomena such as rapid transport through macropores, preferential flow due to the spatial variability of hydraulic properties, or the instability of wetting fronts.

Simunek et al. (2003) provides a review of modeling approaches for describing non-equilibrium and preferential flow.

## Summary

Research in the vadose zone is by its nature interdisciplinary. Porous media constituents and living participants are highly variable in their functions as well as spatial and temporal distributions. Coupled with processes and properties that are highly non-linear, VZ models are unavoidably complex.

Water centrally frames much of the interdisciplinary interest in the vadose zone. The flow of water governs gas, heat and solute transport, affects rates of biogeochemical processes, water supply to plants and transpiration, groundwater recharge, and runoff, and has many other important functions in the critical zone. Applications in soil science, hydrology, agronomy, climatology, ecology, engineering and other related disciplines greatly benefit from simulations of water flow and distribution in the vadose zone. Consequently, one may approach teaching VZ processes through lenses of water distribution, flow and interactions (see Figure 1).

While the flow of water through the vadose zone is commonly modeled by the Richards (1931) equation, biogeochemical processes at large are intrinsically coupled and thus must be modeled as an integrated system. A few such modeling codes are available. However, because of the heterogeneity in the vadose zone and complexity of interactions, sufficient data for accurate parameterizations and scaling approaches limit integrated and interdisciplinary modeling. Nevertheless, recent advances in numerical simulation models offer unprecedented opportunities for a more holistic understanding of vadose zone processes and importantly as teaching tools for interdisciplinary integration.

With this short compendium of and case study for teaching interdisciplinary modeling we have but touched on the advances in interdisciplinary research in the vadose zone. The in-class course which motivated this compendium integrated teaching the interdisciplinary significance of vadose zone processes with an overview of soil-water physics and the governing equations plus a HYDRUS 1D modeling exercise. We hope that the lecture and this compendium have served to inspire discourse in future scholars and contributed to a connection to the evolving roles of vadose zone and soil science in the academy and a changing world. This new world will have to solve more complex issues in which the vadose zone plays a key role.

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# Economic Foundations for the Interdisciplinary Modeling of Water Resources Under Climate Change

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**Abstract:** Climate change is likely to alter the scarcity of water resources, contributing to increased concern among policymakers and water managers about how to best allocate water among competing uses. Hydroeconomic models provide a means of integrating human and biophysical systems to understand the impacts of alternative water policies. This article discusses foundational concepts related to economic efficiency, with a specific focus on the equimarginal principle, and presents a modeling framework that demonstrates how to use these concepts as a starting point for an interdisciplinary model of water resources management. The modeling framework accommodates concerns about allocating water across competing uses, over time, and with stochastic water availability.

**Keywords:** *Efficiency, equimarginal principle, hydroeconomic modeling*

The need to understand the complexities of water systems is increasing as climate change renders water supplies increasingly uncertain and variable. Though the impacts of climate change on water availability are not known with certainty, climate change is expected to significantly alter the spatiotemporal distribution of water resources due to changes in precipitation and runoff patterns, sea level rise, and land use (Frederick and Major 1997). Changes in water availability carry particularly important implications for agricultural production and food security. Irrigated agriculture produces approximately 40 percent of the world's food supply and accounts for 70 percent of global water withdrawals and 90 percent of global consumptive water use (Kundzewicz et al. 2007; Turral et al. 2011). Arid and semi-arid regions that rely heavily upon irrigation are projected to become hotter and drier. With increased water scarcity, the questions pertaining to how water is used, by whom, and the economic impacts of alternative water management practices will be of increasing concern to policymakers and water users worldwide.

Comprehensive evaluation of the impacts of climate change on water systems necessitates an integrated approach that reflects not only the biophysical impacts of climate change, but also changes in human activities that result from and/or contribute to biophysical changes. Significant advances in the field of hydroeconomic modeling over the past 25 years provide the foundation for just such an approach. Booker et al. (2011) and Harou et al. (2009) provide a broad and comprehensive review of these advances and discuss applications of hydroeconomic modeling tools to a number of water management problems, including those related to climate change.

Our objective in this paper is to contribute to the interdisciplinary litertaure on education in water economics by explaining the intuition and mechanics of economic efficiency as it pertains to water allocation and management strategies. Economic efficiency is a salient guiding principle. Though there are a number of economic principles that are relevant in any discussion of efficiency, we allocate our limited space in this special issue to a discussion of the equimarginal principle. We choose this emphasis because we believe that greater familiarity with this concept can enhance the interdisciplinary modeler's understanding of what economists mean by efficiency in water allocation and why, when, and how they may integrate this economic concept into models of water systems. A short paper on the topic of economic efficiency and the equimarginal principle serves as a complement to other papers appearing in this special issue on interdisciplinary water resource modeling.

Within the context of our discussion of the equimarginal principle, we provide a basic framework for integrating biophysical and economic modeling components to determine the optimal allocation of water across uses and over time under stochastic climate conditions. Such a framework encourages researchers to account for the complex tradeoffs between various water uses as well as linkages and feedbacks between human and natural systems when investigating the impacts of climate change and/or water policies[2]. Though we present only one of many potential modeling approaches, the framework outlined here is meant to be a starting point for researchers interested in integrating human and natural systems to examine the impacts of climate change and to evaluate alternative water policies.

## Economic Efficiency in Water Distribution

This section addresses the non-trivial question: Given the limited availability of water resources, who receives water and when? The discipline of economics is fundamentally concerned with how best to distribute scarce resources across unlimited wants. In this section, we define what is meant by "best" and discuss ways in which water is distributed in practice.

### Defining Economic Efficiency

Economists consider it desirable for any resource to be allocated to its highest value use. In this paper we refer to a water "use" in the most general sense: Water uses can be defined by sector, such as irrigation, commercial, or domestic; across individuals, such as different irrigators; and across time, such as water used for irrigation this year versus water used for irrigation next year. The marginal value of water in a particular use is the value associated with one more unit of water and is determined by society's marginal willingness to pay (MWTP) for additional unit of water in that use. Society's MWTP for water in a particular use is described by a demand curve. A demand curve (illustrated in Figure 1) reflects consumer preferences, climatic conditions, and the characteristics of the population (Griffin 2006; Koch and Vogele 2009; Tanaka et al. 2006). Consistent with economic theory, a demand function illustrates the quantity of water that users demand at different prices, all else constant[3]. The area under the demand curve and to the left of the equilibrium quantity of water demanded (W′ in Figure 1) is the gross benefit associated with allocating water to a particular use. Subtracting the total payments made for water (the cross-hatched rectangle in Figure 1 assuming that the price paid for water is P′) from the gross benefit yields the net economic benefit (the lighter grey shaded area in Figure 1)[4]. With a demand curve specified for each use in a system, the analyst can determine the optimal allocation of water by maximizing the sum of net benefits across uses. Customarily, the economic value of a resource is defined from an anthropocentric perspective, and includes demand curves for water in both market and non-market, or indirect, uses. For example, if the population derives value from the existence of fish habitat, a demand curve exists for water in this use and, once determined, can be included in an analysis.

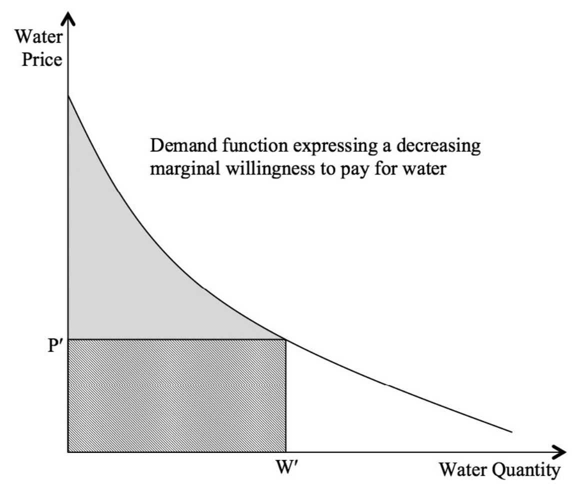

**Figure 1.** A representative demand function for water use.

Barring any constraints on the allocation of the resource, maximizing the sum of net benefits across uses yields an efficient, or Pareto optimal, allocation of the resource[5]. Put simply, a Pareto optimal distribution implies that no alternative feasible reallocation of the resource is possible which makes at least one individual better off without making anyone else worse off. In many contexts there are multiple ways of distributing a resource that are consistent with Pareto optimality. This complicates policy formation for the management of scarce resources. A related concept that economists often rely on in such situations is that of Potential Pareto Optimality (PPO). PPO implies that no redistribution of a resource is possible such that the beneficiaries of the redistribution could "compensate" the losers and still be better off than before the redistribution. PPO allows for a policy to produce losing parties as long as the benefits enjoyed by the beneficiaries of the proposed policy exceed the losses endured by the losing parties[6]. In many situations, PPO is more useful for identifying a single optimal policy strategy than is Pareto optimality.

Consider an example in which an agricultural irrigator holds the right to use a certain quantity of water to produce crops. Suppose further that if that water were not diverted for irrigation, a downstream hydropower producer could use that same quantity of water to produce additional electricity. If the value of the last unit of water used in electricity production exceeds the value of the last unit of water used in crop production, the hydropower producer could potentially pay the irrigator not to divert his water and still see an increase in profit from the additional hydropower produced with that extra unit of water. As long as that potential exists, a reallocation of water from irrigation to hydropower production satisfies the PPO criterion[7]. PPO remains the standard for allocating resources in an economically efficient manner and is a useful gauge for measuring the relative performance of various water management policies, despite some existing concerns (see Griffin 1995). This concept also serves as a foundation for standard cost-benefit analysis, which is often used as a tool to evaluate whether policies or regulatory actions should be undertaken.

The example of the previous paragraph demonstrates the equimarginal principle, which often holds at a Pareto optimal resource allocation. This principle ensures that the net economic benefit of the last unit of water is equal across uses. Continuing with the same example as above, let the net benefit of water in irrigation be given by $B_I(w_I)$ and the net benefit of water in hydropower be given by $B_H(w_H)$, where both are concave, twice-differentiable functions[8]. The total net benefits accruing from water use are given by $NB_T(w_I,w_H) = B_I(w_I)+B_H(w_H)$[9]. The maximization of net benefits requires that $|B_I'| = |B_H'|$, i.e., that the net benefit of the last unit of water used in irrigation equals the net benefit of the last unit of water used in hydropower production[10]. If this condition holds, it is not possible to redistribute the last unit of water from one user to another such that the receiving user could compensate the losing user and still be better off, i.e. the water allocation is PPO.

In a perfectly competitive economy, free market exchange in a resource ensures that the equimarginal principle holds and that a Pareto optimal allocation of the good is obtained (a result known as the First Theorem of Welfare Economics)[11]. However, departures from the assumptions of perfect competition prevent a free market system from achieving an economically efficient distribution of a resource, resulting in market failures. In the allocation of water resources, market failures are the rule, rather than the exception, because of the public good characteristics of water resources; the third-party effects, or externalities, associated with water use; natural monopolies in water conveyance and storage infrastructure; over-discounting; and high transactions costs (Griffin 2006; Young 1986)[12].

### Water Allocation Mechanisms

Although markets hold the theoretical promise of achieving an economically efficient allocation of water, the allocation of water across uses has rarely been accomplished in this manner (Libecap 2011). So, how is water practically distributed across uses and how do existing allocation systems perform in terms of economic efficiency?

In practice, differing sectors often employ different methods of allocation, the result of which is a mix of distribution systems that may or may not be economically efficient, taken alone or in combination. Dinar et al. (1997) outline three categories of water allocation systems in addition to water markets—marginal cost pricing, public allocation, and user-based allocation. Marginal cost pricing sets a price for water equal to the cost of providing the last unit and is most often used by public utilities providing water for residential consumption. Like water markets, this pricing rule is theoretically capable of achieving an economically efficient distribution of water.

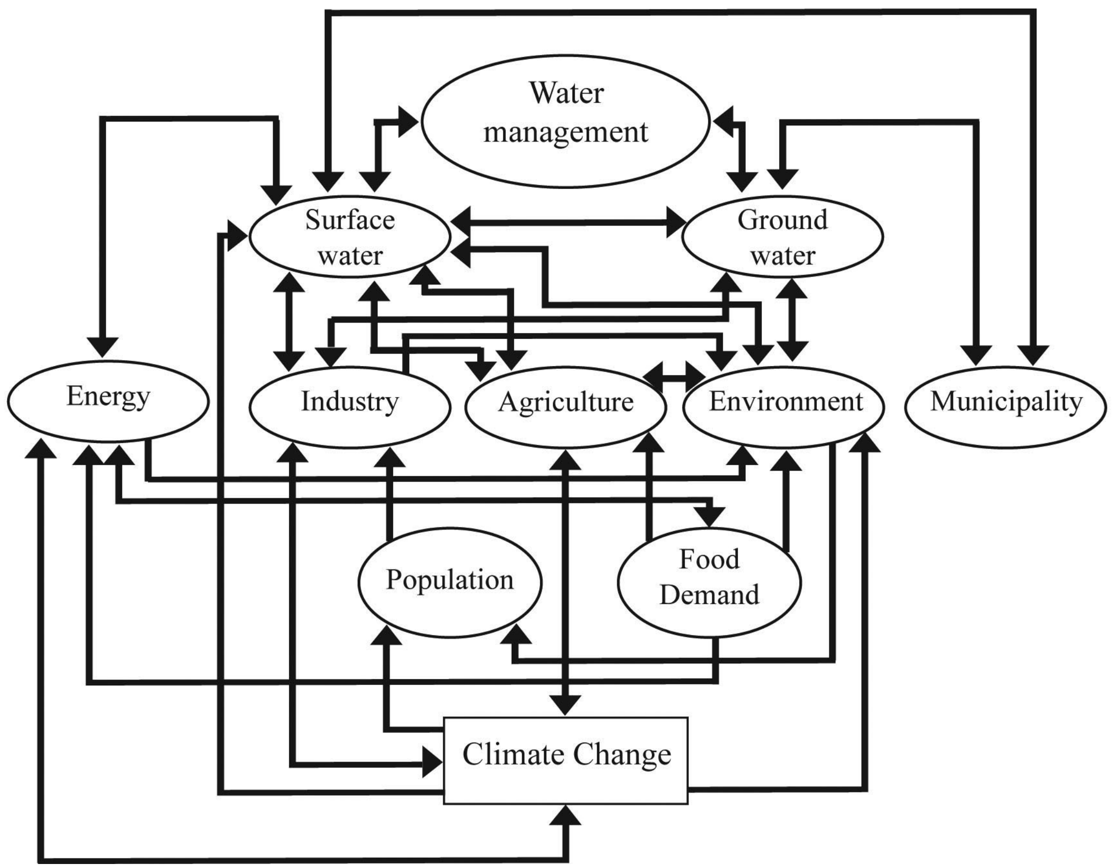

**Figure 2.** The components of a complex water system and their interactions.

Public and user-based allocation systems involve distributing water via a set of institutional rules. One common example of a public system is the prior appropriation doctrine, which is widely used to distribute surface water across the western U.S. In this system, the public retains the ownership of water resources, which are distributed according to a system of rights that specify when, where, and by whom water may be used. A user-based allocation system is similar, but a group holds the water right and apportions water among group members according to internal rules. A common example is an irrigation district or a canal company. The allocation of water in either of these systems does not necessarily correspond with an economically efficient outcome[13].

Given that water is rarely distributed in a way that guarantees economic efficiency, the modeler's task is often to quantify the relative economic efficiency of various policy alternatives. These policies can be represented in a hydroeconomic model in one of two ways. Rules that govern water distribution may be incorporated via a set of constraints that specify who receives water and when. Alternatively, policies like taxes or subsidies, which affect the net benefits associated with various water uses, can be incorporated by modifying the model's objective function. The researcher can begin by specifying a hydroeconomic model that determines the most economically efficient allocation of water and then alter the model to reflect the specifics of various policies. By comparing the net benefits attained under the most efficient allocation and the net benefits under various distribution rules, the researcher can compare a set of feasible alternatives on the basis of their relative economic efficiency. The next section specifies a modeling framework that can be used as a starting point for this type of exercise.

## Hydroeconomic Modeling Framework

The holistic modeling of a water system requires the inclusion of all water uses and their associated benefits in order to maximize the total net economic benefits associated with water use (or, equivalently, ensure that the equimarginal principle holds). Figure 2 provides a general overview of various water use categories and their linkages within a holistic system. This depiction is not representative of all situations, but may be adapted to reflect the specifics of a particular context. Our intent in Figure 2 is to demonstrate the extent of the complexity that a holistic approach to water systems management and modeling entails. Because of the complexity associated with comprehensive modeling, most studies examine sub-systems from Figure 2, holding constant excluded system components. While disciplinary research can address individual, or sometimes even several, links in Figure 2, broader questions are typically addressed in interdisciplinary projects combining biophysical and human modeling components.

The remainder of this section presents an economic modeling framework that can be used as a platform for unifying the biophysical and economic aspects of water resource management when the objective is the maximization of total benefits from water use. The sub-sections build sequentially on one another: The first describes the allocation of water across uses within a single time period; the second section adds time into the problem; the third integrates uncertainty and risk. The basic framework is common to that of most hydroeconomic models in the sense that the objective function reflects the economic benefits associated with water use and the constraint set reflects the biophysical properties of the system as well as additional engineering or socio-economic factors that affect the distribution of water.

### Allocating Water Across Uses

The basic problem for allocating water across uses within a single time period can be written as follows. Assume that there are $k = 1,\dots, K$ uses of water. The demand curve for each water use is given by $D_k(x_k)$, where $x_k$ is the amount of water allocated to use $k$. Since the demand curve corresponds to MWTP, the gross benefit of water in use $k$ is given by the area underneath the demand curve: $B_k(x_k) = \int_0^{x_k} D_k(x_k)dx_k$. The total cost of using water in $k$ depends on the amount of water used and the amount of water available for use (denoted S): $C_k(x_k,S)$. The net economic benefit of water in use $k$ is $NB_k(x_k,S) = B_k(x_k)$-$C_k(x_k,S)$. The problem is to choose $x_1^*=(x_1^*,\dots,x_k^*)$ to maximize the total net benefits of water use:

$$\max \textstyle\sum_k NB_k\,(x_k,S) \qquad (1)$$

subject to set of biophysical, engineering, and socio-economic constraints[14]. An example of a simple physical constraint is that the total amount of water allocated across uses does not exceed the total amount of water available for use[15], i.e. $\sum_k x_k \leq S$.

The first-order necessary conditions for this optimization problem require that the equimarginal principle holds for the net benefit of water in each use, i.e., $NB'_1 = NB'_2 = \dots = NB'_k = \lambda$.

In addition to generating the solution for the economically efficient allocation of water across uses, this framework also provides the marginal value of having an additional unit of water in the system. This value is given by the lagrangian multiplier (λ) associated with the water availability constraint. Economists commonly refer to this value as a shadow price, which represents the increase in net benefits (objective function 1) if the water availability constraint is relaxed by one unit. Numerous studies have examined multiuse water management strategies within the context of climate change, including Keplinger et al. (1998), McCarl et al. (1999), Mendelsohn and Bennett (1997), Schaible et al. (1999), and Tanaka et al. (2006).

### Allocating Water Across Time

To add time to the model, we use the same basic approach presented in the previous section, but consider the allocation of water across time periods, where time is indexed by $t = 1,\dots,T$. As in the previous section, the gross benefit of water in any particular use $k$ and in any time period $t$ is given by the area below the corresponding demand curve: $B_{kt}(x_{kt}) = \int_0^{x_{kt}} D_{kt}\,(x_{kt})dx_{kt}$. The period-specific net benefits of water in use $k$ are given by $NB_{kt}(x_{kt},S_t)=B_{kt}\,(x_{kt})$-$C_{kt}\,(x_{kt},S_t)$.

A key economic concept that must be incorporated at this point in the model development is that of discounting. Discounting reflects the relative value that society places on benefits received today versus benefits received in the future. If the social discount rate is zero, society weights the benefits in all time periods equally, in which case the benefits of water use today and tomorrow are equally weighted in the objective function. A social discount rate greater than zero implies that individuals prefer to receive benefits today over waiting to receive the same benefits in the future. The objective function should reflect the tradeoff between consuming water today versus saving water for use in future periods.

The problem facing the water manager is to choose $x_t^*=(x_1^*,\dots, x_{kt}^*)$ in each period $t$ in order to maximize the present value of net benefits over the problem's time horizon:

$$\max \textstyle\sum_t \beta^t \{\sum_k NB_{kt}\,(x_{kt},S_t)\} \qquad (2)$$

where $\beta=1/(1+r)$ is the discount factor and $r$ is the discount rate[16]. Objective function (2) is maximized subject to a series of constraints, including a period-specific total water constraint, $\sum_k x_{kt} \leq S_t$. In a dynamic problem, decisions about water use today may (and most often do) affect decisions about water use in the future. For example, decisions to pump from an aquifer in the current period carry consequences for pumping costs in future periods, and thus determine the optimal extraction of water from the aquifer (Gisser and Sanchez 1980). In this case, the problem must include inter-temporal constraints, or equations-of-motion, that describe how the availability of water in the future depends on decisions made about the amount of water used today. An example of a general equation-of-motion is:

$$S_{t+1} = H(S_t,x_{1t},\dots, x_{kt}) \qquad (3)$$

where the availability of water in the next period, $t$+1, depends on the availability of water in period $t$ and water used in period $t$. This dependence is expressed via the functional relation $H$.

An optimal inter-temporal allocation of water requires that the equimarginal principle holds across uses and across time, i.e., the marginal net benefit of water used today must equal the discounted marginal net benefit of using that water in the future. The equimarginal principle requires that there is no opportunity to shift water use from one period to another in order to increase total net discounted benefits over the problem's time horizon. Some examples of studies of water management in multi-use and dynamic contexts are Gurluk and Ward (2009), Knapp et al. (2003), and Watkins and McKinney (1999).

### Allocating Water with Uncertainty and Risk

Elements of the models described in the previous two sections are rarely known with certainty. This is particularly true when modeling involves long-run management under climatic variability. For example, although most dynamic models assume that the relative prices of goods like agricultural commodities or energy remain stable over the period covered by the model, in reality prices are not likely to remain the same and are very difficult to predict. Similarly, parameters describing system hydrology are often stochastic. Building and solving models in which all parameters are stochastic is a tremendous task that is computationally challenging due to curse of dimensionality (Miranda and Fackler 2002).

For the sake of demonstration, we focus on introducing stochasticity in the natural parameters that affect water availability. This particular form of stochasticity enters via the problem's equation-of-motion. Specifically, equation (3) becomes:

$$S_{t+1} = H(S_t,x_{1t},\dots,x_{kt},\tilde{w}_t) \qquad (4)$$

where $\tilde{w}_t$ stochastic water inflows in period $t$. Inflows are distributed according to the probability distribution Φ, which has a period-specific mean and variance, i.e. $\tilde{w}_t \sim \Phi(\mu_t,\sigma_t^2)$. Allowing the mean and variance of the probability density function to change over time reflects potential nonstationarity in the probability density function, which is essential to consider in climate change problems (Milly et al. 2008).

There are a number of ways to alter the total benefits function in (2) to represent decision-making under uncertainty. The simplest is to assume that decision-makers maximize the expected value, or mean, of the net benefits of water use. However, it may be more appropriate to assume that the variability of benefits, which depends on a stochastic process, also affects economic well-being. Economists have devised a number of ways to incorporate both the mean and variance into an objective function, one of which involves maximizing benefits in the current period plus the discounted values of mean-variance functions for future periods (Markowitz 1959). Mean-variance specifications allow the modeler to represent situations wherein increases in variance are likely to affect economic welfare. This is a particularly important consideration if individuals are risk-averse. More risk-averse individuals put greater weight on minimizing the variability of uncertain benefits than do those who are less risk-averse, holding the mean constant. Frequently, an Arrow-Pratt risk aversion coefficient is used to penalize the objective function in proportion to the variability in expected payoffs.

In this problem, we allow the period-specific net benefits of water in use *k* to depend on the stochastic water availability parameter, i.e. $NB_{kt}(x_{kt},S_t,\tilde{w}_t)$. Let the following notation define the net benefits across all uses within period *t*: $f_t(x_{kt},S_t,\tilde{w}_t)=\sum_k NB_{kt}(x_{kt},S_t,\tilde{w}_t)$. The objective function becomes:

$$\max\sum_t\beta^t\{\int f_t(\cdot)\Phi(\tilde{w}_t)d\tilde{w}_t - \Psi\int\{[f_t(\cdot) - \int f_t(\cdot)\Phi(\tilde{w}_t)d\tilde{w}_t]^2\}\Phi(\tilde{w}_t)d\tilde{w}_t\} \tag{5}$$

The first term in the objective function is the expected value of net benefits; the second is the variance of net benefits, which reduces the objective function in proportion to Ψ, a risk aversion parameter. Expression (5) is solved subject to a series of constraints, including equation-of-motion (4). An optimal allocation of water implies that the equimarginal principle holds across competing uses within a time period and across time periods. The difference in this section is that the equimarginal principle applies to the expected net benefits less a term that adjusts for the variability of benefits and users' risk preferences.

A number of studies on aquifer management have combined hydrologic economic frameworks in stochastic contexts. Examples include Georgakakos et al. (2005), Chen et al. (2006), Mendelsohn and Bennett (1997), and Schaible et al. (1999). However, none of these studies have explicitly incorporated risk aversion. Explicit incorporation of risk preferences into water resource studies and management will contribute to the policy relevance of hydroeconomic models because many of the decisions related to water management pertain to tradeoffs related to risk. This is likely to be especially true for models and studies that consider climatic change and variability.

## Summary

The objective of this paper is to present basic economic concepts pertaining to water management in the context of multiuse, dynamic, and stochastic systems. We pay particular attention to economic efficiency and the principle of equimarginality, presenting a modeling framework that integrates biophysical and economic systems to optimize outcomes and which can be applied to problems that consider climate change and alternative water allocation policies. Clearly, space limitations prohibit us from a comprehensive presentation of relevant economic concepts, frameworks, models, and solution methods. Instead, we provide a resource that complements recent work on the breadth of hydroeconomic modeling (Booker et al. 2011; Harou et al. 2009) by covering efficiency in greater detail and by presenting a framework that can serve as a starting point for the interdisciplinary modeler. We strongly encourage the reader to explore additional economic concepts that are relevant to this literature, including, but not limited to, equity, ethics, and the social discount rate (Beckerman and Hepburn 2007; Griffin 1995). In addition to the other references cited here, an excellent starting point for the non-economic modeler is Griffin (2006).

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## Notes

1. In a mature water economy, demand exceeds water supply, and the costs of establishing new water supplies, for example by building new storage infrastructure, outweigh the benefits. This is typical of developed economies. A immature water economy is one in which the benefits to developing new water supplies outweigh the costs, which is, at present, more typical of developing economies (Booker et al. 2011).
2. The conceptual framework in this paper is consistent with the IPCC's call to improve the coupling of climate models with models of anthropogenic activities (Kundzewicz et al. 2007). The report specifically highlights that "relatively few results are available on the economic aspects of climate change impacts and adaptation options related to water resources, which are of great practical importance."
3. Conventional notation in economics is to express demand as an inverse relationship where price is a function of quantity demanded. For additional explanation and illustrations of economic demand functions for water see Harou et al. (2009), Griffin (2006).
4. In the context of agriculture, the price paid for water is oftentimes less than the marginal benefit of water at $W'$. In this case, the cost of water use for irrigation is less than the cross-hatched rectangle in Figure 1.
5. For an introduction to the philosophy underlying social choice and Pareto optimality, see Chapter 3 from Kolstad (2011).
6. Griffin (1995) discusses the limitations and caveats of potential Pareto optimality (PPO). For the purposes of this paper, we sidestep a discussion of the equity implications associated with PPO. Externally determined equity rules can be specified as constraints or in the form of relative weights in the objective function.
7. It is important to note in this example that the economist is concerned with maximizing the economic benefits from water use, not the quantity of water used (Ward and Michelsen 2002).
8. It is a common practice in economics to assume the concavity (or quasi-concavity) of benefit functions, implying decreasing marginal benefits. The net benefits of water in each use are equal to the light grey shaded area under the demand curve for water in each use, as in Figure 1.
9. One can also assign relative weights to the two components of the social benefit function.
10. This condition holds at an interior optimum, but it may not hold at a corner solution, or one in which the optimal allocation of water to one or both of the uses is zero. The first-order condition is sufficient for an optimum given the curvature assumptions for the net benefit functions.
11. This result is precisely the reason that economists tend to favor markets as a means of distributing scarce resources. However, the requirements for a market to obtain this outcome are restrictive: It must be the case that property rights over the good are well-defined, secure, and transferable; participants in the market are numerous and small, i.e. no one individual can influence the market outcome; there must be perfect information; and there must be no transactions costs associated with trade of the good.
12. For definitions and a general explanation of market failures, see Kolstad (2011).
13. However, these systems may perform better than others with respect to equity in water distribution (Dinar et al. 1997). For a review of the institutional aspects of water distribution, see Saleth and Dinar (2004).
14. These constraints typically also include biophysical dependencies between water uses across space and time. We have also implicitly assumed here that water is transferable and that equity issues associated with water distribution are ignored. Such considerations could be incorporated into the model by specifying additional constraints.
15. Examples of other potential constraints are the relational dependence between various water uses; bounds requiring that certain water uses can receive no less water than some specified amount; etc.
16. We have taken a discrete-time dynamic programming approach with a finite time horizon in this example. For a thorough treatment of dynamic optimization problems, see Miranda and Fackler (2002).

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# The Fourth Dimension of Interdisciplinary Modeling

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**Abstract:** Space and time are the domains used by every model in the applied environmental sciences, with the latter normally considered to add a fourth dimension to our simulated versions of reality. Dealing with modern challenges in water-related disciplines requires that we extend our historical perspective as far back as possible to capture underlying long-term dynamics that would otherwise be impossible to detect. At the same time, performing and interpreting retrospective studies demands an understanding of their strengths and weaknesses. Here I attempt to clarify both the importance of the past and the inevitable "paleo conundrum" associated with it by drawing on personal experience and on research projects conducted using tree-ring records in the western U.S. How to best incorporate proxy data, together with instrumental observations, into models used to manage water resources for coping with an uncertain future remains a non-trivial task.

**Keywords:** *Paleoscience, proxy data, tree-ring records*

In modern times, the impact of human activities on ecosystems and the services they provide, from water to biodiversity, has reached a global level of unprecedented proportions (Daily 1997). In particular, modifications of the climate system caused by the buildup of greenhouse gases in the atmosphere is a major concern of policy makers and resource managers (Field et al. 2012). Scientists, who are tasked with providing tools for coping with the increased complexity of existing and predicted climate impacts, can take highly diverse approaches with regard to time. On one hand, it is common to emphasize either contemporary conditions, used to initialize simulation models, or future scenarios, which are produced by the models and are required to design management and policy strategies (Stott et al. 2013). On the other hand, one can focus on acquiring a longer perspective to better evaluate recent changes given that "we cannot generate realistic null hypotheses about the composition and dynamics of ecosystems from our understanding of the present alone, since all ecosystems have almost certainly changed due to both human and natural environmental factors." (Jackson et al. 2001: 630).

A significant impact of climate variability is drought, which has been shown to be among the top natural hazards in many areas of the world (Wilhite 2000). In the summer heat of 2012, multiple media reports highlighted that the drought experienced in most of the U.S. was part of a "new normal," and that such a disaster, which was predicted by models used to simulate the impact of greenhouse forcing, could continue for years to come (Schwalm et al. 2012). By the end of the year, when the annual National Oceanic and Atmospheric Administration (NOAA) report on the *State of the Climate* was published, a less frightening picture had emerged. The 2012 drought had indeed been the most severe in the 13-year history of the U.S. Drought Monitor, but when projected against the longer background of divisional climate data (back to 1895), it was not unprecedented. Drought conditions are normally quantified using the Palmer Drought Severity Index (PDSI; Alley 1983; Palmer 1965). The extent of areas in the contiguous U.S. that experienced moderate to extreme drought (i.e., PDSI less than or equal to negative two) in 2012 was found similar to other events in the 1950s, and ranked below some of the Dust Bowl years, such as 1934 (NOAA 2013). The lesson is simple: having access to a longer baseline record can substantially alter the perception and interpretation of an extreme event.

Space and time are the domains used by every model in the applied environmental sciences, with the latter normally considered to add a fourth dimension to our simulated versions of reality (National Research Council 1991). While there are a number of numerical techniques for handling the unidirectionality of temporal processes happening in three-dimensional space (Christakos 2000) as well as to identify deterministic or stochastic properties in the time domain alone (Hamilton 1994), in this essay I am mostly addressing the issue of how to properly incorporate knowledge of the past for interdisciplinary modeling. Together with providing a philosophical approach to what I have called the "paleo conundrum," I will use personal experience and recent research projects to discuss how proxy data can be incorporated in modeling applications dealing with water resources in the Great Basin of North America.

### A Pedagogical Experience

In 2005, 2010, and 2012 I participated in a multi-faculty, multi-institutional graduate course on Interdisciplinary Modeling for Aquatic Ecosystems with a focus on water-related issues under a changing climate. The course introduces students to models utilized in different disciplines to address aquatic ecosystem issues and provides them experience in working as members of interdisciplinary teams to apply modeling approaches learned in class to real world problems (Saito et al. 2007). My contribution to the class has been based on presenting a lecture on "Why the Past Matters" that is focused on explaining how proxy records of hydroclimatic variables (especially from tree-ring records) can provide a longer baseline reference for assessing the range and variability of water-related phenomena such as droughts. The interdisciplinary nature of dendroclimatic reconstructions is made clear by highlighting the connections with similar branches of hydrology (including stochastic simulation and record extension) and with the required understanding of the ecological and biological properties of tree growth. At the beginning of the lecture I provide the students with a hands-on activity aimed at emphasizing the need to understand the past history of the system under investigation for correctly designing a scientific model. Results from the activity lead directly to a discussion of the main presentation topic, i.e., the "paleo conundrum," and the rest of the lecture then follows the same line of reasoning that is provided in the remainder of this paper.

## The Paleo Conundrum

The importance of understanding the past history of natural systems has been explained by several authors, most recently with respect to ecological legacies generated by phenomena occurring decades or centuries ago that still have residual influences on modern ecosystems (Bain et al. 2012). The impact of past legacies on natural and human systems becomes especially relevant for predicting future conditions under known forcings such as climate change. As shown in Figure 1, ecosystem trajectories cannot be correctly simulated using only its current conditions and the expected forcing, since the future will ultimately be influenced by the effect of past drivers.

With regard to managing natural resources, "historical perspectives increase our understanding of the dynamic nature of landscapes and provide a frame of reference for assessing modern patterns and processes" (Swetnam et al. 1999: 1189). A revealing example is provided by fire management in the western U.S., which during most of the 1900s was aimed at suppressing all wildfires, without recognizing the ecological role of fire because no long-term records existed to reveal its natural regimen (Pyne 1997). Such records have become available mostly through the dendrochronological analysis of long-lived fire-scarred trees (Fritts and Swetnam 1989). After allocating a tremendous amount of resources, both financial and human, to fighting wildfires for several decades, it has been recognized that large areas, in the western U.S. and elsewhere, are now much more likely to experience a high-intensity crown fire because of the accumulation of fuels caused by fire suppression policies (Minnich 1998). One cannot forget that such policies were supported by the best available science during the many years of their implementation.

Incorporating knowledge of the past into models used for decision making in the environmental sciences is fraught with difficulties. One of the

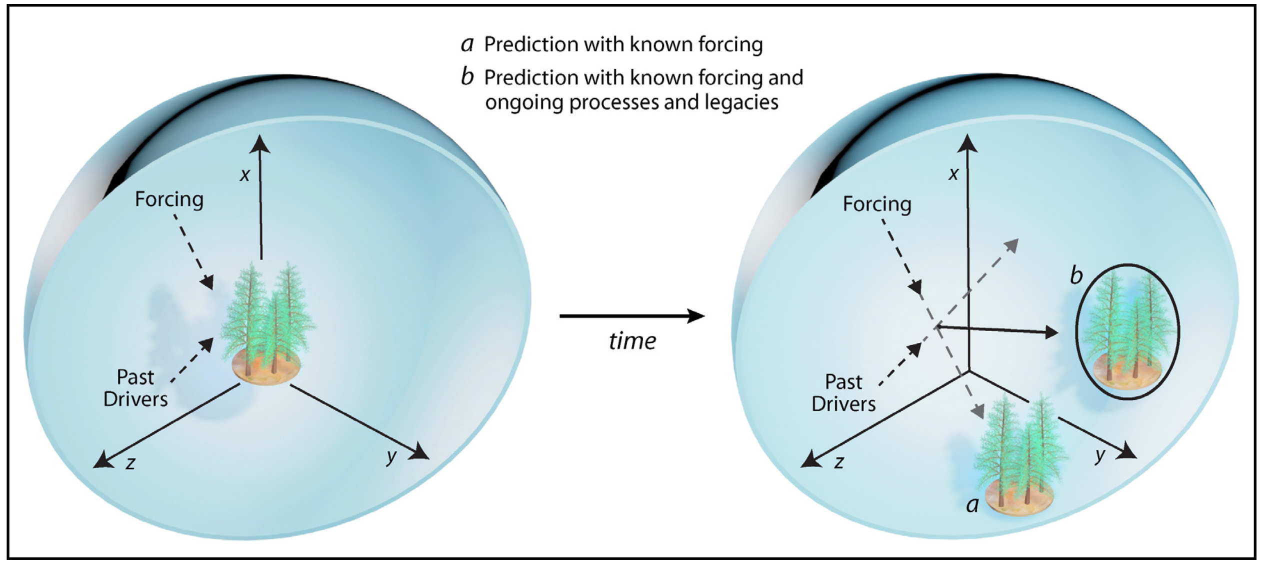

**Figure 1.** Diagram showing how the trajectory over time of an ecosystem and its features cannot be correctly predicted using only its current conditions and the expected forcing (the "a" scenario in the right-hand graph), since the future ecosystem will ultimately be influenced by the effect of past drivers (the "b" scenario in the right-hand graph, which takes into account "ongoing processes and legacies").

major obstacles is represented by the impossibility of actually performing experiments, so that retrospective studies are limited to observational and iterative approaches (Cochran 1983). Although researchers are constantly refining and expanding the tools used for environmental reconstruction – for example, by means of radiometric and geochemical markers (Bowen 1991; Clark and Fritz 1997) – all of paleoscience is inexorably limited by the lack of an outcome that can determine model skill. By contrast, the rapid advance in recent times of other observational and iterative disciplines, such as weather prediction and opinion polling, is intimately linked with the ability to objectively compare model predictions with observed outcomes, which is an obvious impossibility when dealing with the past. This is the main reason for the "paleo conundrum": despite its importance, knowledge of the past can never be verified (sensu Oreskes et al. 1994).

Confidence in the results provided by retrospective studies can yet be increased when multiple lines of evidence corroborate one another (National Research Council 2006). While this is a perfectly legitimate approach for achieving more reliable information, it comes with many insidious dangers, which have been described by various authors (e.g., Wunsch 2010). Briefly, as in any other type of circumstantial investigation, researchers need to recognize potential sources of bias, since inevitably a strong urge arises to emphasize confirmatory evidence and to downplay contradicting one. A lucid and compelling analysis of how paleoscience operates, and more generally of how knowledge is accumulated, tested, revised, but also lost or discounted, was recently provided by Jackson et al. (2012). Perhaps the only remedy to the paleo conundrum may be the explicit acknowledgement that multiple reconstructions of the same variable can, and will, differ depending on the sources used, methods employed, and other decisions made by the investigator(s). Recent analyses of proxy records of the same variable that diverge from one another can be found for tree-ring reconstructions focused on the Pacific Decadal Oscillation (Kipfmueller et al. 2012) and on summer air temperature for northern Scandinavia (Esper et al. 2012).

## Incorporating Proxy Records of Climate into Watershed Models

Despite the limitations of retrospective studies, dealing with modern challenges in water-related disciplines requires that we extend our historical perspective as far back as possible to capture

underlying long-term dynamics that would otherwise be impossible to detect (National Research Council 2007). In the hydrologic sciences, a large body of literature deals with the issue of record extension (Hirsch 1982; Salas et al. 2008), and disciplinary boundaries ought to be overcome to clarify how these methods compare with those used for proxy reconstructions. The main difference is that, in hydrological record extension, a variable measured at a given location either has missing values or a shorter time series than the same variable measured at other locations (Helsel and Hirsch 2002). These methods then fall under the general category of statistical imputation (Little and Rubin 2002), and have been characterized in hydrology by a search for ways to force equalities in mean, variance, first-order autocorrelation, and cross-correlation between the predictand and its predictor(s) (Grygier et al. 1989; Matalas and Jacobs 1964). Hydrologic records can also be extended by using stochastic approaches to generate synthetic data (Santos and Salas 1992; Sharma et al. 1997): in this approach probabilistic properties associated with the instrumental time sequence are preserved over the longer period assuming that instrumental data adequately represent the range and characteristics of hydrologic variables well beyond the actual period of observations. On the other hand, in most proxy reconstructions (National Research Council 2006), a statistical model is used to link the proxy records with instrumental data (calibration), and this model is then used to obtain the proxy climate information (reconstruction). The predictors in this case are of a different nature than the predictand; for instance tree-ring chronologies can be computed using various numerical, or "standardization," options, which were reviewed in detail by Cook and Kairiukstis (1990). Because of differences in standardization methods, tree-ring chronologies have no set mean or variance or autocorrelation, either at short or long ranges, as these parameters depend on the particular standardization chosen by the investigator (Biondi and Qeadan 2008).

It is generally recognized that tree-ring reconstructions of hydrological parameters are interdisciplinary by their very nature, because a biological system (trees and forest stands) and its ecological settings (the environmental conditions controlling tree growth) are used to reconstruct the properties of a physical system (a watershed or landscape and the precipitation or streamflow that characterizes it). In this approach, instrumental records are typically extended using regression techniques, usually at seasonal to annual time steps over several centuries (Loaiciga et al. 1993; Meko and Woodhouse 2011). Dendrochronological records can be seen as more reality based, and less prone to the ripple effects generated by the death of stationarity (Milly et al. 2008), than stochastic simulation, since the past is rich with dry and wet episodes with characteristics outside the bounds of instrumental observations (Biondi and Strachan 2012). However, not only reconstructions are unverifiable by definition, but for streamflow in particular there is no direct physical link between growth of sampled trees and river discharge.

Tree-ring samples used for extending runoff records are typically collected far away from the stream bed (Loaiciga et al. 1993). Hence statistical relationships between river discharge and tree-ring chronologies are based on connections that both wood accumulation and stream runoff have with local or regional climate (Biondi et al. 2010). Because of this lack of a direct relationship between predictor and predictand, dendrohydrological reconstructions cannot easily incorporate the influence of watershed factors that can change streamflow even when upstream climate remains the same. Such factors include stream channel profile (affected by incision, alluvial deposition, beaver activity, etc.), vegetation cover (affected by plant species dynamics, wildfire regime, landslides, etc.), land use (due to human activities, such as cattle or sheep grazing, clearcutting, crop production, urban development, etc.), diversions and their return flow (caused by either natural or human agents). While obtaining historical records on these various factors can be difficult, a partial solution to this aspect of the paleo conundrum is introduced in the following paragraph.

A way to incorporate non-climatic landscape-level changes into reconstructions of streamflow is to simulate them using a watershed model driven by climatic inputs derived from proxy records (Saito et al. 2008). Using model experiments and sensitivity studies, one can then evaluate the influence of the non-climatic factors mentioned above, obtaining error bounds for the long-term proxy runoff estimates that would otherwise be impossible to compute. These ideas, which were first proposed for the Walker River Basin between California and Nevada by Saito et al. (2008), were further applied to a small watershed in the Great Basin of North America by Solander et al. (2010), and have found application to a much larger geographical region and to a much longer time frame, either looking at past or future periods, through the work of Gray and McCabe (2010).

In conclusion, how to best incorporate proxy data, together with instrumental observations, into models used to manage water resources for coping with an uncertain future remains a non-trivial task, and novel ideas are crucial for making progress in the interdisciplinary combination of data and models to represent aquatic ecosystems in four dimensions. A stimulating point of view on how different scientific disciplines can be combined in mutually beneficial ways to study and manage natural systems calls for a synthesis of the "Newtonian" and "Darwinian" approaches to science (Harte 2002). The example mentioned above of using tree-ring records as inputs to a watershed model to derive information on hydrological parameters was proposed as a step in that direction, and provides at least one alternative way to use information from the past for interdisciplinary modeling of aquatic ecosystems.

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# Collaborative Community Hydrology Research in Northern New Mexico

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**Abstract:** In New Mexico, increasing demand for water, combined with limited supplies and periodic drought, is placing additional stress on traditional acequia communities. Research on the hydrology of acequia agriculture in northern New Mexico has been carried out in three communities and their associated watersheds and irrigated valleys. Critical to the effort has been the participation of the acequias and individual farmers, ranchers, and other community member stakeholders. Participation in hydrology research included assistance in altering flows in acequias, and access to private property and wells, critical to obtain ground and surface water measurements. Further research that integrated hydrologic data with ecosystem, land-use, economics, and sociocultural data, via development of a system dynamics model, required community member participation through surveys, interviews, and workshops to develop, calibrate and refine the model.

**Keywords:** *community hydrology, collaborative hydrology, acequia*

Acequias are traditional community irrigation systems of New Mexico and southern Colorado (Hicks and Peña 2003; Rivera 1998; Rodriguez 2006). Several hundred are located in north-central New Mexico and a number of them are over 400 years old. During their existence they have adapted to year-to-year fluctuations in water availability as well as cycles of drought. They have also adapted to socioeconomic and cultural changes brought on by changing governments, policies, markets and demographics. However, acequias are now faced with urbanization and Southwest climate-change scenarios that may add levels of stress that they have not experienced before. Acequias vary to a significant degree in terms of canal length, number of acres irrigated, growing season, predominant crop species irrigated, associated riparian vegetation, community population density, and infrastructure and maintenance characteristics. A small acequia may have fewer than 10 members (parciantes), and a large one may have over 200. In some cases, the large number of members is due to agricultural land being subdivided for residential lots where, for example, a former 10 acre irrigated field has now become 10 one-acre lots. Acequias located at high altitude may have growing seasons of less than 90 days, or have risk of frost any time during the growing season, factors that strongly influence which crops are grown. Some acequias that divert water from small streams may have short irrigation seasons if significant streamflow occurs only during spring snowmelt runoff. Acequias diverting from larger streams may have more than sufficient water available throughout the growing season.

Amount and reliability of available irrigation water have a great influence on a particular acequia's or group of acequias' (when sharing the same source stream) governance and water-sharing customs and rules. A general operating principal of acequias is water-sharing in which all members receive more in times of plenty and all receive less in times of scarcity (Fernald et al. 2012).

Although there is much sociocultural similarity across acequias, there is also much diversity – increasingly so as new residents from other areas buy property and relocate to acequia communities.

The rich diversity makes it challenging to understand and model existing cause-effect relationships. This paper gives an overview of ongoing project work in what we refer to as "community hydrology" – essentially, involving community collaborators in the hydrology research. We use the phrase "community hydrology" because we feel it describes the project: initially, getting input from community acequias as to what types of hydrologic data would be of value to them, and then building relationships with them and other community members to enable us to collect the data. The hydrology work then expanded in a similar way with community collaborators to collect data and carry out research in the social sciences and other natural resource disciplines as discussed below. Kongo et al. (2010) and Gomani et al. (2010) have documented the effectiveness of participatory approaches to establishing hydrological monitoring networks. Stakeholders in their study areas were engaged in the process of collecting hydrologic data with the aim of better managing the water resource.

Our initial efforts were to work with community collaborators to both form hydrologic research questions and collect field data. This hydrology research has led into a multidisciplinary collaborative project seeking to model relationships and interactions within and among natural and human systems in which acequias are a focal point. Specific steps in the multidisciplinary project included establishing positive working relationships with community members, forming technical teams with input from the community, capturing and quantifying community knowledge, and using understanding to inform future resource decisions. The multifaceted aspect of the case study made it well suited to interdisciplinary modeling. Because we worked with the community extensively and gathered information on multiple components of acequia hydrology and culture, students with different backgrounds were able to tap into these different components when the case study was considered in an interdisciplinary modeling course (see Saito et al. this issue). This is a community effort in which participants become part of the community research. They may not derive immediate agronomic benefits, but by participating strengthen the study and community fabric.

## Collaborating with Community Members on Hydrologic Research

When beginning our hydrology research along the Acequia de Alcalde, our team met with local acequia officials to discuss the type of hydrologic research and information that would be of interest to them and their acequia community. Although experienced acequia irrigators and water managers understand the general effects canal and irrigation seepage and river flow may have on groundwater levels, detailed data quantifying surface and groundwater hydrology in acequia irrigated valleys had not been collected. Some initial research questions formulated to fill gaps in knowledge included:

1. What is the amount and timing of acequia canal seepage recharge to shallow groundwater?
2. Is seepage from flood-irrigated fields a significant source of recharge to shallow groundwater?
3. What are contributions of acequia canal and field seepage to groundwater return flow and river flow?
4. What are the projected effects of future management scenarios on timing and magnitude of seepage, groundwater return flow and river flow?

Almost all of the land in the irrigated corridors of the study consists of small farms or residential lots such that to be able to collect field-based data it has been critical to install or use existing wells on community members' properties. A large part of the collaborative effort consisted of educating landowners and community members about the goals of the project. This occurred during acequia and other community meetings, conferences, field days, etc., at which the project was presented and further input obtained. Since beginning the hydrology work in 2002, three lead hydrology researchers have participated in at least 25 such meetings and educational events. Even more critical was on-the-ground discussion and presentation of the research when out "knocking on doors" to look for community collaborators who had property at sites where well data or acequia flow data were critical to develop water table maps, water budgets, and input data for simulation models. As New Mexico State University's Alcalde Sustainable Agriculture Science Center is located at Alcalde, New Mexico, research began there. Transects of monitoring wells were installed to collect groundwater level and water quality data in order to provide initial information on groundwater response to seasonal irrigation inputs (Fernald and Guldan 2006). The Alcalde Center derives its irrigation water from the Acequia de Alcalde. With the collaboration of acequia members and officials, research began on estimating seepage losses out of the acequia canal. The mayordomo (ditch boss or superintendent; Rivera 1998) assisted in opening and closing gates at the correct time for acequia seepage tests and flow measurements as well as inspecting for diversions and leaks.

A more detailed understanding of the hydrology along the Acequia de Alcalde as well as a larger reach of the river required additional monitoring wells and flow measuring beyond the Alcalde Center's boundaries. Success in accomplishing this was due largely to the Alcalde Center's farm supervisor Mr. David Archuleta, a well-respected and active community member, who was the point person to find, and assist others to find, potential collaborators and present to them the proposed project. Community interest in water issues and our research was verified as almost all residents approached became willing collaborators.

Typically, the farm supervisor would visit potential collaborator sites in person. If no one was home at or near key sites, he would attempt again later. As a rule, when a contact was made, he would introduce himself, New Mexico State University (NMSU), and the nature and goals of the project and the need for wells, flow-station sites, or access through private property to the desired site. In some cases, a significant amount of time was spent discussing and answering questions about the project and water issues in general, not only with the collaborator and property-owner, but often times with relatives and neighbors who would come up and ask what he was doing. When returning to the site with other researchers to take measurements or monitor equipment, it was often important to take time to visit the collaborator as a courtesy and discuss project progress and results. For example, during the intensive initial six years of hydrology research along the Acequia de Alcalde, Mr. Archuleta spent on the order of 750 hours looking for and/or interacting with collaborators and inquiring community members.

Once collaborating acequias and/or community stakeholders engaged in the project, there were times when they needed particular data or an update on data collected (for example, ditch flow). Although we the researchers might often view the stakeholders or community members as collaborating with us, we were in a sense collaborating with them. At these times we would respond to specific requests, and organize subsets of data to present to them on their timetable and for their specific purposes and needs. These specific requests for data and information usually reflected a key value or priority of the individual or group. Responding to the requests adequately also strengthened collaboration. Some communication and information sharing with stakeholders took place electronically through email and a hydrology website that described the project, research personnel, and posted publications (this website is now being incorporated into the expanded website www.waterconnections.org).

At one point in the research in the Alcalde Valley study area, we had 12 monitoring wells on property of 12 community collaborators including farmers and ranchers and village residents. Based on this community-supported research effort, a water budget was developed for the Acequia de Alcalde (Fernald et al. 2010). Valley-scale hydrologic modeling beyond the Alcalde study area required additional field measurements of flow and groundwater level. For this, 18 more collaborators were found. In a recent effort to connect the hydrology of the upland to the valley, an additional five collaborators are assisting. Obtaining the detailed field data needed to develop the water budget, provide model inputs, and carry out other aspects of the hydrology research simply would not have been possible without the interest and cooperation of the community residents and acequias.

## Cross-Disciplinary Team Building and Community Stakeholder Input

Given the limited availability of water in New Mexico, steadily increasing demand, and future uncertainty of water supplies, we participated with

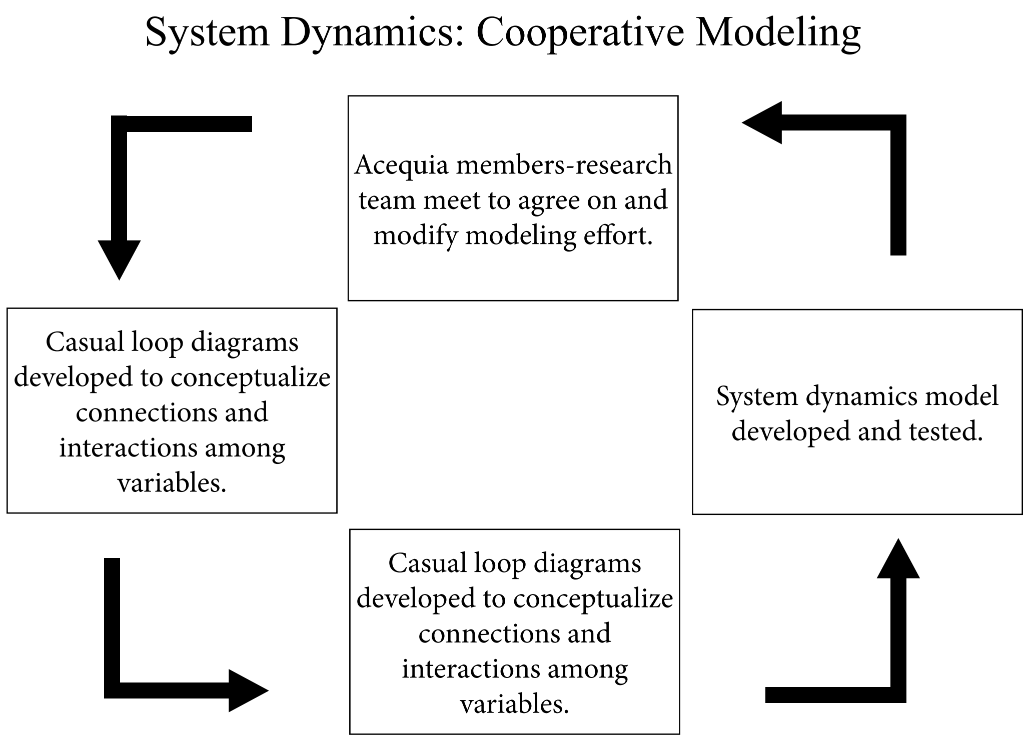

**Figure 1.** Generalized overview of system dynamics model development.

a number of other researchers in the development of a statewide proposal to build research capacity in water and climate change. This proposal was funded by the National Science Foundation's (NSF) program Experimental Program to Stimulate Competitive Research (EPSCoR) and was titled "Climate Change Impacts on New Mexico's Mountain Sources of Water." A component of the proposal focused on acequia systems, from hydrologic, socioeconomic, and cultural perspectives. The team responsible for this part of the research included social and natural scientists, although most research remained disciplinary. The NSF's program Dynamics of Coupled Natural and Human Systems (CNH) provided an opportunity for the team to expand and delve deeper into cross-disciplinary work. Members of this expanded research team represent several disciplines including hydrology, cultural anthropology, rural development and planning, economics, ecology, agronomy, remote sensing, livestock and rangeland science, community coordination, and systems modeling.

The CNH acequia project expands hydrology research to two more irrigated valleys, El Rito and Rio Hondo, and integrates the disciplines hydrology, ecosystems, socioeconomics, and sociocultural systems in all three valleys (Fernald et al. 2012). As was done for the Alcalde area, collaborative relationships with acequias, community leaders and other individuals were expanded upon or developed in the additional valleys of El Rito and Rio Hondo.

To explore the connections in the acequia system, four disciplinary subsystem conceptual models were constructed: hydrology, ecosystem, sociocultural, and land use/economics (Fernald et al. 2012). Causal loop diagrams were used as a visual and intuitive aid to develop these models. Over several months, team members interacted through meetings, workshops, and phone calls, to develop the conceptual models. In addition to constant research team interaction, in a retreat setting, community leaders, farmers and ranchers, and Cooperative Extension Service agents and specialists evaluated the project's goals and objectives and vetted the conceptual models, resulting in identification of additional variables and connecting links in the causal loop diagrams (Figure 1). In an ongoing system dynamics modeling effort, members of our research team are using these causal loop diagrams as the basis for parameterizing and testing relationships among variables. Once a working model is ready, it will be calibrated using field and historical data followed by review. This review step integrates disciplinary expertise of team members into the integrated model. Output from model runs will allow the team to evaluate feedback across disciplines, testing understanding about how the various subsystems interact and influence one another. Then, stakeholders will match model performance against their past experience (Fernald et al. 2012). Review of model conceptualization and performance by experts and community stakeholders provides powerful input for model calibration (Tidwell and Van den Brink 2008).

## Turning Community Knowledge into Research Data

An important challenge and goal of this project has been to translate community socioeconomic and cultural values and knowledge into data that can be integrated into a systems framework with cause-effect linkages to other components of the acequia system. Several approaches are being used in an ongoing effort to collect physical and socioeconomic data that capture socioeconomic and cultural relationships in these systems. Hydrology data collected is being integrated with data from the ecosystem, sociocultural, and land use/economics subsystems. Surveys and interviews have been conducted to quantify the socioeconomic and cultural values critical to understanding these acequia communities (Fernald et al. 2012) and their adaptive strategies and capacity (Mayagoitia et al. 2012).

In these acequia systems, various land-use/economics and sociocultural subsystem variables are intrinsically related to water and land management issues and this has been reflected in the data we have collected. For example, across three communities studied, 81 percent of respondents indicated that it is important to protect community water from outside influences and diversions (Mayagoitia et al. 2012). This commitment likely translates into many decisions that affect variables in other subsystems. For example, a decision to irrigate an old, low-yielding hay field, which has the primary purpose to preserve a water right for the individual and the community as a whole, would in turn affect variables in the hydrology and ecosystem subsystems. A commitment to protect community water could also translate into participating in the annual ditch cleaning and acequia meetings, strengthening acequia governance and the moral economy, variables in the sociocultural subsystem.

In efforts to package and deliver information and insight gained from the research and stakeholder interaction, the model that is being developed will be broadly accessible to stakeholders, resource managers and decision makers. Once developed, the model will be used to test future scenarios involving perturbations to climate, community economics, and urban demand of water. Model outputs are designed to inform policy recommendations for traditional irrigation communities and urban areas, relevant to forest, wildlife, water, and agricultural land use planning. It is expected that decision makers and community members will be able to use the model (that they helped develop) to explore future scenarios relevant to their decision space. Stakeholders in the small communities and urban areas can see how their futures may be impacted by land and resource use in remote but linked locations.

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We express sincere thanks to the acequias and community members who participated in this research; and, to David Archuleta, Farm Supervisor at the Alcalde Sustainable Agriculture Science Center, for his ongoing assistance in various technical and community engagement aspects of the hydrological research. This study was funded in part by the New Mexico Agricultural Experiment Station and National Science Foundation grants #814449 New Mexico EPSCoR, and #1010516 Dynamics of Coupled Natural and Human Systems.

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# Qualitative and Visualization Methodologies for Modeling Social-Ecological Dimensions of Regional Water Planning on the Rio Chama

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**Abstract:** Courses in modeling often employ techniques based on mathematical or other computer-based quantitative models. In this article the authors update a range of social science qualitative and visualization methodologies presented to graduate students at an interdisciplinary modeling course on water issues related to climate change. In part the modeling course featured the coupling of natural and human system dynamics in the context of acequias, gravity flow irrigation systems in New Mexico that depend on winter snowpack for water supply in the form of spring run-off. While student teams were able to employ STELLA and other models, they were free to explore alternative approaches. As course instructors, we assigned a pilot case study that utilized qualitative methodologies along with visualization tools to model land use, built environment, geo-spatial, natural systems, and human settlement morphology. Our project described a social-ecological history of the Rio Chama, a tributary of the upper Rio Grande, where we applied a cross-disciplinary and inter-temporal approach on how the land and water resources of the Rio Chama have been developed over time. The case study highlights the social-ecological dimensions of regional water planning while demonstrating the potential of visualization methodologies as a unique approach to modeling distinct from models based on quantitative data.

**Keywords:** *Rio Chama watershed, social-ecology, visualization methodologies*

A research team at the University of New Mexico is currently investigating the coupling of natural and human systems within the Rio Chama basin of New Mexico as a case study of society at the regional scale. In scope we plan to characterize the social-ecological history of the Rio Chama by surveying the breadth of human and nature interactions that have shaped the region since the collapse of Chaco around 1200 AD. The final research monograph will conclude with an analysis of post-World War II urbanization and the attendant issues of population growth in the metropolitan centers of New Mexico into the new millennium. In June of 2012, we developed a pilot case study for use by graduate students from Idaho, Nevada, and New Mexico enrolled in an interdisciplinary modeling course on water issues related to climate change in the Western states. As a departure from the more standard use of models based on mathematical or statistical methods, we instead applied social science qualitative research and visualization methodologies derived from ethnographic histories, archeological surveys, geographic mapping, hydrographic survey maps, census data, along with the use of emerging theories into linked physical-social-ecological systems (Fernald et al. 2012).

In a background report for use by the modeling students, we presented a brief history of the Rio Chama basin as a resource system that has supported multiple and sometimes competing cultures over centuries of human occupation. For reader context this article will outline the historical role of the Rio Chama during early Hispanic land grant settlements, and how reclamation projects developed the river into a trans-basin delivery system for urban growth centers in the twentieth century. Next, the main body of the article will describe how visualization methodologies can unpack abstract ideas or data and translate them into images that enhance the

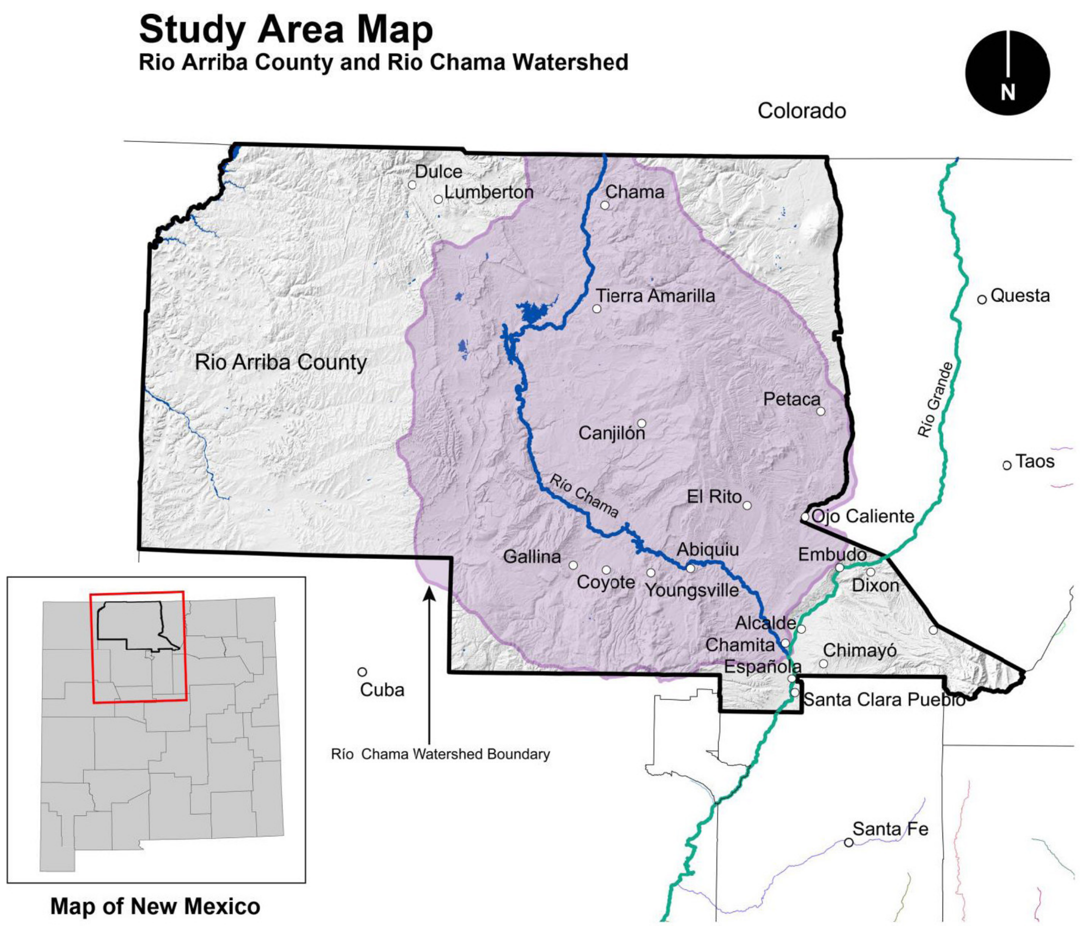

**Figure 1.** Study Area.

understanding of complexity in the built and natural environment while bridging historical timelines with contemporary spatial information by way of cross-disciplinary mapping.

Lastly, the article describes the results of the student modeling course, and concludes with the proposition that the modeling of landscapes in visual communicative forms can be used successfully to describe physical and natural systems in a way that will facilitate the development of collective strategies for water policy development.

## The Rio Chama Watershed

### Geographic and Hydrographic Extent

The Rio Chama watershed drains roughly 3,157 square miles, from the San Juan Mountains on the Colorado-New Mexico border in the north, to the confluence with the Rio Grande in the south, and is bounded by the Continental Divide and the Tusas Mountains on the west and east, respectively (Figure 1). The watershed is located in a biogeographical transition zone, encompassing the edge of the Colorado Plateau and its associated shrub and steppe biome on its northwest, the southern reach of the Rocky Mountain region and its pine forests on the northeast, the Jemez Mountains on its southwest and the Rio Grande Rift valley on its southeast. The watershed's highest points are the ridge of 10,000-14,000 foot San Juan peaks that form its northern border in Colorado, and Brazos Peak at 11,410 feet located in Rio Arriba County of New Mexico (Rio Chama Regional Water Plan 2006).

The Rio Chama is only 130 miles in length but functions as a vital tributary of the Northern Rio Grande, and itself is fed by numerous creeks, streams and arroyos. Due to semi-arid conditions in the landscape, most of these tributaries are diverted by centuries-old acequias for small-scale irrigated agriculture in the valley bottomlands: the Rios Tusas and Vallecitos that together flow into the Ojo Caliente, the El Rito, Canjilón Creek, Rito de Tierra Amarilla, and the Rio Brazos, among others. In the lower stretch below Abiquiu Dam, the mainstream Chama is diverted for acequia agricultural uses for about 28 miles before reaching the confluence with the Rio Grande at Chamita. The Rio Chama is a snowmelt-dominated river flowing into the Rio Grande north of the Otowi gauge, and this location makes it an important contributor to the Rio Grande index flow involved in water deliveries to the Middle and Lower Rio Grande of New Mexico as well as the interstate stream compact with Texas (New Mexico EPSCoR 2008).

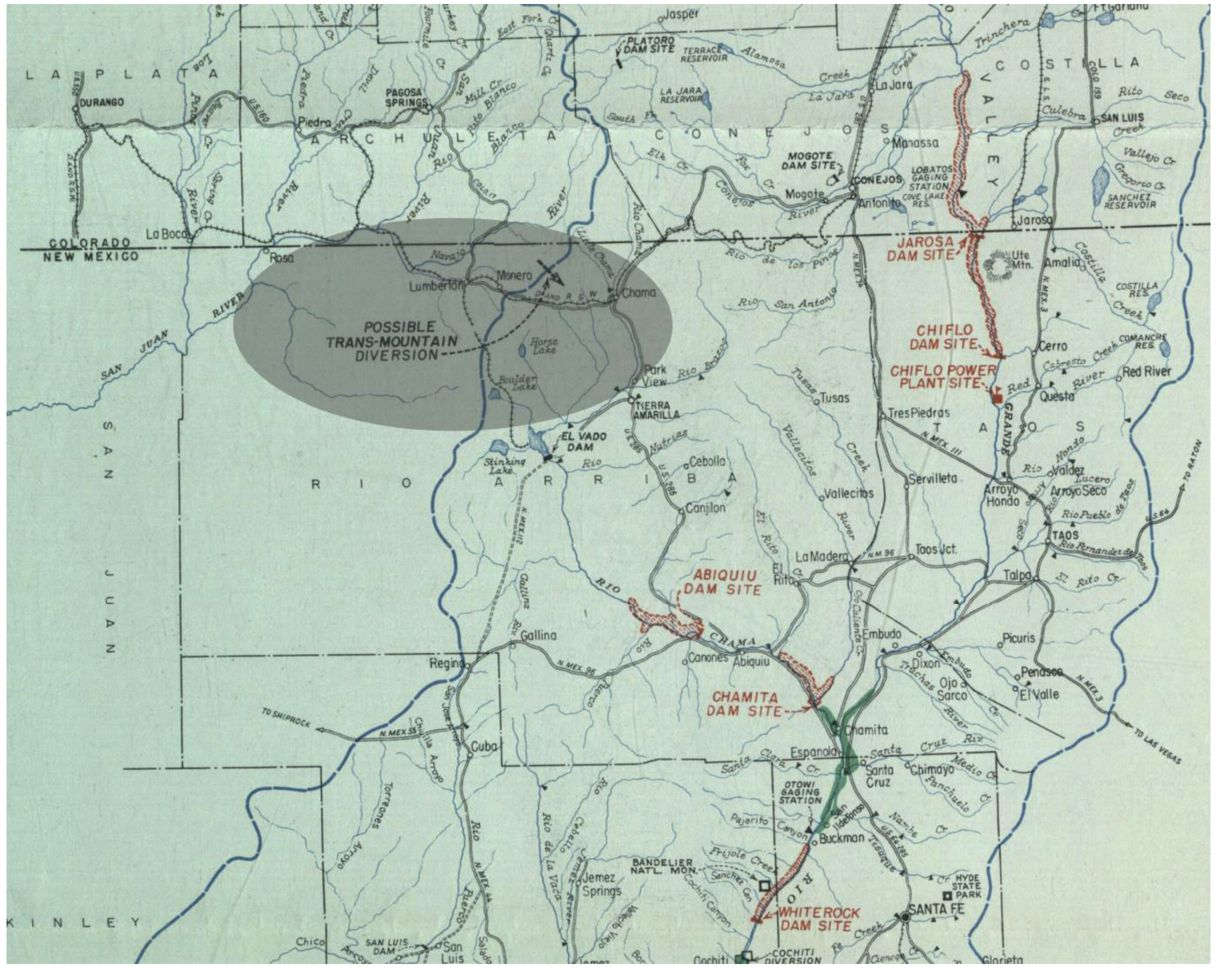

**Figure 2.** Bureau of Reclamation, Middle Rio Grande Project - NM 1947.

### Water Engineering History

The oldest Spanish acequia in New Mexico was constructed on the Rio Chama around 1598 under the direction of colonial Governor Juan de Oñate at San Gabriel, now Chamita. To recruit settlers from the central valley of Mexico, the Spanish and Mexican governments offered community land grants within the remote province of Nuevo México, the northern frontier in the borderlands of New Spain (Rivera 1998). After the Santa Cruz land grant in 1692, settlements followed the Rio Chama in its northwesterly direction toward Abiquiu, Ojo Caliente, El Rito, and Cañones. This dispersal pattern eventually led to dozens of farm and ranch settlements on the expansive Tierra Amarilla land grant from 1821 to 1848. With the transition to U.S. rule in 1846-1848, resulting in the aftermath of the United States-Mexican War, roughly sixty-five percent of the lands in the Rio Chama basin were transferred from communal ownership and use to Federal and Tribal control while much of the remaining land was partitioned, privatized or homesteaded (Rio Arriba County Comprehensive Plan 2009).

Additional and more dramatic impacts occurred during the early and middle twentieth century when the hydrology of the Rio Chama was reengineered by the construction of three reservoirs and an inter-basin tunnel. The first dam, El Vado, was built by the Middle Rio Grande Conservancy District in the 1930s to provide flow regulation for the irrigation district that stretches from Cochiti to San Marcial. The second dam, Abiquiu, was built north of the historic plaza of Abiquiu for flood and sediment control in the 1950s, and in the 1970s was joined by Heron reservoir designated to hold San Juan-Chama Project water (Glaser n.d.). Constructed by the Bureau of Reclamation, the latter project diverts water from San Juan tributaries of the Colorado River to the Rio Chama through a tunnel carved beneath the Continental Divide. The water from the project enters Heron through Willow Creek and then passes through the Chama for utilization by a number of entities downstream, with the bulk of water contracted to the City and County of Santa Fe, the Middle Rio Grande Conservancy District, and the Albuquerque Bernalillo County Water Authority (Thomson 2012).

The San Juan-Chama Project inextricably links two of the most vital water planning districts in the State of New Mexico: Region 12 in the Middle Rio Grande and Region 14 in the Rio Chama basin. In recent years, however, decreased snowpack in the San Juan Mountains of Colorado threaten the reliability of this imported water with curtailments on the horizon in response to dwindling reserves at Heron and El Vado alongside other pressures on the Colorado River basin where urban demands are rising and already exceed the supply (United States Bureau of Reclamation 2012). Figure 2 depicts a project map of the late 1940s for the proposed location of this trans-mountain diversion as well as other federal storage reservoirs of the Middle Rio Grande Project sponsored by the Bureau of Reclamation, not all of which were constructed (Figure 2).

### Socio-Demographic Development

Most of the Rio Chama watershed lies within the boundaries of Rio Arriba County, a rural agricultural county with a land base about the size of the state of Connecticut. According to county records, there are approximately 30,000 acres of farmland in the Rio Chama Valley irrigated by surface water canals or community-based acequias (Rio Arriba County Comprehensive Plan 2009). In recent years the recession and its economic impact have resulted in significant cuts in federal funding to agencies such as Los Alamos National Laboratory and the United States Forest Service, causing job losses in the area and shifting the population growth pattern of the last three decades. At the time of the 2010 United States Census, Rio Arriba County had a population decrease of 2.3 percent over a decade and faces new challenges of out-migration by young adults. During this same period, prolonged drought, a reduced snow pack, and forest fires have placed additional pressures on the viability of acequia-based agriculture. Other stressors on limited water supplies have resulted from population growth in Santa Fe, New Mexico's capital city, and particularly in the urbanizing area located within the Middle Rio Grande Regional Water Plan, a New Mexico planning district that includes Albuquerque and fast growing Rio Rancho. The City of Albuquerque currently relies on forty percent of its water supply from the San Juan-Chama Project due to a diminishing underground aquifer, and according to the Albuquerque Bernalillo County Water Utility Authority, this dependency could rise to ninety percent in future years when the perpetual rights of up to 48,200 acre feet will be needed annually (Albuquerque Bernalillo County Water Utility Authority 2011).

In the coming decades of increased water scarcity, and the possible effects of climate change, the contest over water resources in the upper Rio Grande basin could emerge as a battle of sprawl development in downstream cities versus water uses in area of origin communities such as the historic acequias dependent on snowpack in the northern mountains. The population differences are dramatic. Whereas Rio Arriba County is home to 40,466 residents, the total population in the urbanized counties of Santa Fe, Sandoval, Bernalillo and Valencia is about 1,030,000 (United States Census Bureau 2011). And unlike Santa Fe and Albuquerque, the acequia farmers of the Rio Chama do not have storage rights at Heron reservoir and can divert water into their headgates only from their share of native water or natural flow existent prior to the construction of the San Juan-Chama Project (Watermaster's Report 2009).

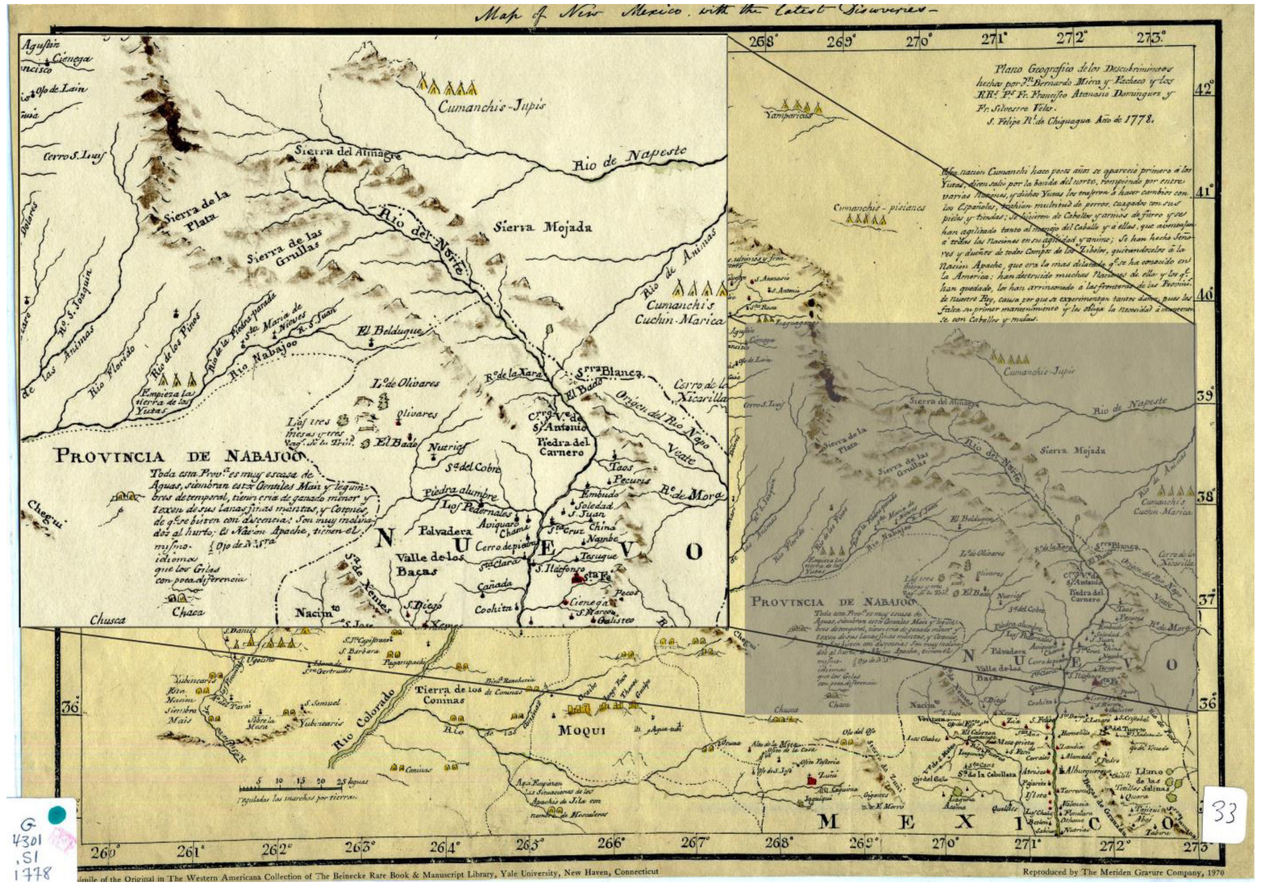

**Figure 3.** Bernardo de Miera y Pacheco Map 1778.

## Data Study Methodologies

### Social Science Research

Data made available to the students in the modeling course included: archival repositories of primary source documents, census data and other public records, ethnographic histories, archeological surveys, sociological reports, historic cartography of the region, field-based ethnographies, bibliographic references, along with data embedded in the Rio Chama hydrographic survey and regional water plan. Temporal and spatial data were intermixed covering events that led to major shifts in land use conditions. Analysis of historical context can help researchers comprehend the dynamic nature of landscapes in order to assess current conditions essential to informed resource management (Swetnam et. al. 1999). In addition to historical ecology as a conceptual model, we found that archival maps too can provide a visual tool for examining natural features, places, landscapes, and the connection of people and cultures to physical forms. New Mexico in particular has a rich cartographic history where archival maps represent hundreds of years in data points (Eidenbach 2012). A single map of Nuevo México drawn by Spanish cartographer Miera y Pacheco in 1778, for example, locates rivers and mountain ranges, among other physical features of discovered lands, but also depicts the human cultures previously existing such as the Navaho, Ute, Comanche, along with the Hopi, Zuni, and numerous other pueblo villages on the Río del Norte (now Rio Grande). In the inserted text, this cartographer notes that the Provincia de Nabajoo (Navajo Province) suffers from water scarcity, but the people manage to cultivate corn and legumes "de temporal," farming on dryland plots to supplement their economy of livestock raising and weaving (Figure 3).

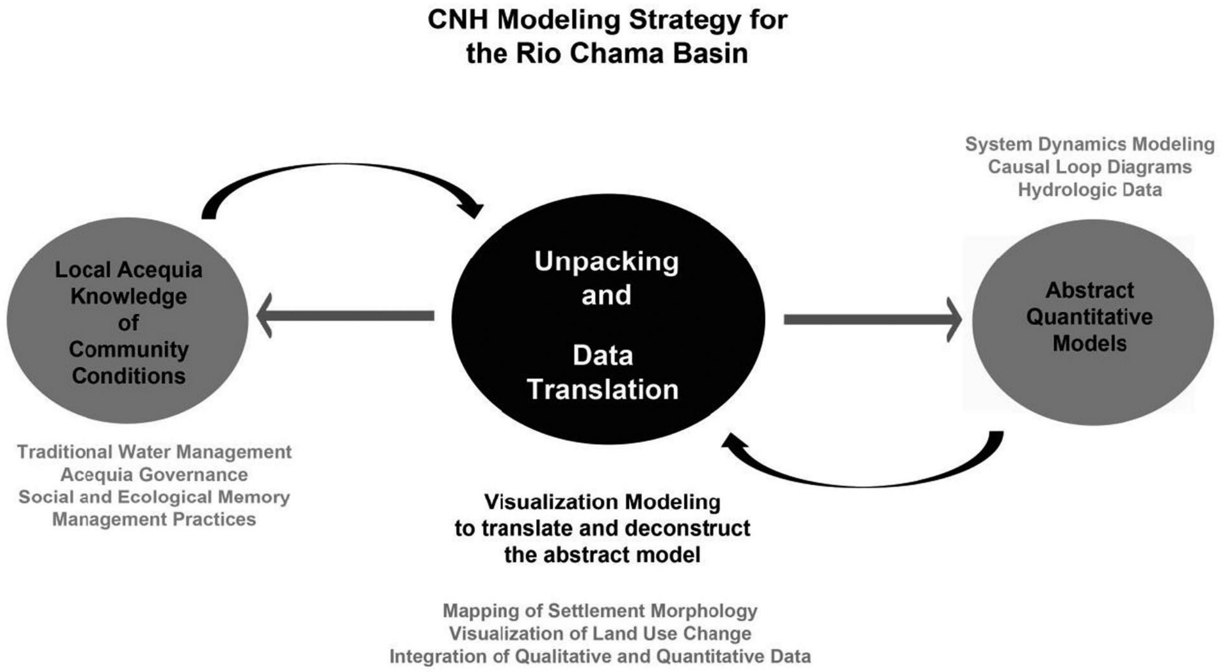

**Figure 4.** Unpacking and Data Translation Diagram.

### Visualization Modeling

Qualitative and quantitative methods are both needed to conduct cross-disciplinary studies and can be enhanced by the use of new visualization technologies to unpack and re-translate system complexity. Visualization methodology takes abstract ideas or data and translates them into images that communicate information about the built and natural environment (Figure 4). Visualization modeling tools and techniques assist in the comprehension of factors that transform the cultural landscapes and explicate settlement morphology. Settlement morphology examines changes in urban form, resolution, and time that shaped and altered the built environment and natural systems (Carmona and Tiesdell 2007). In the context of water planning, the modeling of landscapes in visual communicative forms can be used to engage community stakeholders in the understanding of physical and natural systems. Geo-spatial mapping of natural systems was originally developed by Ian McHarg (1969) to conduct analysis of regional ecological conditions by layering multiple data inventories such as riparian zones, slope, settlement patterns, and land use, a process that eventually led to the development of Geographic Information Systems. Today, in addition to GIS spatial mapping, water planners utilize a range of visualization tools such as three-dimensional modeling and geo-spatial software as a way to display graphic information that can integrate historical, qualitative and quantitative data to model cultural landscapes (American Planning Association 2006).

Qualitative visualization strategies in urban design and environmental planning derive from the same theoretical principles of visualization modeling in the scientific disciplines. According to McCormick and DeFanti (1987: 324), “visualization… transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. Visualization offers a method for seeing the unseen.” Langendorf (2001: 324) expanded this notion of visualization methodology in the planning field because of its potential application, “… the NSF examples of scientific visualization are directed at displaying information about physical phenomena, always with spatial dimension, and often with temporal. Though some of this has been used in natural resource and environmental work, it has not impacted most other areas of planning.” In the last decade, visualization modeling has allowed planners, urban designers, and decision makers the opportunity to experience the impact of policy on the built and natural environment. Cultural landscape morphology as a method and a research strategy spans the fields of geography, history, archeology, architecture and planning (American Planning Association 2006).

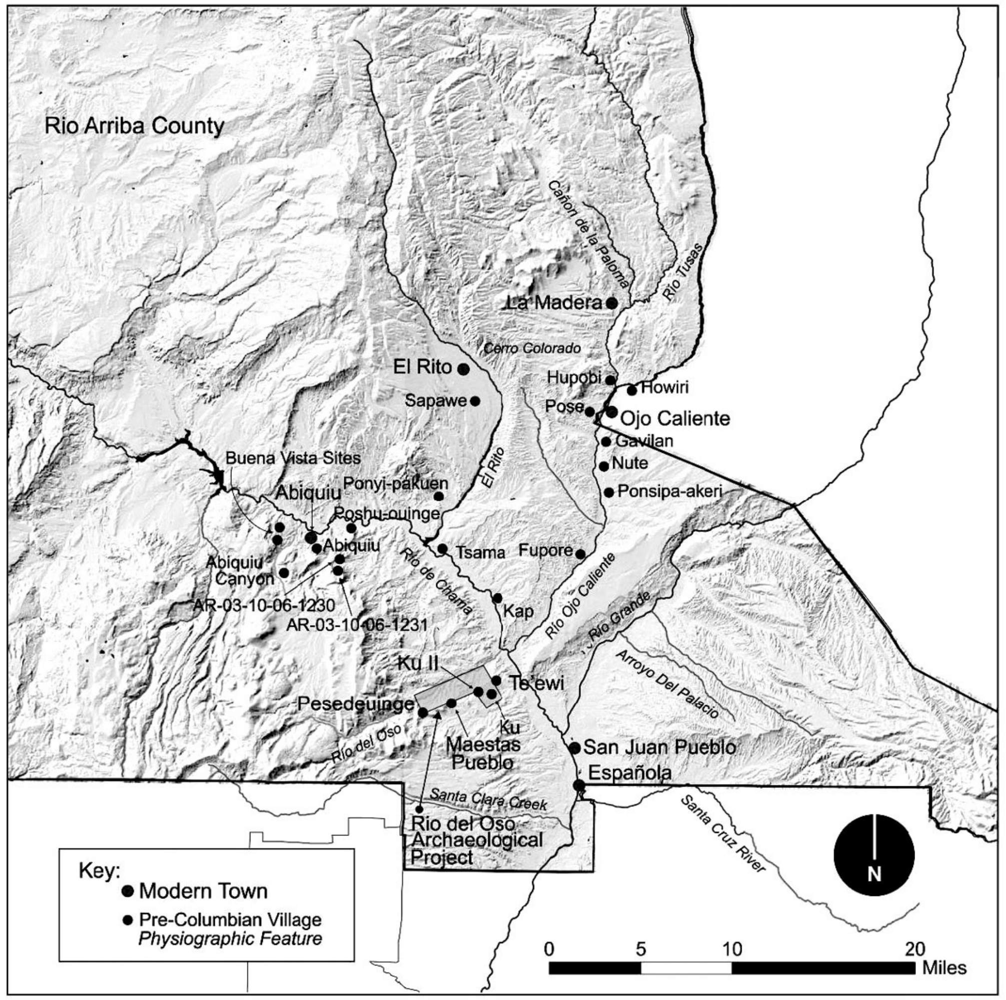

**Figure 5.** Riverine Settlements Map Adapted from Anschuetz 1998.

The challenge of contemporary mapmaking in modeling is the complexity of transforming multiple forms of data into interactive maps that can be used for analysis rather than communicative tools of representation. Our strategy is to go beyond the production of maps as graphic communication and to utilize visualization as an analytical tool in understanding the relationships and trasnformation of natural and human systems. “With the added scope and complexity of spatial data and methods of representation, and the possibility of interactivity, the interest of cartographers and spatial data users shifted from static maps to multiple views into the data, both concurrenlty and sequentially” (Langendorf 2001: 314). When mapping the social-ecological history of the Rio Chama watershed, at times we encountered difficulty in translating historical and archival maps into forms of data that are usable in a desktop mapping framework. The process of georeferencing historical maps, such as historic hydrographic surveys that are built into thematic spatial data, is difficult and often time consuming. However, when analog data are converted into usable mapping data sets, the result creates a deeper level of analysis into historic land use change as happened in our own Rio Chama visualizations.

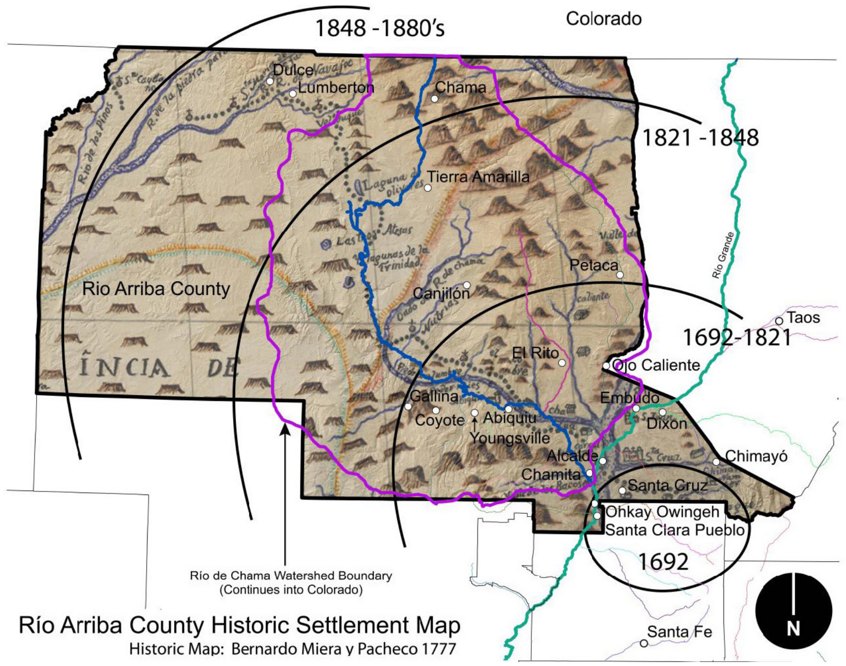

**Figure 6.** Adaptation of Bernardo Miera y Pacheco Map 1777.

We developed a map series to examine the evolution of settlement patterns beginning with riverine Pueblos before the arrival of Europeans, expansion of villages in the basin during the Spanish and Mexican land grant periods, and transformation of community form with the arrival of the railroad and Anglo Americans starting in the territorial period and into statehood of New Mexico in 1912. The modeling of adaptations in land use practices provided insights into how community land uses were altered and changed after subsequent historical events such as World War II. To analyze the cultural landscape evolution in the Rio Chama basin, the study team mapped early human colonies by geocoding Puebloan riverine village locations. A sample of Puebloan communities from the period 1300 AD to 1540 AD identified in archeological surveys were then geocoded and mapped in relationship to existing towns (Figure 5). Drawing from archeological investigations of building complexes, organization of agricultural grids and gravel-mulched plots, we developed an understanding of land use practices and systems of water management by Pre-Columbian Pueblo farmers (Anschuetz 1998).

In formulating a social-ecological narrative of the Rio Chama, we constructed additional map sequences to demonstrate the expansion of human colonies upon the arrival of Hispanic village settlements into the territory controlled by nomadic tribes such as the Navajo, Comanche, Ute, Apache, and Kiowa. As the next step, additional archival and historic maps were interpreted and regenerated into spatial data and map overlays onto existing geographic information for further analysis and reinterpretation. For example, historic maps from cartographers such as Alexander von Humboldt in 1804 detailing nomadic tribal contested territory, in addition to a second Bernardo de Miera y Pacheco Map of 1777, were geo-referenced and projected onto a 1983 North American Datum State Plane coordinate system. Through the comparison of maps generated and verification of archival documents, the study team began to understand geo-spatial territory of the Rio Chama watershed by settlement date, land use practices, and territorial control by various populations, a key step in developing the social-ecological narrative for the case study. Figure 6 depicts the timeline of Hispanic settlement expansion from Santa Cruz to the upper reaches of the Chama Valley from 1692 to the late 1880s (Figure 6).

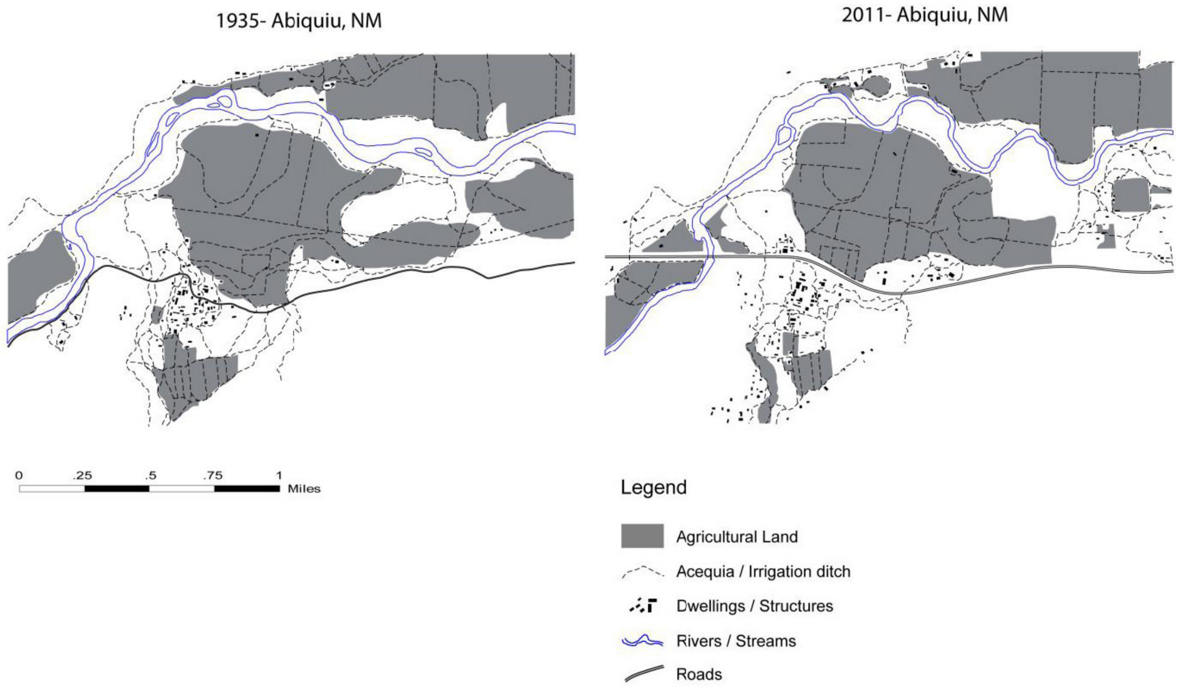

**Figure 7.** Abiquiu, New Mexico, 1935-2011 Land Use Settlement Morphology.

In order to illustrate land use change at the community scale, the study team also formulated a mapping catalog of settlements along the Rio Chama to document land use change from 1935 to 2011. In a community scale mapping series, each localized map provides detailed information of settlement form, agricultural parcel size, spatial organization of the acequia network, in addition to assessing riparian conditions along the Rio Chama. To analyze land use change within the Rio Chama, morphology mappings were developed for Tierra Amarilla, Los Brazos, and Los Ojos in the upper basin in addition to El Rito, Abiquiu, and Hernandez in the lower stretch of the Rio Chama. These maps provide key information on how land use conditions have been altered and what land use alternatives may be considered in planning for long-term drought mitigation in the basin.

To produce the settlement pattern maps, base mapping of key physical elements in built and natural systems were traced over 1935 aerial photography (Earth Data Analysis Center 2010). The 1935 aerial photography is one of the most important mapping series in the context of studying land use change for several reasons: (a) 1935 is the first deployment of aerial photography technology in the Rio Chama basin; (b) the photography was produced at the advent of World War II which brought significant changes in technology and farming practices in the region; and (c) the high resolution of the imagery is such that landscape and settlement features allows for fine grain mapping at the community scale. Community scale maps provided the study team with a baseline data set for understanding land use conditions along the Rio Chama such as diverse crop types, smaller farm plots, compact settlement form, and a more natural riparian network characteristic of a pre-channelization river system. In addition, the same geographic layers were mapped over the 2011 aerial photography for each of the selected village settlements. We were then able to analyze localized land use change from 1935 compared to the 1961 hydrographic survey data of the Rio Chama below El Vado (Office of the State Engineer 1961). Findings from the community scale morphology study revealed larger farm plot size, a dispersed settlement form, less crop diversity, and a restricted channelized riparian condition (Figure 7).

Three dimensional modeling in software programs such as 3D GIS in ArcScene and Google SketchUp, in addition to the use of photo montage imagery, were among other visualization tools used in modeling of the study area. Regional 3D visualization of landscape terrain at such a large scale as the Rio Chama basin is a useful tool to describe regional

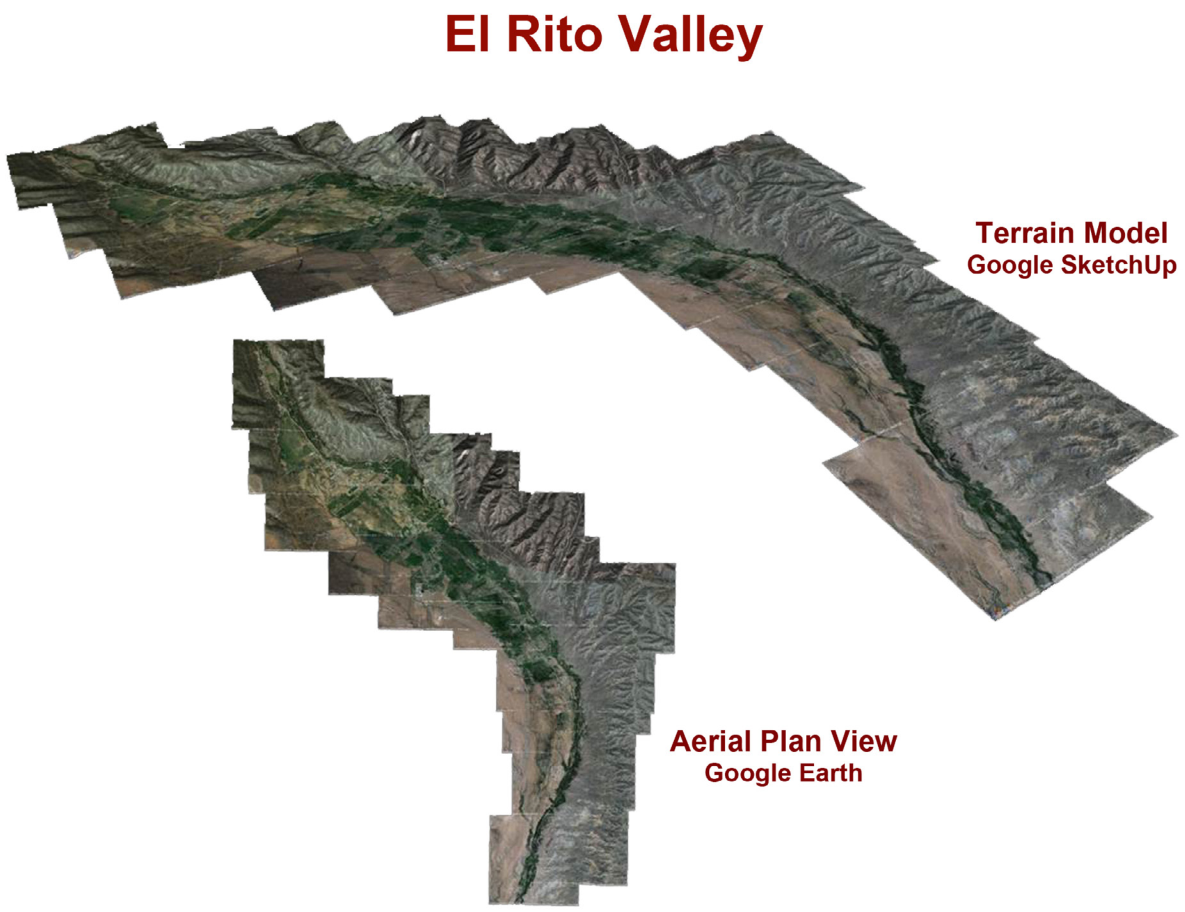

**Figure 8.** El Rito Valley Terrain Model.

complexity of systems and networks as well as engaging community members. Regional and community scale terrain models were developed in 3-D GIS based on digital elevation data and existing land use classification data generated by the study team (United States Geological Survey 2004). We then developed terrain models to illustrate physical spatial features at the community and regional scales (Figure 8). Terrain model visualization provides the ability to communicate abstract geographic locations in an understandable graphic form as a useful tool in regional water planning. The rendering of basin scale three dimensional modeling animations of land use conditions and settlement patterns can help acequia based communities in framing land use policy alternatives based on the possibility of prolonged drought conditions (Figure 9). Mapping visualization products create an opportunity for developing policy and land use alternatives in working through complexity of social and natural factors (Corner 2011).

Participatory three dimensional modeling in community capacity building has become widespread practice involving institutional and traditional community perspectives in natural resources planning. For example, in 1999 participatory modeling was used in the resource management planning at the El Nido-Taytay Managed Resource Protected Area in the Palawan coastal region of the Philippines (Rambaldi 2006). The planning process at El Nido-Taytay integrated visualization modeling while involving local fishermen in mapping fishing areas in addition to information about coastal and marine ecosystems. "… P3DM (Participatory 3 dimensional modeling) has been gaining increasing recognition as an efficient method to facilitate learning, analysis and proactive community involvement in dealing with spatial issues related to territory. If properly administered, P3DM can support collaborative natural resource management initiatives and transcend the local context by establishing a peer-to-peer dialogue among communities and central institutions, agencies, and projects" (Rambaldi 2006: 541).

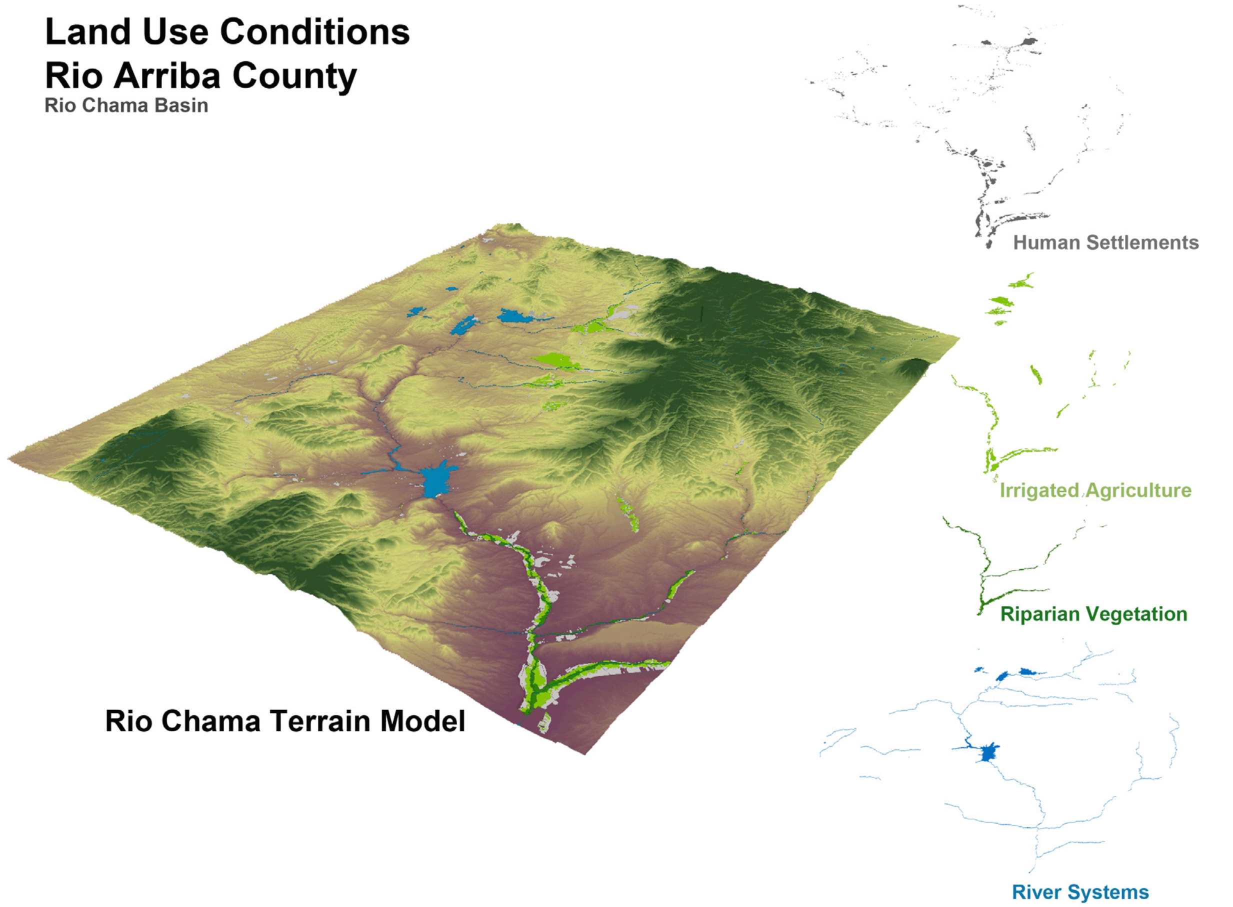

**Figure 9.** Rio Chama 3D Land Use Conditions Model.

## Discussion and Results

### Student Report and Presentation

How do climate change, water scarcity, and continued urban population growth challenge acequia water uses in the Rio Chama watershed, and conversely, how do acequia operations affect water flows of the Rio Grande downstream into the middle Rio Grande valley? Are there water policy alternatives that can encourage water sharing and conservation among rural and urban stakeholders and reduce conflict over water demand? Can system dynamics modeling help to facilitate collective strategies that might lead to improved communication and a transparent process for decision making as some modelers advise (Gupta et al. 2012)?

Those were among the questions posed to the team of modeling course students in June of 2012 as a pilot case study of the larger Rio Chama research monograph that is still in progress. The task for the students was to develop and evaluate future conditions of potential urban growth impacts on acequia-based communities in the Rio Chama watershed driven by climate change and other socio-economic factors within the context of the upper Rio Grande basin as a whole. We presented the students with three "what if" scenarios that linked both water planning regions, the Rio Chama and the Middle Rio Grande: a Status Quo Policy with no changes in water use by stakeholders in the two regions; a Moderate

Shift Policy with some water conservation practices adopted for both urban domestic and rural agricultural uses; and a Significant Change in Water Use Policy where municipal water consumers reduced per capita water use by 50 percent and the acequia communities increased on-farm irrigation efficiencies.

At the end of the course, the students made a final presentation and submitted a written report. In our view, the students successfully completed the assignment and managed to integrate a number of modeling approaches, both quantitative and qualitative, and included cross-disciplinary analysis that covered Rio Chama settlement history, social and cultural aspects of acequia agriculture, socio-economic demographic data, urban growth impacts on water demand into future years, and a discussion of the policy regimes presented in each of the three scenarios. The socio-economic modeling focused on the Rio Chama Regional Water Plan followed by a series of land use analysis maps depicting rural low development and agricultural uses and concluded with a MacHargian Land Suitability Analysis Terrain Map. For system dynamics modeling the students utilized STELLA to incorporate a diverse array of data and to conduct the Rio Chama policy alternatives sensitivity analysis, and also GAP Habitat for modeling changes in species richness in the Rio Chama basin.

As to lessons learned when integrating models across disciplines, such as spatial (GAP) models and systems driven models (STELLA), the student team noted that interdisciplinary modeling holds substantial value, albeit with difficult challenges to keep the group dynamics in sync given inherent differences within each of the models used, the different languages across disciplines, and the fact that different analysis types employ units of measurement that are not always compatible. With more time, and more learned experience on how to work in teams, they concluded that the process of interdisciplinary group modeling will result in projects that can be "both effective and efficient for addressing issues such as acequia land, water, and community dynamics" (Corrao et. al. 2012).

## Future Policy Collaborations

The upper Rio Grande basin does not produce an adequate water yield to satisfy the multitude of conflicting values and demands based on current conditions and uses. These competing uses include a growing human population in the cities, irrigated agriculture resistant to water transfers for urban consumption, and declining reserves in the storage reservoirs of the Rio Chama. These factors are exacerbated by a period of multi-year drought and the uncertainty about impacts of climate change on mountain sources of water in the upper Colorado River basin and the Rio Grande (NM EPSCoR 2008; United States Bureau of Reclamation 2012). Public engagement in an interactive modeling community-based process, as we conclude and propose here, will help promote dialogue about water conservation and other options drawn out by a number of "what if" scenarios that stakeholders can consider and evaluate if provided with equal access to relevant scientific data (see Tidwell et al. 2004 for an example of system dynamics community-based water planning with application to the Middle Rio Grande).

To aid with the translation of abstract numerical models, we contend that qualitative analysis and visualization methodologies can make a difference, level the playing field, reduce uncertainties, generate a multitude of ideas, and set the stage for collective decision-making across stakeholders, water planners and resource managers at local, state and regional levels. Beyond the pilot case study developed for the June 2012 modeling course, additional iterations of this cross-disciplinary and inter-temporal approach will be conducted in the fall of 2013 at stakeholder workshops along the Rio Chama. To facilitate the workshops the study team will present the social-ecological history of the Rio Chama watershed in a visual narrative form to deconstruct and unpack complexity of system dynamics modeling and then re-organize information so that stakeholders can develop alternatives based on possible future land use and water policy scenarios. As happened already with the modeling course, these workshop presentations will likely result in further improvements in the use of qualitative and visualization methodologies as tools for community-based water planning.

## Acknowledgments

The modeling course in June of 2012 was held on the campus of New Mexico State University and was sponsored by the Tri-State Western Consortium of EPSCoR projects funded by the National Science Foundation in the states of Idaho, Nevada, and New Mexico. The purpose of the course was to conduct interdisciplinary modeling on water issues related to climate change based on five case studies presented by the course faculty: the Upper Rio Grande Basin, the Rio Chama Watershed, El Rito, Alcalde and Rio Hondo. Research for the Rio Chama project was made possible by subawards to the University of New Mexico from NSF award #0814449 to New Mexico EPSCoR and NSF award #101516 to New Mexico State University. We also acknowledge and thank the units at the University of New Mexico that supported the work conducted by the team of faculty and graduate students: the Center for Regional Studies as the grant administrator; the Community and Regional Planning Program and the Resource Center for Raza Planning, both housed at the UNM School of Architecture and Planning, for providing space facilities and technical mapping support.

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# Hydrologic Connectivity of Head Waters and Floodplains in a Semi-Arid Watershed

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**Abstract:** Hydrologic connectivity can be important when assessing the role of water availability and distribution in sustaining different natural processes and human activities in a given landscape. We present a study that served as one of five case studies for an interdisciplinary modeling course. The main objectives of the study presented are: 1) to characterize the hydrologic connectivity between the uplands and the irrigated valley and; 2) to set the foundations for understanding the connections between hydrology and complementary disciplines of ecology, rangeland management, and system dynamics modeling in a semiarid watershed in the southwestern United States. Study results show a strong hydrologic connectivity between surface and groundwater in the lower agricultural valley that follows a seasonal pattern, driven primarily by irrigation contributions to the shallow aquifer. The interdisciplinary modeling team assigned to this study was able to use data from it and outside sources to create a working model that addressed these interconnections and highlighted the study value of concurrent consideration of multiple components of linked hydrologic, economic, ecological, and social systems.

**Keywords:** *Hydrologic connectivity, surface water, groundwater*

The hydrologic connectivity between upland water sources and floodplain irrigated valleys, through shallow groundwater systems, can be an important determinant of hydrologic resilience in the face of climate variability. Understanding hydrologic connectivity that links water provisioning with its many uses is important when assessing the role of water availability and distribution in sustaining different natural processes and human activities in a given landscape. The importance of hydrologic connectivity becomes even more evident in arid and semi-arid environments where water resources are scarce and where central economic activities are heavily dependent on the proper management of this vital resource.

In many parts of the southwestern United States, particularly in watersheds of northern New Mexico, the melting of the snow pack that accumulates during the winter provides most of the streamflow that is released throughout spring and summer times. Within these watersheds, farming is typically confined to narrow floodplains along the main stems of a river or a creek. These alluvial floodplain farms are dependent on the connectivity between surface and shallow groundwater. Specifically, precipitation, runoff and infiltration processes in the upper watershed are directly associated with aquifer recharge and late-season streamflow levels critical to the survival of both crops and riparian communities.

Several researchers have documented the temporally variable hydrologic connectivity between upland water sources and downstream valleys and have recognized the importance of spatial variability within the landscape (Jencso et al. 2009; Ocampo et al. 2006). As stated by Schulz et al. (2006), hydrologic connectivity within a landscape is affected by different spatial patterns on the land surface (e.g., elevation, vegetation, soils type) but also in the subsurface (geology).

Alterations to the landscape due to human and natural activities can modify the spatial and temporal patterns of hydrologic connectivity. In

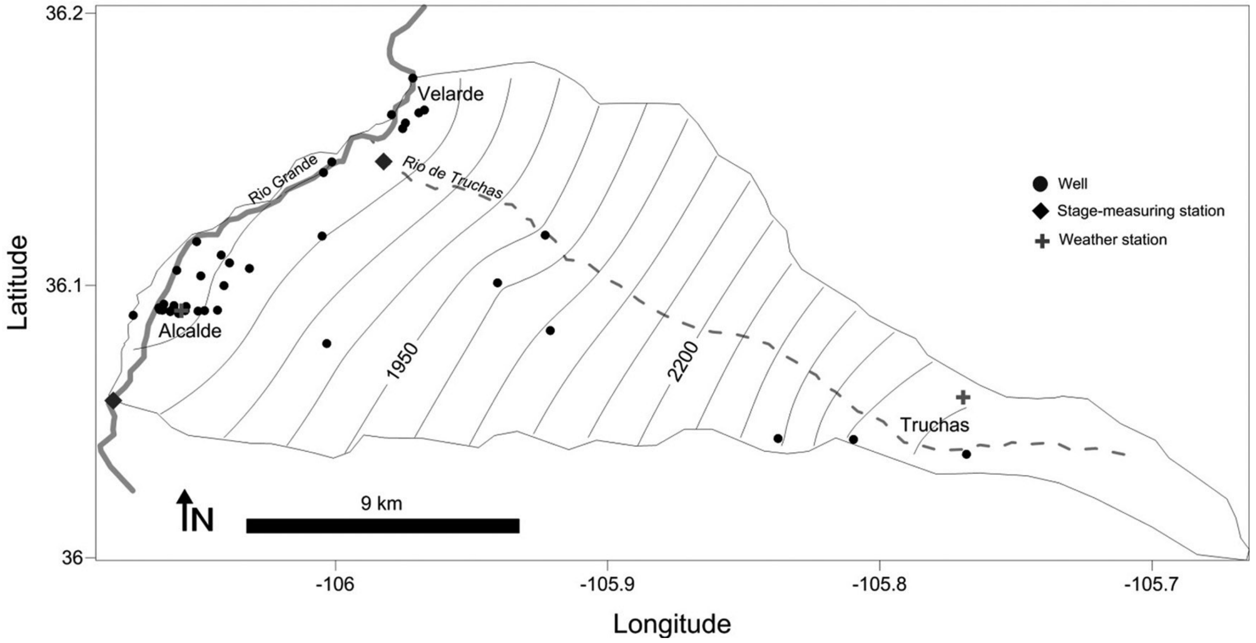

**Figure 1.** Study area showing water table (meters above sea level) map and monitoring locations for surface water, ground water, and weather parameters.

multiple watersheds of northern New Mexico, farming in the valleys and ranching in the upper watershed are two activities that are closely related and still embrace a lot of the traditional way of managing the land and the water and that has been passed down through generations (Fernald et al. 2012). Many farmers in this region of traditional irrigation systems (acequias) are also ranchers that raise cattle in the upper watershed rangelands (Lopez et al. 2013).

The Millennium Ecosystem Assessment (2005) categorized ecosystem services as provisioning (e.g., food, water, and fiber), regulating (e.g., disease regulation), supporting (e.g., nutrient cycling, soil formation), and cultural services (e.g., recreational hunting). Many of these ecosystem services, as well as biodiversity, are dependent on the connectivity and distribution of water within the landscape.

Improved understanding of hydrological connectivity becomes critical for proper management of land and water resources and for expanding our recognition of the potential environmental effects due to transforming of the system (Lexartza-Artza and Wainwright 2009). The aim of this paper is to improve knowledge of the interconnectedness of different hydrologic components and of the mechanisms of water distribution within the landscape. The main objectives of the study presented are: 1) to characterize the hydrologic connectivity between the uplands and the irrigated valley, and 2) to set the foundations for understanding the connections between hydrology and complementary disciplines of ecology, rangeland management, and system dynamics modeling in a semi-arid watershed in the southwestern United States.

## Study Area

The study area encompasses a 330 km$^2$ watershed (36.1° Latitude; 105.9° Longitude) in the Velarde sub-basin of the Española basin and includes three main communities, Alcalde, Velarde, and Truchas (Figure 1) with a per-community population count of 282, 502, and 560, respectively (Newmexico-demographics 2013). Main economic activities in the area are agriculture and ranching.

Land ownership in the study area is a mixture of private property in the lower valley (Alcalde and Velarde) and in the village of Truchas, and federal land in the upland rangelands and forested areas. Agricultural land in our study area is concentrated along the Rio Grande valley in the Alcalde-Velarde reach and in areas near the village of Truchas. Rangelands in our study area are federally owned and leased for livestock grazing by the United States Department of Interior, Bureau of Land Management. Livestock grazing in this watershed occurs mostly during fall and winter months, and since the early 1980s the watershed has been stocked moderately at approximately 16 ha per Animal Unit Month (AUM) (Lopez, S. unpublished data).

There are two main weather stations in the study area, one located in the valley at the Alcalde Science Center (1735 m) and one located at mid-elevation (2364 m) near the village of Truchas. Annual precipitation in the study area ranges from about 250 mm in the lower valley, to about 400 mm near the village of Truchas, to more than 750 mm, at 3500 m elevation, in the Sangre de Cristo Mountains (Borton 1974; WRCC 2006).

Overstory composition in the riparian areas is dominated by Rio Grande cottonwood and Russian olive trees, followed by shrubs such as New Mexico olive and coyote willow (Cusack 2009). Relatively small areas of fir, spruce, and aspen are common in the higher eastern corner of the watershed. Downslope, ponderosa pine communities occupy about 10 percent of the watershed based on Southwest Regional Gap Analysis Land cover data (Lowry et al. 2007). However, piñón-juniper and juniper woodlands occupy most of the watershed (55 percent), semi-desert shrub steppe and grasslands occur on the uplands above the riparian areas. Agriculture is identified on 3.1 percent of the watershed.

Groundwater is mostly affected by Rio Grande flow and by drainage from its main tributaries (Rio de Truchas and Cañada de Las Entrañas) coming from the Sangre de Cristo Range in the east side of the basin (Stephens 2003). The main aquifers in the area are the Tesuque Formation and the alluvium along the Rio Grande and its tributaries. Depth to groundwater varies from 1.5 to 10 m in the irrigated valley (Ochoa et al. 2013) to more than 200 m in the higher part of the watershed (Borton 1974).

For the watershed as a whole, stream losses during flood or snow melt events are probably the most important source of recharge of the groundwater reservoir (Borton 1974). Canal and crop field irrigation losses are the primary contributor to the replenishment of the shallow aquifer in the Alcalde-Velarde reach, in the lower valley (Ochoa et al. 2013). The proportion of areal recharge in the entire Española basin including precipitation and streambed recharge does not exceed 5 percent of the annual precipitation (Cevik 2009).

Most of the water used in the lower valley goes to agriculture (Ortiz 2007), with about 99 percent coming from surface water sources (Cevik 2009). Various forage, fruit, and vegetable crops are grown in the area and they are irrigated using primarily surface (border and furrow) irrigation water that is gravity-driven from the river. Limited groundwater extraction in the study area is mainly used for stock and domestic purposes. This groundwater comes from old domestic wells (mostly shallow, some hand dug) and from recently drilled (deeper) mutual domestic wells that provide water to the villages of Alcalde, Velarde, and Truchas. Also, a few windmill wells that are used for providing water for livestock are located in the upland rangelands of the study area.

## Field Data Collection

At New Mexico State University's Sustainable Agriculture Science Center in Alcalde, NM (Alcalde Science Center), we have conducted several research activities aimed to better understand and quantify different field and valley water budget components, and to characterize landscape hydrologic connectivity at different scales. For example, since 2002 we have continuously monitored groundwater level fluctuations in multiple experimental wells at the Alcalde Science Center. Also, we have gathered information regarding canal and river flows. Since 2005, we have conducted several irrigation experiments to augment basic knowledge of the hydrologic connectivity between surface water irrigation and shallow groundwater response. Multiple weather (rainfall, air temperature, wind speed, shortwave radiation, and relative humidity) and other hydrologic parameters such as soil moisture, runoff, irrigation diversion, etc., were monitored for these irrigation experiments. In addition, and with the support of multiple collaborators in the area, we have expanded our

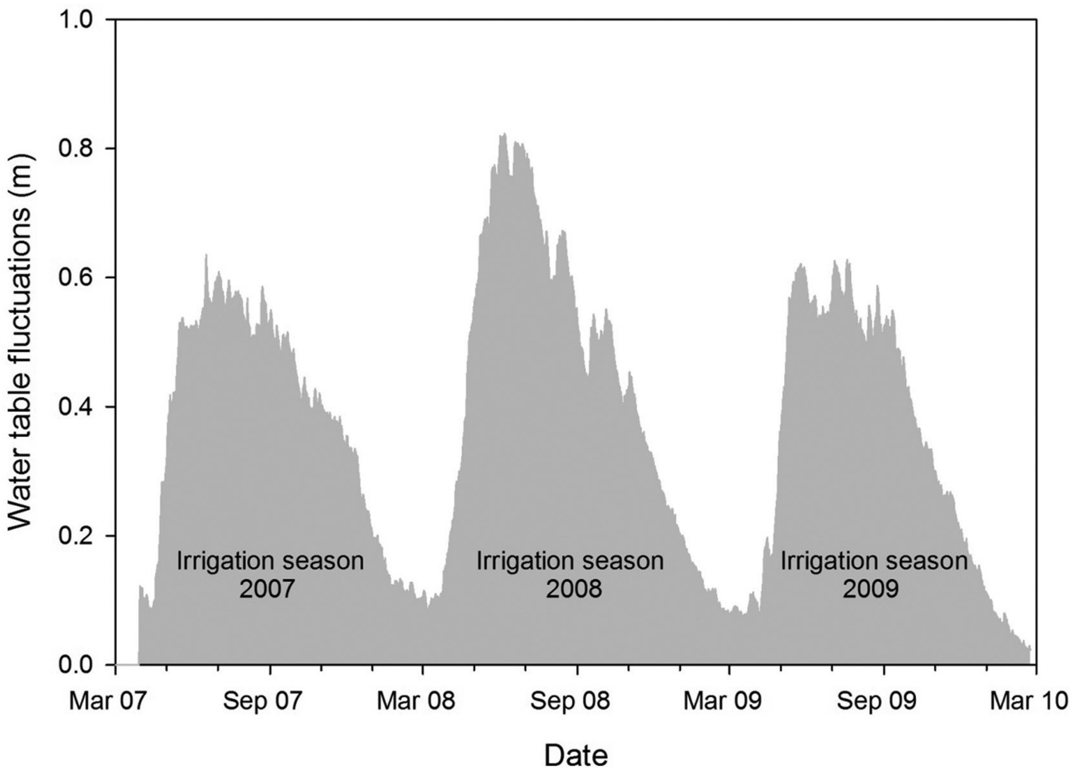

**Figure 2.** Seasonal surface and ground water connectivity in the lower valley during years 2007 through 2009 in response to floodplain irrigation inputs.

monitoring of groundwater levels to other locations (including domestic wells) in the floodplain valley, covering an area of approximately 40 km$^2$. More recently, we began monitoring groundwater levels in several wells located in the upper watershed.

## Surface and Groundwater Connectivity

In order to characterize the hydrologic connectivity of surface and groundwater we used data from 31 wells located in the lower valley portion of the watershed. This valley encompasses a section of approximately 20 km along the Rio Grande and up to 2 km to the east of the river and it is split by irrigation canals into dry land, where most of the residential development is located, and irrigated land, near the river (see Figure 1). We used data from 15 non-pumping monitoring wells (50-mm diameter) that we installed in the irrigated floodplain. Also, we monitored 16 wells from our collaborators in the dry land portion of the valley. These wells in the dry land varied on their level of use, ranging from marginal, to household use, to heavy use (in one case). All wells were instrumented with stand-alone water level loggers (model U20-001-01, Onset Computer Corp.; Bourne, Massachusetts) that were set for recording data hourly.

Our results show that there is a strong hydrologic connectivity between surface and groundwater in the valley. These connections follow a seasonal pattern that appears to be driven by irrigation contributions to the shallow aquifer. Each year, the water table reaches a peak increase of up to 0.8 m three to five weeks after the onset of irrigation (Figure 2). The seasonal water table fluctuations observed each year have been attributed to irrigation percolation and canal seepage inputs that raise and maintain shallow groundwater levels throughout the irrigation season. Relatively rapid (three to four hours) transient water table rise in response to irrigation percolation inputs has been observed during irrigation experiments at the Alcalde Science Center (Ochoa et al. 2013). Also, a previous study showed that on average, 33 percent (12 percent canal seepage and 21 percent deep percolation from irrigation) of the total water distributed for irrigation in an acequia of this agricultural valley contributed to the recharge of the shallow aquifer (Fernald et al. 2010). In the winter, when no irrigation occurs, the river acts as a drain and the water table drops. The effects of surface irrigation water inputs in raising the water table go beyond the irrigated floodplain and extend at least 1 km into the dry land portion of the valley (Ochoa et al. 2013). In effect, the irrigation system has replaced the function of spring floodplain inundation. Rather than the uncontrolled flooding, the irrigation system now moves water onto the floodplain and irrigation recharges the aquifer, which in the later months replenishes the Rio Grande.

Surface and groundwater connectivity is also being assessed at the entire watershed scale. These strong links have been previously recognized by Borton (1974) who stated that groundwater in the alluvium and in the Tesuque formation is closely related to surface water along the river valleys. In order to better understand surface and groundwater connections in the watershed, we recently began monitoring wells in the mid to higher elevations of our study area. In January of 2013, we conducted a three-day campaign to measure groundwater depth in 39 wells throughout the entire watershed (see Figure 1). We used a water level indicator (Model 16036, Durham Geo Slope Indicator.; Mukilteo, Washington) to take manual readings of groundwater depth in the monitoring wells. Groundwater depth data were used to create a water table map of the watershed. Our results show that groundwater flows west towards the Rio Grande; this is similar to that reported by Borton (1974). Depth to the water table ranged from 0.5 m in the downstream valley to 72 m in the higher upland locations. However, very shallow water levels (0.7 m) were also seen in higher elevation wells. Also, the presence of a spring that was noted near the lower valley, at an elevation of 1797 m, suggests the existence of perched water tables in some locations of the study area. The presence of perched aquifers in the area has been previously reported by Borton (1974) who stated that these perched water table systems are an indication of stream losses during times of flood or snow melt.

## Head Waters and Floodplain Valley - Hydrologic Connectivity

In order to monitor upland-valley connectivity, we installed a crest-stage gauge equipped with an automated water level logger in the outlet of the Rio de Truchas tributary near the Rio Grande (Figure 1). The sensor was programmed to collect data every 10 minutes and it was installed in the middle of the channel cross-section, which has a trapezoidal shape with 20.9 m in the upper level, at 1 m height, and 16.6 m in the lower base. We used Manning's equation to calculate discharge based on water level collected with the automated device. Also, we used data from a previously installed stage monitoring station in the Rio Grande at the downstream boundary of our study area (see Figure 1). At this location we have a water level logger to monitor river level fluctuations every one hour.

Infiltration excess is the main mechanism of runoff generation in juniper woodlands of New Mexico (Wilcox 2002) and it is greatly affected by antecedent soil moisture (Ochoa et al. 2008). A study conducted to determine rainfall, soil moisture, and runoff interactions in piñón-juniper woodlands of northern New Mexico showed that runoff was commonly observed during high intensity convective storms and also during frontal storms with low intensity but longer duration rainfall periods that resulted in greater levels of sediment movement (Ochoa et al. 2008). The latter seemed to be the case in our upland-juniper dominated study area, where rainfall (22.4 mm total) from a frontal storm recorded on 11 October 2008 in the upland weather station resulted in an increase of up to 0.8 m in the Rio de Truchas ephemeral stream in the lower valley (WRCC 2013). This frontal storm that generated a peak discharge of 17.9 m$^3$/s at our monitoring location also affected discharge levels in the Rio Grande, where peak river level rose 0.3 m three hours after tributary peak flow was reached (Figure 3). Rainfall only occurred in the mid to high elevation parts of the watershed; no rain was observed in the lower valley. This runoff event generated a relatively rapid increase in river flow that also affected shallow groundwater levels in wells located at variable distance near the river (Figure 4). Water level rise in the different wells ranged from 0.05 m in two of the wells located at 80 m (W4) and 130 m (W2) distance from the river

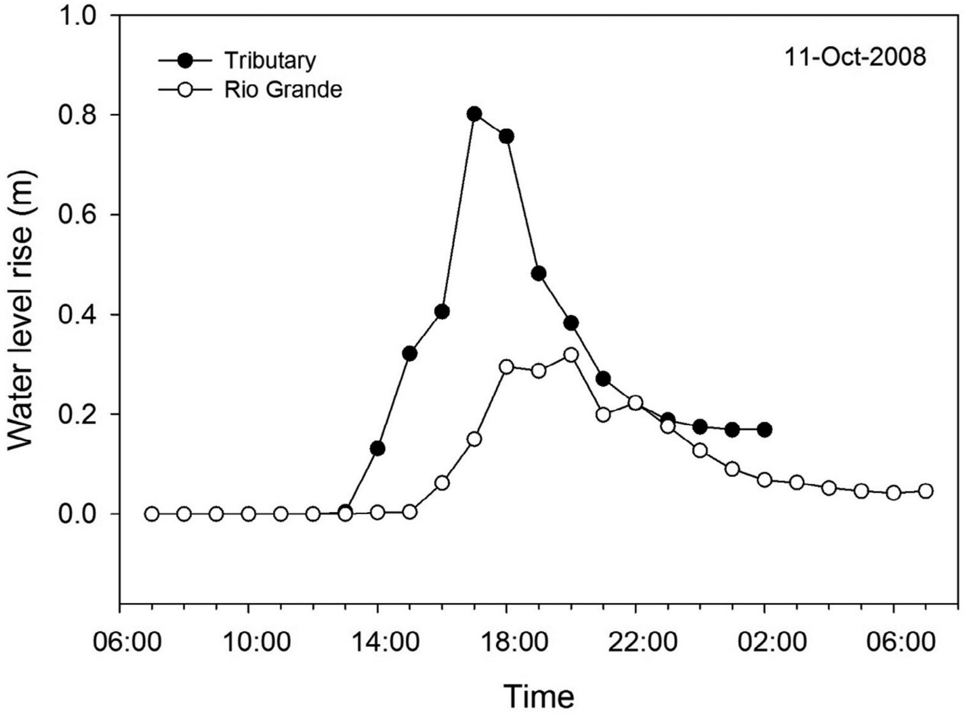

**Figure 3.** Tributary and river stage response to rainstorm on 11 October 2008.

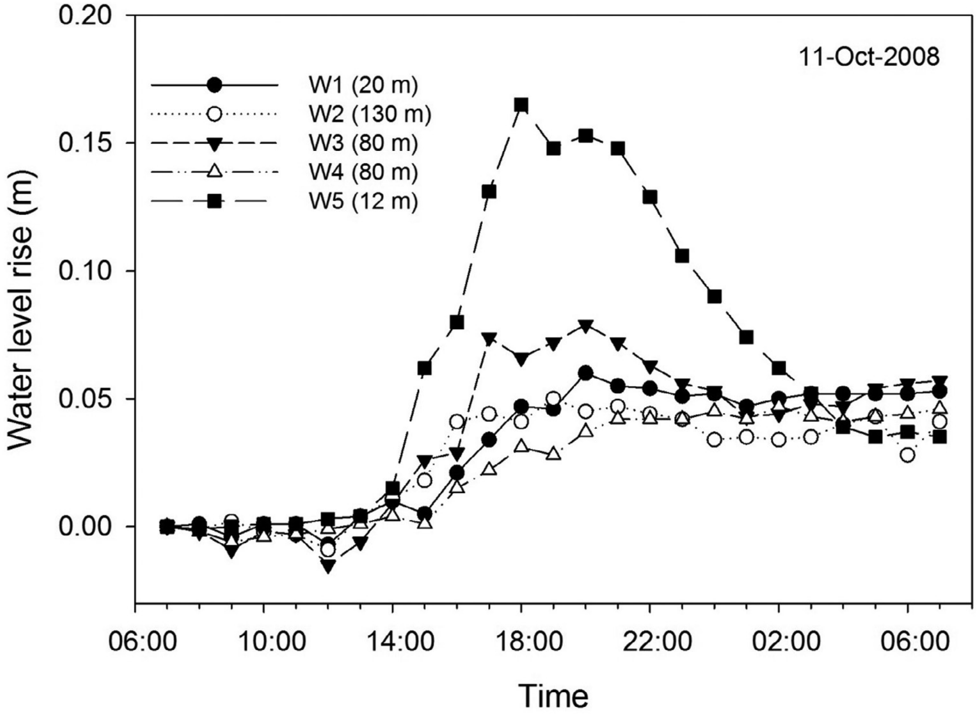

**Figure 4.** Water table rises in wells located at variable distance from the river in response to a rainstorm on 11 October 2008.

to 0.17 m in a well located at 12 m (W5) distance. No water level rise was observed in wells other than the ones near the river.

## Modeling Interdisciplinary Connectivity

In order to better understand the hydrologic interactions occurring between the head water sources and the irrigated valley downstream, we are using a combined, intensive field data collection and multi-modeling approach to characterize the hydrologic connectivity of the Alcalde-Velarde-Truchas watershed. We have used different models to characterize different aspects of surface and groundwater connectivity in the watershed. For instance, we have used the one dimensional Root Zone Water Quality Model (Ahuja 2000) to simulate surface water irrigation and deep percolation relationships in different soils and crop types in the irrigated floodplain (Ochoa et al. 2011). Similarly, we have used the model HYDRUS 2D (Simunek et al. 2011) to look at the movement of the wetting front through the unsaturated zone in response to various levels of flood irrigation in different soil types (unpublished data). In an ongoing effort, we are developing a system dynamics model aimed to simulate different hydrologic interactions occurring in the watershed, including hydrologic connectivity. In particular the model will help describe how changes in climate, forest management regimes, wildfire and grazing in the uplands impact surface and groundwater flows to the irrigated alluvial valleys. In turn the model also attempts to describe how changes in water availability impact the downstream ecosystem, economics, and traditional culture of the acequia communities.

The combined field studies and modeling have provided insight into the operation of the acequia conveyance system with its associated leakages which provides a critical ecosystem service in reducing peak flows during snowmelt and increasing river flow during summer and fall low flow periods (Fernald et al. 2010). Spring snowmelt peaks are diverted into the irrigation system, from which the water percolates to groundwater, is stored underground for weeks to months, and then returns by shallow groundwater flow to streamflow.

The evolution of our research has demonstrated that understanding of land use change and climate change impacts on hydrology must incorporate not only hydrologic connectivity between forested headwaters, rangeland uplands and irrigated riverine valleys, but it also must include connectivity to the other disciplines directly impacted by the changing drivers that will disrupt the highly human-managed hydrologic systems. We find the natural science disciplines are categorized biophysically. Watershed hydrology is important for forest management impacts on water yield; rangeland science is critical for understanding of grazing impact on vegetation, and runoff quantity and quality but also human management of upland and valley landscapes with livestock and wildlife grazing. Ecosystem science is critical to characterize wildlife and biodiversity impacts of hydrology and management connectivity in a landscape where 85 percent of the vertebrate fauna spend at least part of their life cycle in riparian areas that are created and maintained by irrigation and upland runoff. Finally, the human sociology, economics, culture, and spirituality dictate links to the landscape that ultimately guide changes in managed hydrology and the interconnected hydrologic systems.

This research provided the basis of a team interdisciplinary modeling exercise during an interdisciplinary modeling course offered in 2012 (Saito el al. current issue). Students were given an overall theme of acequias and climate change, and were provided access to datasets from ongoing research into multiple components of linked hydro-social systems (Fernald et al. 2012). The students were grouped into five teams representing multiple disciplinary strengths, and assigned a team leader who was in charge of bringing together a case study within the overall theme. The five case studies were geographic, representing three separate study watersheds and two regional basins. The case studies were interdisciplinary and directly confronted the interactions between social and natural components by including them all within a single system dynamics model. For example, the student team that addressed hydrologic connectivity at the Alcalde study site discovered fascinating linkages beyond the original hydrology focus: 1) economic and climate drivers of aquifer recharge including potential future pumping impacts; 2) aquifer recharge lag time due to surface and groundwater interactions in turn impacted by agricultural land use; and 3) riparian ecological species richness benefits of irrigated agriculture by crop type. Although the student team described a need for more detailed modeling to fully characterize the different system components, they were able to extract important linkages related to hydrologic connectivity by pulling the pieces together within an interdisciplinary modeling framework.

## Conclusions

This study shows that there is a strong hydrologic connectivity between the uplands, the irrigated valley, and the groundwater in a semi-arid watershed of the southwestern United States. This watershed hydrologic connectivity provides many functions such as terrestrial and aquatic habitat support and aquifer recharge. It also helps to sustain important economic activities in the region such as ranching and farming. The understanding of water spatial distribution within the landscape will help in management of water and land resources under increased demands and stresses, especially during drought. Study results indicate a seasonal connectivity between surface and groundwater in the valley due to irrigation inputs. The presence of perched water systems in the study area indicates that there is a clear connection between surface and groundwater in the entire watershed. Runoff from precipitation in the higher elevation parts of the watershed can significantly increase Rio Grande flow in a relatively short period of time. Preliminary results of the hydrology system dynamics model suggest that there is a strong hydrologic connectivity between snow-melt driven runoff in the headwaters and the recharge of the shallow aquifer in the valleys, mainly driven by the use of traditionally-irrigated agricultural systems. This study adds to the understanding of the interconnectedness of different hydrologic components and of the mechanisms of water distribution in semi-arid landscapes. Study of hydrologic connectivity has established the foundation for ongoing multidisciplinary research related to traditional irrigation and community water management and the social, cultural, environmental, and economic drivers that themselves impact hydrologic connectivity. Making the multiple data streams available to students within the context of an interdisciplinary modeling course yields exciting examples of connectivity beyond hydrology to social, economic, and ecological systems.

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# Tracking the Influence of Irrigation on Land Surface Fluxes and Boundary Layer Climatology

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**Abstract:** When the land surface is altered as a first order change in the climate system, it affects the latent heat flux and evaporative cooling, thereby altering the surface temperature and boundary layer development. Modeling the processes associated with land surface alteration requires an interdisciplinary approach in which the hydrologic processes such as evapotranspiration and soil moisture influenced by human-induced changes are connected to the atmospheric system. The Noah Land Surface Model (LSM) coupled with the Weather Research and Forecasting (WRF) model was modified to represent irrigation in the Snake River basin. By simulating the surface energy balance components and the boundary layer in the growing season, we compared the differences between irrigation and no-irrigation (control) simulations to assess the differences in climatology attributed to irrigation-induced cooling. Differences such as increased latent heat flux from the irrigated areas and decreased potential temperature, wind speed, and planetary boundary layer height were evident. This study reiterates the importance of the anthropogenic processes defining the nexus between the land and atmosphere on the local and regional weather and climate.

**Keywords:** *irrigation, boundary layer fluxes, WRF modeling*

Land surface conditions can impact atmospheric properties both locally and regionally. Koster et al. (2004) investigated the strength of land-atmosphere feedbacks for various regions and categorized them as “hot spots” where the exchanges between the land and atmosphere through the transport of heat, moisture and momentum are extensive. Tracking the behavior and magnitude of these exchanges of heat, moisture and momentum between the earth’s surface and the atmosphere is vital not only to improve our understanding of weather and climate, but also to represent the land surface heterogeneity and transient state of surface variables including soil moisture, vegetation, and surface albedo. Thus, enhancing current generation numerical weather prediction models with appropriate land surface parameterizations merits attention due to the nature of their interdisciplinary impact such as climate feedbacks, regional weather modification, ecosystem functioning, hydrology, and farming. For example, model refinements to simulate water vapor transport for predicting precipitation (Evans and Zaitchik 2008) or improving exchange coefficients to capture the dynamics of land surface-atmosphere coupling (Chen and Zhang 2009) are critical. Since the land and atmospheric processes are tightly coupled, it is therefore important to run the coupled model to understand the feedback between these systems for water sustainability, ecosystem services, and landscape conservation (Cook et al. 2010; Dirmeyer et al. 2006).

Anthropogenic-induced alterations to a landscape such as agriculture, deforestation and urbanization can impact the local climate. Since many of the land surface characteristics such as stomatal conductance, roughness, leaf area index, and soil moisture are related to land surface fluxes in non-linear and complex ways, numerous studies have reported that representing the land surface heterogeneity with proper initialization and parameterization in models is important for predicting local and regional weather and climate variables including surface winds, temperature, and humidity (Case et al. 2008; Dirmeyer et al. 2006; Seneviratne et al. 2006). Thus, model development and refinement to address such impacts has an interdisciplinary dimension that encompasses water management, land use changes, hydrological analysis, ecology, biology, meteorology, and climatology.

Impacts of irrigated agriculture, in particular on mesoscale circulations, regional hydrometeorological perturbations and changes in the hydrological cycle, have been extensively studied (Cook et al. 2010; Lobell et al. 2009; Moore and Rojstaczer 2002; Ozdogan et al. 2006, 2010). Irrigation reduces diurnal temperature ranges, increases atmospheric moisture, and precipitation recycling (Haddeland et al. 2006; Mahmood et al. 2006; Ter Maat et al. 2006) and also substantially changes evapotranspiration feedback magnitudes. To further exacerbate these effects, the Pacific Northwest region has been experiencing a general warming trend between 1920 and 2000, with an increase in temperature of about 0.5 °F per decade. Increase in temperature is not always accompanied by increase in latent heat flux and there is no study investigating the trends over the same period by considering feedbacks between the land and atmosphere. While it is known that the latent heat flux is the most sensitive and the radiative heat flux is least sensitive for surface heterogeneity (Baidya and Avissar 2002; Henderson-Sellers et al. 1993), the impacts of these fluxes on the diurnal variations and their feedbacks is less known in the Snake River Basin.

Mesoscale models that simulate the land surface fluxes, when run in a coupled fashion, can provide reasonable estimates of evapotranspiration from agricultural lands if they are considering seasonally varying vegetation and supplemental moisture provided by various irrigation methods. In regions where rainfall is relatively low (less than 250 mm per year) and cropping is carried out with the supply of additional water either from the surface or ground water source, evapotranspiration from farmlands is normally higher than that of non-irrigated farmlands. Coupled mesoscale models that run land surface and atmospheric modules in an integrated fashion in such regions can underestimate actual evapotranspiration and overestimate near-surface temperature as well as the sensible heat flux primarily because they misrepresent the amount of additional soil moisture added to the soil or lack appropriate irrigation parameterization in the model. This, in turn, can lead to inaccurate partitioning of the surface energy balance. As a result, model-simulated soil temperature, air temperature, wind distribution, and long wave upwelling radiation can be erroneous (Adegoke et al. 2007; Lobell and Bonfils 2008; Sacks et al. 2009).

Incorporating irrigation-induced cooling while estimating the surface energy balance is needed when warming due to climate change is expected (Cook et al. 2010). An integrated analysis that has impacts on various complementary disciplines such as hydrology, weather, climate and agriculture makes the study vital. For example, accurate evapotranspiration leads to better streamflow prediction and water management. Also, accurate surface temperature and humidity estimation provides reasonable boundary conditions for water vapor transport and convective processes. In order to understand the warming masked by irrigation under both current and future climatic conditions, we investigated the changes in surface fluxes in response to irrigation in the Snake River basin using the Noah Land Surface Model (LSM)-Weather Research and Forecasting (WRF) model. Also, this paper explores the difference in the thickness of planetary boundary layer with and without irrigation in the simulation.

## Methodology

### Weather Research and Forecasting

The WRF model is a state-of-the-art weather forecasting tool used extensively for both operational purposes and research (Skamarock et al. 2008). We used the Advanced Research WRF (ARW) version 3.2.1 in this study. It has multiple schemes for various processes to comprehend the hydrometeorology by dynamically linking the land surface, planetary boundary layer, surface layer, cumulus development, atmospheric moisture, and shortwave and longwave radiation. Many other options provide parameterizations for various aspects of the model. The non-default selections used in this study are provided in Table 1.

We have used three nested domains to downscale the North American Regional Reanalysis (NARR; Mesinger et al. 2006) data set that includes initialization data and lateral boundary conditions (Figure 1a). NARR has a horizontal resolution of approximately 32 km and provides both meteorological and soil variables for initializing the model. The horizontal resolutions of the WRF domains are 36 km, 12 km, and 4 km. All three WRF domains have 38 vertical levels. The region of interest for this study was the agricultural area along the Snake River in southern Idaho. The innermost WRF domain was created to encompass this region and provide adequate additional surrounding area for the model to develop high resolution meteorological structures. Likewise, the surrounding domains were large enough to allow modeling space for the transport of thermodynamic conditions of the atmosphere, turbulent exchanges and convection into the inner grid, and a two-way nested interaction was specified.

**Table 1.** Various schemes and implementation details of the WRF system.

| | |
|---|---|
| Grids | Triple nested domain (36 km with 90 x 99, 12 km with 115 x 103, 4 km with 82 x 67 grid points) |
| Numerics | Primitive equations based on nonhydrostatic frame |
| Vertical Resolution | 39 vertical levels, model top 10hPa |
| Boundary Condition | Time inflow/outflow dependent relaxation |
| Boundary Update Frequency | 3-h interval by North American Regional Reanalysis (NARR) data on 36 km domain |
| Time Integration | 10/1/2009 Oz - 1/1/2011 9z |
| Horizontal Advection | 6th order positive definite |
| Microphysics | Thompson Scheme. Thompson, Field, Rasmussen and Hall (2008, Monthly Weather Review) |
| Deep Convection | Grell 3D |
| Planetary Boundary Layer | Mellor-Yamada-Janji Scheme with Veg dependent Czil enabled (iz0tlnd) |
| Surface Layer | Eta similarity |
| Longwave and Shortwave Radiation | RRTMG scheme (radt = 5 min) |
| Land Surface Model | Noah Land Surface Model |
| Land Cover Dataset | MODIS (20 land types) |

### Study Domain

Idaho, with 3.3 million acres of irrigated land, ranked fifth in the nation by acreages for irrigated croplands in 2007 (USDA 2007). Most of this irrigation occurs in the Snake River Plain, which predominantly covers Southern Idaho and stretches into Eastern Oregon. Mean annual precipitation over the Snake River Plain is about 250 mm. Higher elevation mountain ranges bordering Idaho and Wyoming generally receive a mean annual precipitation of about 1000 mm and serves as the source of runoff for the Snake River. Agriculture in the Snake River Plain is quite extensive due to the availability of water as a result of diversions from surface runoff, and ground water pumped from the aquifer. Figure 1b shows the topography in the innermost WRF domain with elevations ranging from 1000 m to 5000 m. The orographic effects of the mountains, combined with the coastal range to the west, create a typical leeward effect and foehn winds, causing an arid climate. The land cover map shown in Figure 1c contains croplands, grasslands, shrublands and mixed forests in the area. Agricultural lands are generally situated along the Snake River where the land is flatter and irrigation water is available. The soil map in Figure 1d shows that the croplands tend to be in loamy soils mixed with sand and silt.

Both furrow and sprinkler irrigation is common in the study area. The degree to which irrigation can impact the regional climate is dependent upon the nature of irrigation, crop type and the geographical extent. For our modeling analysis, a brief background on the two types of irrigation is discussed here. Furrow irrigation saturates the top layer of soil for an extended amount of time, roughly 12 to 24 hours, to provide an adequate supply of water throughout the root zone. Excess water leaches nutrients and prevents adequate

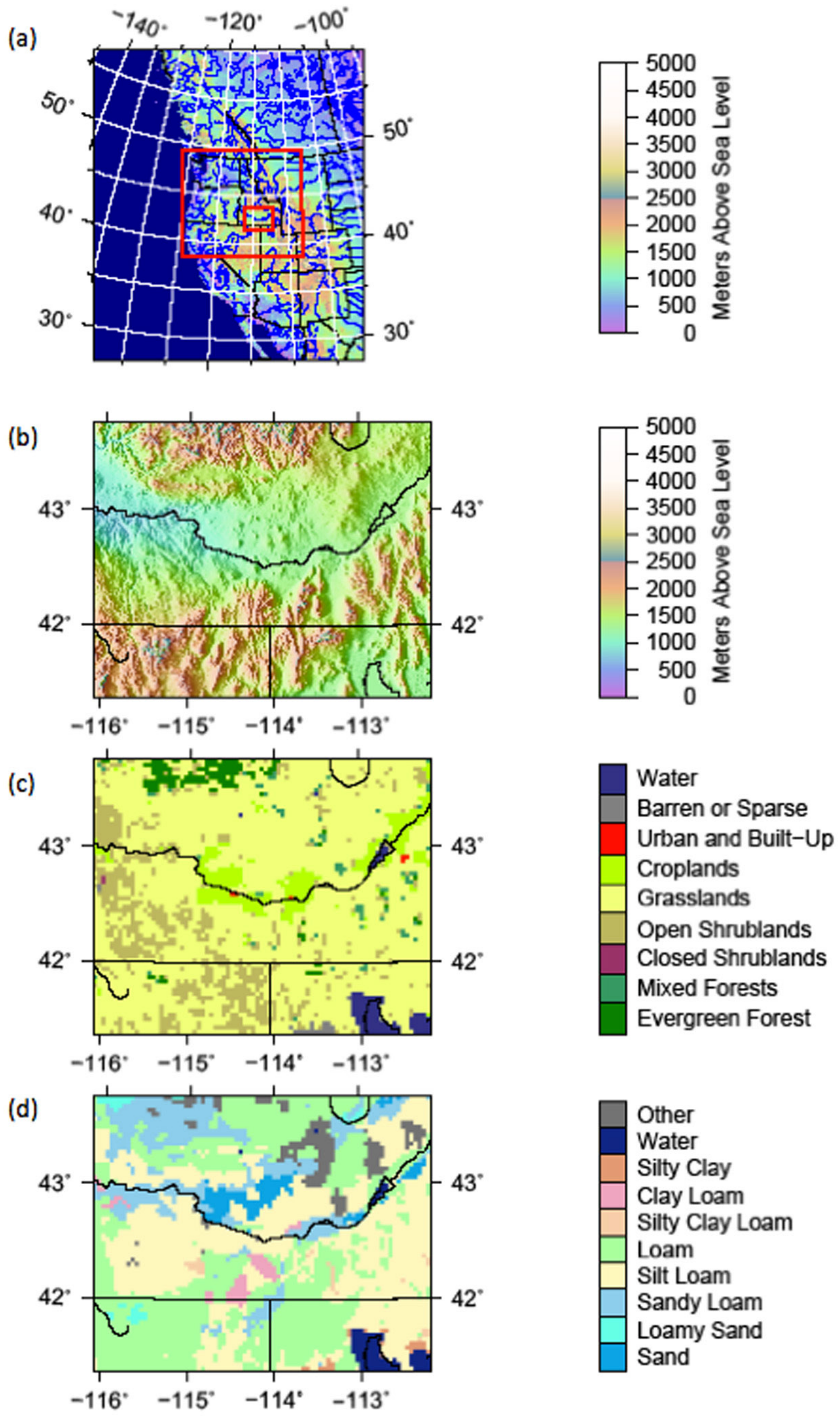

**Figure 1.** (a) Three WRF nested domains, with the outer edge of the diagram being the outermost domian. (b) Topography of the Snake River which is also the innermost WRF domain. (c) Land cover map of the inner domain with irrigated areas shown as cropland in bright green color. (d) Soil map of the inner domain with silt loam as the common types over agricultural regions.

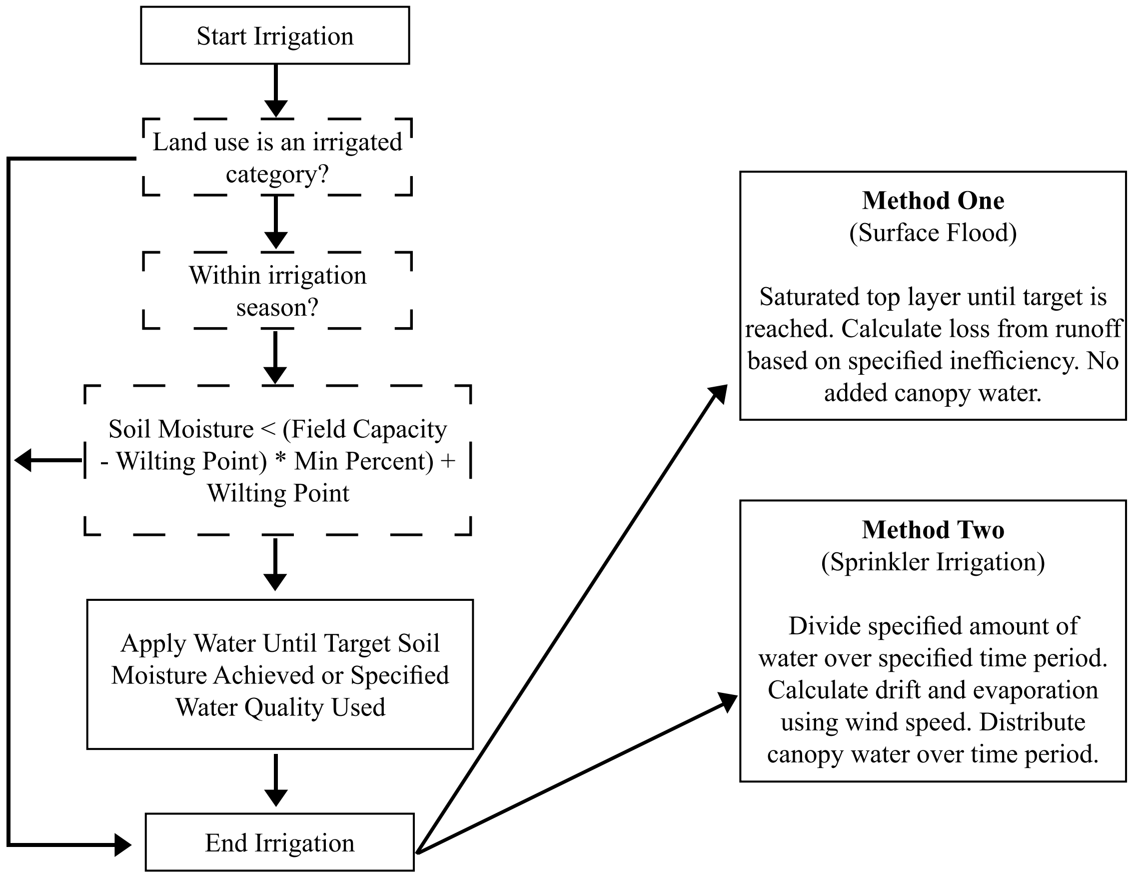

**Figure 2.** The irrigation scheme implemented in the Noah Land Surface Model (LSM) WRF.

oxygen from reaching the roots and percolates laterally in the subsurface, thus contributing to return flows in the downstream segments of the river. Much of the water used for furrow irrigation is lost as runoff or return flow and as recharge to the aquifer after crop consumptive use. Center-pivot sprinkler irrigation is typically designed to provide as much water in a single pass as the top layer can absorb the moisture without allowing runoff. The top soil layer is often saturated with soil moisture, which is generally lost as evaporation and plant transpiration; and any excess water left normally drains to the lower layers. During the peak of the summer, the amount of water that can be applied during a pass of the sprinkler may not be adequate to fully replenish the amount of moisture lost through evapotranspiration (ET), and in those cases the sprinklers are run 24 hours a day. Sprinkler irrigation can be subject to some loss of water to wind drift and evaporation. The application inefficiency for center pivot sprinklers, which are the most common sprinklers used in Idaho, is often about 10 percent for winds below 10 mph (King and Kincaid 1997).

### Irrigation in Noah Land Surface Model

Noah Land Surface Model (LSM), which is part of WRF, is employed for this retrospective simulation analysis. The irrigation scheme developed in this study is given in Figure 2 and the scheme can vary between furrow irrigation or surface flooding and sprinkler irrigation. Source code was added to the WRF model that allows the user to specify for a specific run time which land use categories can be irrigated and what is the threshold amount of water depletion to be used to trigger an irrigation event. The threshold was specified as a percent of the range of soil moisture between the field capacity and permanent wilting point. Both field capacity and permanent wilting point were determined when the soil category for the cell was determined during grid preprocessing. Noah LSM already tracks soil moisture for each grid cell from each of the four soil layers: 10, 30, 60, and 100 cm. Crops only use the three uppermost layers, down to 1m deep. When determining whether the threshold was reached, only the second soil layer, 10 to 40 cm deep, was checked for dryness. Because of direct evaporation, the top layer might dry out before any lower layers need water and trigger an unrealistically early irrigation event. Evaluation of the need for irrigation was done independently for every cell and at every time step. Additionally, the beginning and end of the irrigation season can be specified as run time parameters.

The interactions between the lowest layer of the atmosphere and the physical earth surface were calculated during model integrations. This was done by including four soil layers for modeling subsurface temperature and moisture. Each grid cell contained a land cover category and a soil type category, allowing detailed parameterization of physical processes such as absorption and reflection of short and long wave radiation, heat transfer, direct evaporation, vegetation transpiration, absorption and runoff of precipitation, and the freezing and thawing of surface and subsurface moisture. A monthly greenness fraction data set available with WRF at 0.144° resolution is used to define the vegetation dynamics. WRF interpolates the greenness fraction for the grid cell from these average monthly values and uses it to adjust the albedo, surface roughness, leaf area index, and long wave emissivity for use in the model computation. Our approach was to replicate irrigation frequency as done in the actual field conditions in order to correctly partition the surface fluxes. Also, it should be noted that the irrigation scheme only changes the soil moisture based on soil moisture stress level. However, considering the whole study area, there was significant variability in irrigation frequency and quantity primarily based upon percent of available soil water used by different crops without causing yield or quality losses (King and Kincaid 1997). Some cells had up to 17 irrigation events per growing season and 405 mm of water applied. The average was 8 events and about 190 mm of water added per growing season. Some cells did not trigger any model irrigation.

### Land Cover

The 2001 MODIS data set within the WRF model was chosen for land cover. Land cover is divided into 20 categories based on a modified International Geosphere-Biosphere Programme classification scheme. Only two categories indicate agricultural use: 1) Croplands and 2) Cropland/natural vegetation mosaic. The latter does not occur in our study area. Data from USDA (2007) indicates that the great majority of cropland within the study area was irrigated; therefore all the grid cells classified as cropland were irrigated during the simulation.

### Model Setup and Simulation

Two WRF simulations were run that used identical formulation and running parameters except that one had added irrigation and the other did not. Using a specified irrigation season of May 1st through September 15th, the simulations were run from March 1, 2010, 00:00 GMT to October 1, 2010, 09:00 GMT. The times of the data presented in this study have all been converted to Mountain Standard Time (MST). The simulation time before the beginning of the irrigation season allows precipitation and snowmelt to provide realistic values for soil moisture initialization. For our simulations, a threshold of 50 percent of the range between field capacity and wilting point was chosen to trigger irrigation events. Although this threshold value can be calibrated with observed soil moisture or evapotranspiration, we did not perform calibration of this threshold due to the lack of gridded root zone soil water content or evapotranspiration data for the area. Although higher levels of soil moisture are suggested for maximum crop yield for some plants (for example, 65 percent for potatoes), 50 percent is common for the majority of crops (King and Kincaid 1997) and is used in this simulation.

In our analysis, Planetary Boundary Layer (PBL) calculations are done for each cell independently from other cells. Since advection of turbulent kinetic energy from the neighboring cells was not considered, heterogeneity of land cover exhibited less effect on PBL height calculations in surrounding grid cells than on temperature and humidity.

## Results and Discussion

### Surface Energy Balance

Figure 3 (a-c) shows the energy balance components from irrigated and non-irrigated simulations and validation of modeled ET against ET Idaho derived for three sites (Twin Falls, Rupert and Aberdeen) respectively located in the innermost WRF domain (http://data.kimberly.uidaho.edu/ETIdaho/). Monthly ET from WRF was validated with field ET obtained from ET Idaho for the growing season in 2010 (March to September). Average daily ET for the crops available around the stations was computed from crop-specific ET. For Twin Falls, a composite value of ET for alfalfa, field corn and dry bean was used. Alfalfa, field corn, dry bean and sugar beet were used for Rupert and alfalfa and potatoes were used for Aberdeen. Monthly values were then computed from the average daily ET and it was found that Aberdeen showed good correlation of 0.63 while Twin Falls and Rupert had moderate correlations of 0.42 and 0.43, respectively. Overestimation of ET by the model was primarily attributed to the warm bias in NARR (Jaksa et al. 2013). For each month from March to September in 2010, a monthly averaged flux was created by averaging the fluxes from the same times for each day of the month and for all cells of the specified land use category (i.e., irrigated or non-irrigated). These fluxes that were modeled by using the same green vegetation fractions for non-irrigated cropland and grasslands were similar as the soil dried out in the summer. For shrublands, whose vegetation fraction generally peaks earlier in the summer with a higher shade fractions and canopy resistance, partitioning of the net radiation was modeled with a slow transition from latent heat to sensible heat in the later part of the growing season.

Figure 4a compares net radiation from irrigated and non-irrigated croplands ranging between 300 to 650 W/m$^2$ during the growing season. Depending on the surface albedo, roughness and the location, both

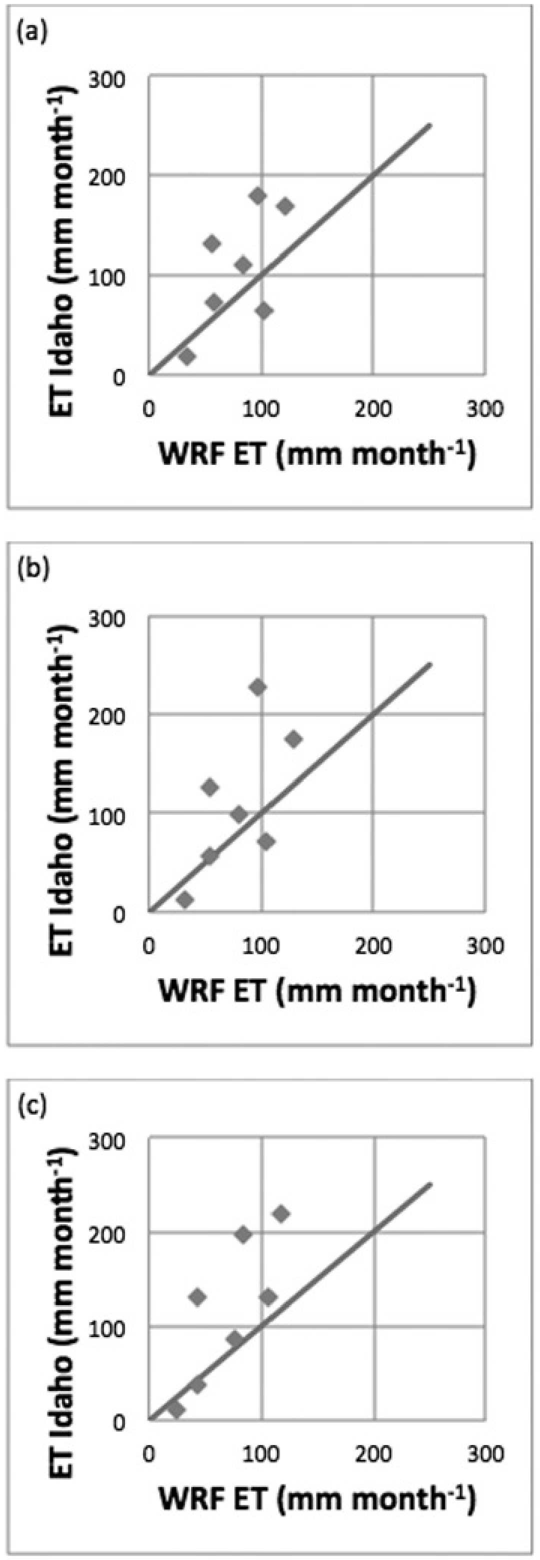

**Figure 3.** Validation of WRF-Noah evapotranspiration estimations with observations from ET Idaho for (a) Twin Falls (b) Rupert and (c) Aberdeen.

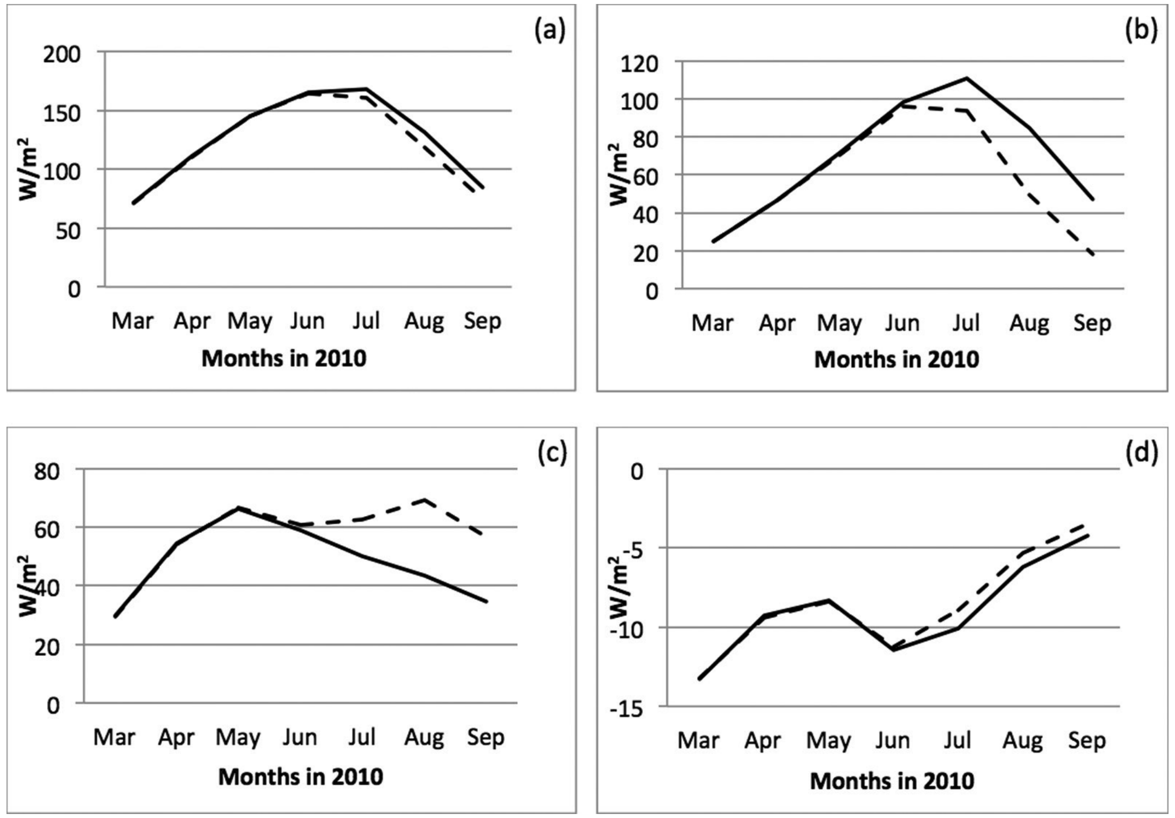

**Figure 4.** Monthly averaged fluxes of crop cells from irrigated and non-irrigated simulations. Fluxes from irrigated runs are denoted by the solid line and non-irrigated runs are denoted by the dashed line. The four panels are (a) net radiation, (b) Latent heat flux, (c) sensible heat flux, and (d) ground heat flux.

fields showed a slight difference in net radiation. As evident in Figure 4b, until the soil moisture content began to diverge in mid-June, the latent heat flux in the irrigated croplands closely follows that of the non-irrigated lands. The natural vegetation showed a decrease in latent heat flux in July because of the lack of available soil moisture in the root zone. The irrigated croplands, however, continued with substantially more latent heat flux than that of the non-irrigated areas. The latent heat flux appeared to decrease due to decreasing net radiation as shown in Figure 4a because latent heat tracked the net radiation pattern in summer months. Differences in latent heat flux between irrigated and control runs ranged between 20 to 50 $W/m^2$ during the growing season, particularly between July and September. In the absence of soil moisture to allow latent heat flux generation, the non-irrigated croplands converted the available energy mostly into sensible heat, as can be seen in Figure 4c. Even in August when net radiation was decreasing from 170 $W/m^2$ to 130 $W/m^2$ in July, non-irrigated croplands showed an increase in sensible heat from 60 to 70 $W/m^2$. In July, the ground heat flux also diverged (Figure 4d). The irrigated croplands tended to experience a reduced daytime heating of the soil which in turn has low longwave outgoing radiation at night, thereby causing a reduction in heating of the air by the soil. The higher daytime temperatures and lower nighttime temperatures of the non-irrigated areas was the likely driving factor for heating the soil, although the irrigated croplands showed a slightly higher downward ground heat flux due to increased net radiation. Perhaps this is due to the manifestation of a higher specific heat imparted to the soil by the model with the additional irrigation water.

Figure 5 shows how the maximum and minimum daily values of temperature, specific humidity and wind were altered by irrigation. For the minimum and maximum daily values, the difference of irrigated minus control run results were averaged over August, 2010. August was used because the soil moisture in the two model runs had diverged greatly, yet there was still enough solar radiation to cause large differences in temperature and humidity. In Figures 5a and 5b, the affected area was more diffuse with maximum temperatures because daytime winds were stronger and advected the effects to neighboring non-cropland cells. A dip in maximum temperature of about -1.5 °C was seen whereas a difference of about +1.5 °C in minimum temperature was observed. Some effects away from any cropland cells were most likely caused by irrigation creating small differences in cloud and rain distribution or perhaps by differences in runtime initialization of the shallow convection scheme. The generally dry air in the region allowed a faster dissipation of water vapor from evapotranspiration,

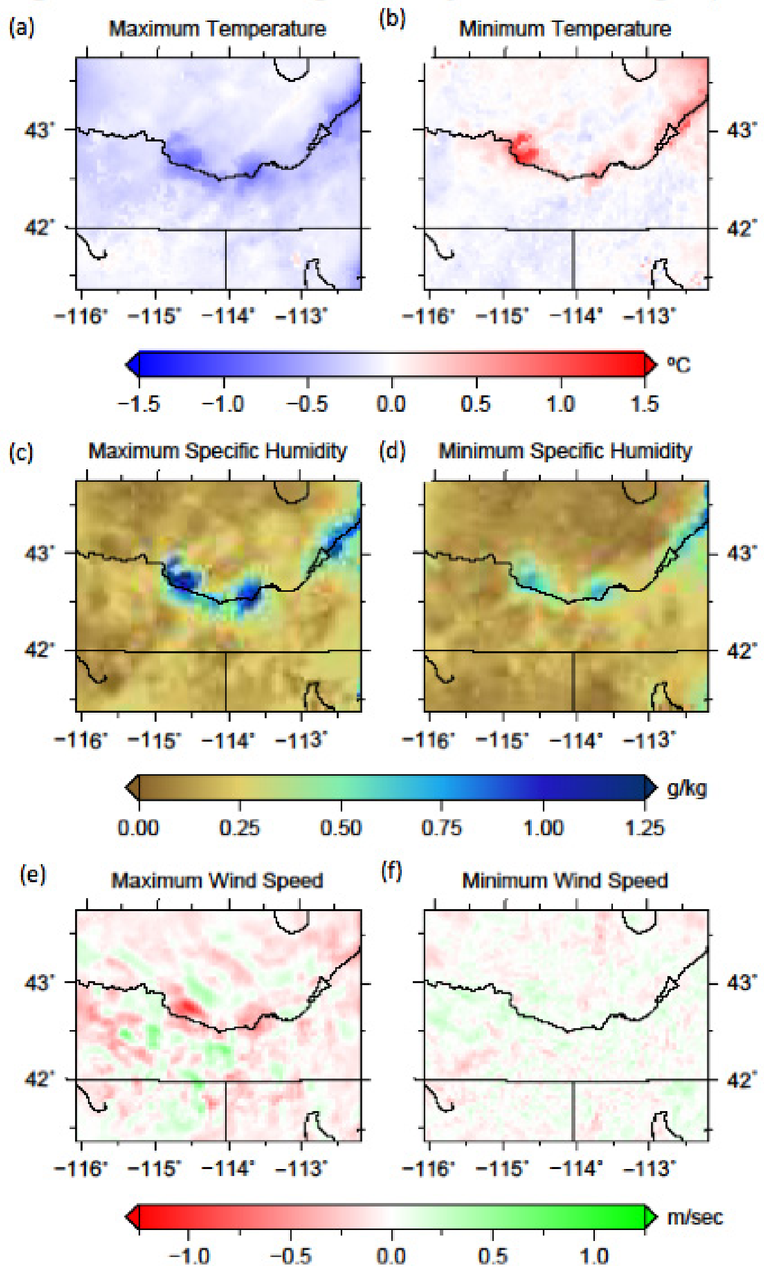

**Figure 5.** Difference between irrigated and control runs for maximum and minimum daily values averaged over August 2010 of (a) and (b) temperature °C, (c) and (d) specific humidity (g/km), and (e) and (f) wind speed (m/s).

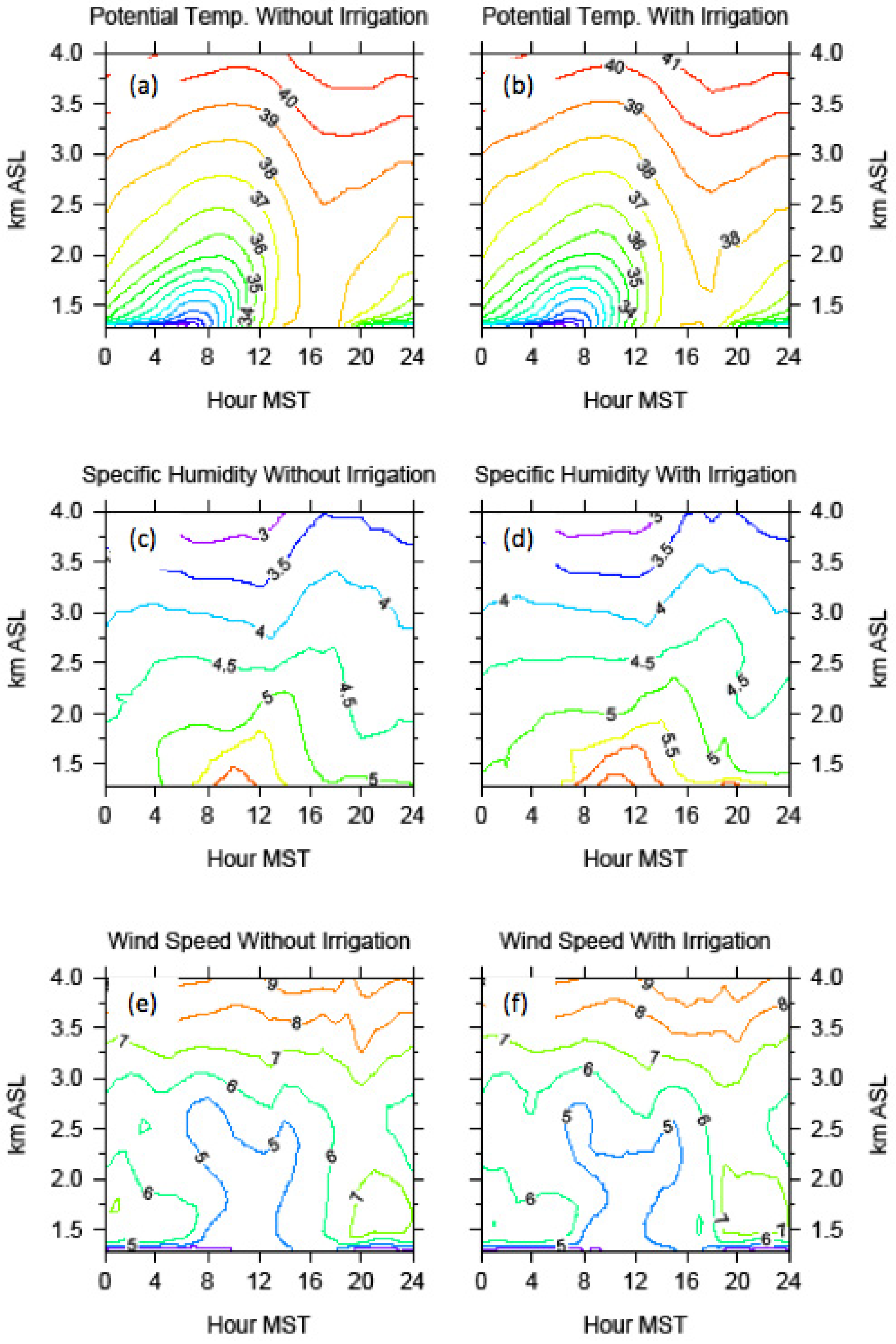

**Figure 6.** Vertical profile development averaged over all of August 2010 for all cropland cells in the innermost WRF domain of potential temperature (°C) (a) without and (b) with irrigation, specific humidity (g/kg) (c) without and (d) with irrigation, and wind speed (m/s) (e) without (f) with irrigation.

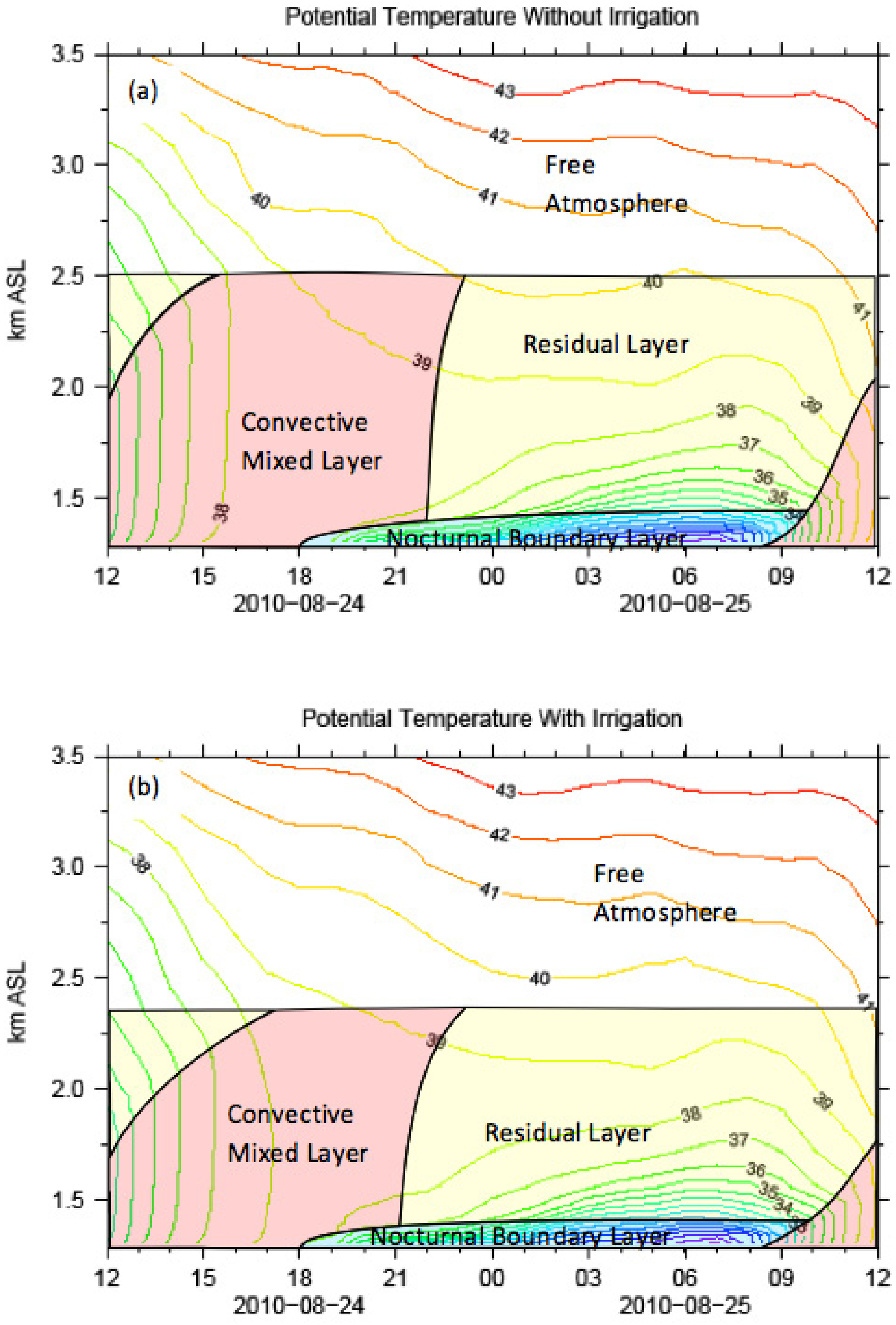

**Figure 7.** Potential temperature profiles (°C) and interpreted boundary layer components for a typical cropland cell for a 24 hour period in hours for August 2010 (a) without irrigation and (b) with irrigation. The mixed layer is shallower due to less convection caused by sensible heat with irrigation.

which may explain why specific humidity effects remain fairly local to the cropland cells with high values centered on a difference of 1.25 g/km (Figure 5c and 5d). As shown in Figure 5e and 5f, even the maximum wind speed was reduced by 1.0 m/s over some irrigated cropland cells. The likely mechanism is that reduced sensible heat caused less convection, which in turn either drew in less surrounding air to replace the upward movement or the reduced convection entrained less of the higher speed, upper winds.

## Boundary Layer Development

Figure 6 shows the development of vertical profiles of potential temperature, specific humidity, and wind speed for a composite day averaged over all of August, 2010 for all the cropland cells in the innermost WRF domain. The general patterns were similar for irrigated versus non-irrigated, especially above the boundary layer where surface effects were minimal. The highest surface wind speeds corresponded to the highest late afternoon temperatures. The highest specific humidity at the surface was closer to the peak of solar radiation when plants were most active. For potential temperature, the monthly averaged control run in Figure 6a shows higher surface temperatures of 38.85 °C at 17:00 MST and with the irrigated, the peak was only 37.85 °C, thereby showing a cooling of 1 °C due to irrigation. For specific humidity in Figures 6c and 6d, the timing of the maximums were earlier in the day than temperature, with the control run reaching a peak of 6.2 g/kg at 10:00 MST and the irrigated surface reaching 6.7 g/kg at both 10:00 and 11:00 MST. During late morning, the canopy was very active because of the solar radiation; however, wind and turbulence were not yet rapidly transporting the moisture away. Also, the humidity remained higher throughout the day in the irrigated areas. Differences in surface wind speeds were evident between irrigated and non-irrigated regions. The most notable difference appeared to be a rapid slowing of afternoon winds as evening coolness progressed in the irrigated regions. Perhaps the reduced sensible heat in the afternoon, which causes turbulence, had lesser influence in entraining faster winds from higher altitudes. In Figure 6e, the non-irrigated averaged surface wind remained over 5 m/s at 18:00, but the irrigated area in Figure 6f showed a decreased wind speed of 4.5 m/s for the same time.

The potential temperature profiles and interpreted boundary layer components for a typical cropland cell for a 24 hour period in August, 2010 are shown in Figure 7. With irrigation, the daytime convective mixed layer and the nighttime residual layer were shallower by a couple hundred meters due to less convection caused by lower sensible heat. This reduction in PBL can affect the radiation budget, particularly the downwelling longwave radiation and hence the surface energy budget partitioning. This has been shown in other studies as well (e.g., Cook et al. 2010; Lobell et al. 2009). The height of the boundary layer can be defined in different ways, but the Mellor-Yamada-Janjic PBL scheme within WRF uses turbulent kinetic energy as the determining factor. An inspection of the source code of the Mellor-Yamada-Janjic PBL scheme revealed that the boundary layer height was given as the bottom of the grid cell in which turbulent kinetic energy fell below a value of 2.02 m/sec$^2$. For those periods of low turbulence, such as at night, the PBL height defaults to a height of two grid cells.

Figure 8 shows the development of boundary layer heights during the growing season caused by the difference in soil moisture. Each sub-panel illustration is the difference in maximum daily PBL height averaged over the month shown. Based on the contours of equal turbulent values that were interpolated from averaged values, the development of the turbulence and PBL height was evident in both cases; however, the magnitude was greater for the control simulation. At the beginning of the summer, differences in PBL heights existed, with 550 m in July and 205 m in June. By August, some irrigated cropland cells experienced a reduction of PBL height of over 600 m and by September, the difference had expanded to over 750 m. Due to the lack of available soil moisture for ET later in the growing season, non-irrigated crop cells partitioned most of the incoming radiation into sensible heat rather than latent heat, resulting in more convection and turbulence. Even though latent heat also reduces the density of air, sensible heat does so to a much larger extent for a given amount of energy.

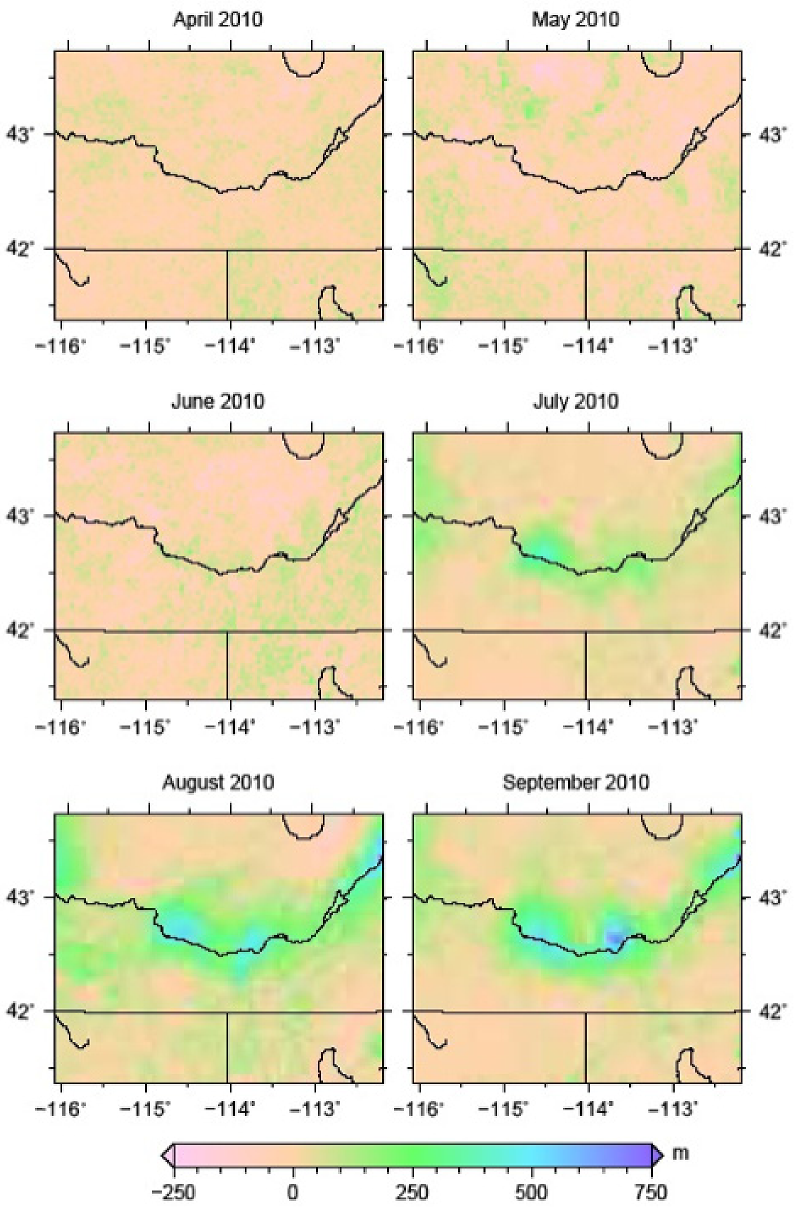

**Figure 8.** Effect on boundary layer height as the difference in soil moisture progresses for irrigated versus non irrigated cropland between April and September 2010.

## Soil Moisture

The driving factor behind the differences between the control and irrigated runs was the amount of soil water available for plant water uptake during the growing season and to meet evapotranspiration demand by which soil water was accessible to the atmosphere. This can impact the surface energy balance, and in turn weather and climate. During July and August, when precipitation was minimal, instantaneous spikes in the surface layer soil moisture was evident and plants converted soil moisture in the three root zone layers to evapotranspiration. The lower fourth soil layer also experienced depletion of soil moisture, but the responses to plant water uptake were moderate as most of the root systems were confined to the top 1 m in the soil profile. In the irrigation simulation, the grid cell began receiving irrigation water in late July when it first reached the specified minimum soil moisture. For the rest of the run, the added irrigation water maintained the soil moisture in the root zone throughout the summer. The second soil layer, 10-40 cm deep, closely followed the top soil layer. When the top layer was saturated, the excess water quickly drained from the upper layer to the layers below. Subsequently, some of that moisture that entered the third soil layer, 40-100 cm deep, was also utilized by plants, but the depletion was slight compared to the upper two layers. The fourth layer, 100-200 cm deep, had relatively higher moisture as it remained untapped by the plants or atmosphere. Thus, the availability of soil moisture dictated the plant productivity and the dynamics of evapotranspiration process.

## Summary and Conclusions

The Snake River Plain has undergone gradual change over the last century by shifting from natural vegetation to croplands. Studies have shown that there is a general rise in temperature of about 0.5 °F per decade over the past 80 years; however, the effects of this rising temperature on the long term climatology and evapotranspiration trends are unclear. Particularly, the effect of irrigation-induced cooling on the surface energy budget against the back drop of increasing temperature is not fully understood. Numerous studies have identified the complex connection between the land and atmosphere over many regions around the world. While there is sufficient literature available to evaluate the hydrologic response to land use changes, it is only limited to identifying the relationship between changing land use and the atmospheric processes. Our simulations of WRF combined with irrigation effects showed large differences in the surface energy balance and boundary layer meteorology and this in turn can have direct impact on local as well as regional weather and climate, and especially for developing better water resources management strategies. Our results based on idealized model simulations showed that differences in latent heat flux caused by supplemental soil water added to the root zone repartitioned the energy budget and altered the development of PBL heights.

Allowing the model to capture land surface dynamics with comprehensive physical processes offers insights into the feedback process with the regional atmosphere. This is especially the case in characterizing the extent of irrigation-induced cooling that could mask the local scale warming when climate change-induced temperature increases are predicted by climate models for the Snake River Plain and the Pacific Northwest. Even though these results are from a set of idealized conditions and for one growing season this study could help formulate algorithms for future applications, such as development of clouds, and in turn, the composition and organization of convective available potential energy, enhancement of atmospheric instability and circulation, advection caused by land surface heterogeneity, and downwind precipitation.

## Author Bio and Contact Information

**VENKATARAMANA SRIDHAR** was an Associate Professor in the Department of Civil Engineering at Boise State University and is now moving to Virginia Tech. His research interests include land-atmosphere feedbacks, surface energy balance modeling, climate change impacts on hydrology and water resources. He can be contacted at vsri@vt.edu.

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# Estimating the Public Water Supply Protection Value of Forests

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**Abstract:** We developed a methodology to assess the economic value of forested watersheds to improve water quality for public supplies. The interdisciplinary approach required collaboration between economists, municipal water managers, regional growth planners, hydrologic and water quality modelers. Data used in this project were derived from federal, state and local entities. We used regional growth projections with linked watershed and reservoir simulation models and cost-based valuation economics. Additional treatment cost to comply with Safe Drinking Water Act regulations was calculated using volume treated and simulated total organic carbon (TOC) concentrations. Simulated base TOC concentrations (3 percent urban) were compared with TOC concentrations predicted by 2020 (22 percent urban). Mean increase in daily treatment costs ranged from \$91 to \$95 per km$^2$ per day. The developed methodology is applicable to other watersheds to estimate water purification ecosystem services and is recommended for use in future interdisciplinary modeling courses.

**Keywords:** *ecosystem services, potable water quality, land use change modeling*

Protecting watersheds that are a source for public water supply can generate large benefits. Many municipalities, such as New York, NY, Boston, MA, and Portland, OR, actively purchase land in their source water catchments to minimize potential water quality problems and avoid costly drinking water treatment plant upgrades (Blaine et al. 2006). While the water quality services from minimally impacted ecosystems are generally appreciated, the actual economic value has rarely been quantified within an existing cost structure related to drinking water quality. This research estimates an economic value (\$ per km$^2$) for the ecosystem services provided by a forested landscape for mitigation of total organic carbon (TOC), a contaminant to drinking water treatment. In addition to the specific value we estimate for a watershed in south Alabama, we present a cost-based methodology that is usable elsewhere. This methodology is necessarily interdisciplinary in approach, drawing upon the expertise and data from regional growth projections, long-term precipitation and meteorological data, watershed modeling, reservoir modeling, drinking water treatment technologies and economic methods (Figure 1).

TOC in drinking water supplies can react with chlorine to form carcinogenic substances called Disinfection ByProducts (DBP) (Singer and Chang 1989). Several DBPs have been identified by the EPA as human carcinogens (USEPA 2005b). The EPA first regulated DBP under the Safe Drinking Water Act in 1979 for systems serving at least 10,000 people. In 1998 the maximum contaminant level for DBP was decreased under the Stage 1 DBP Rule. The Stage 2 DBP was finalized in 2005. EPA believes that this regulation will further reduce exposure to DBPs and decrease potential cancer, reproductive, and developmental risks (USEPA 2012). EPA has projected that the Stage 2 DBP rule will prevent approximately 280 bladder cancer cases per year (USEPA 2012). Approximately 2,260 drinking water treatment plants nationwide are estimated to make treatment technology changes to comply with the Stage 2 DBP rule (USEPA 2005b).

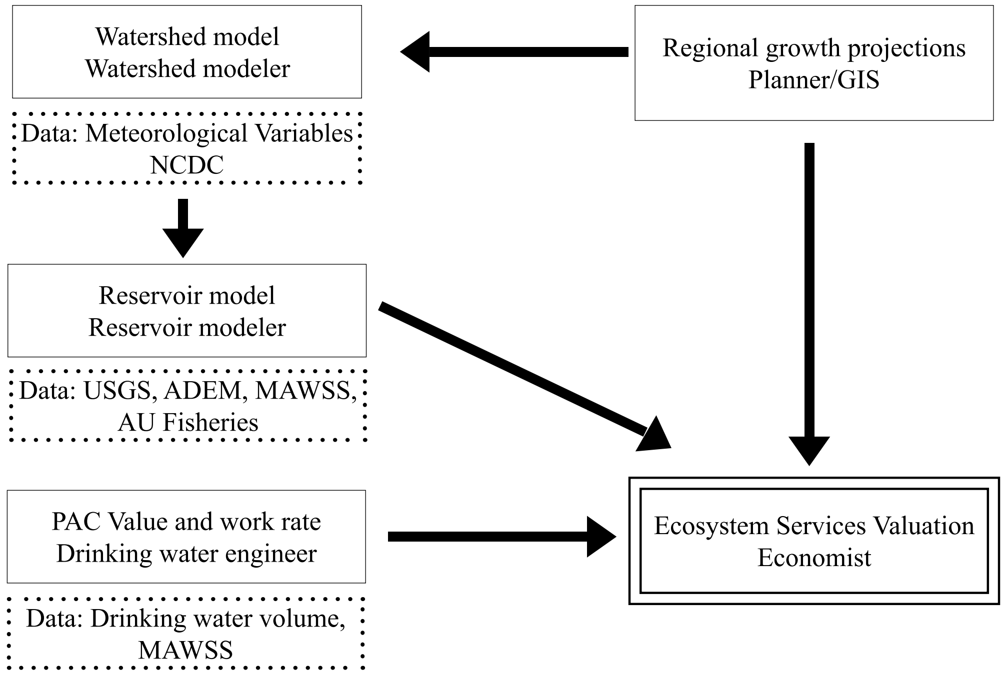

**Figure 1.** Project components and participants.

As a result of DBP rules, water systems with specified source water TOC levels are required to remove a percentage of TOC before chlorination or change drinking water treatment disinfection processes to minimize chlorination. One method to remove source water TOC within a drinking water treatment plant is the addition of activated C prior to disinfection.

This research utilizes robust hydrologic models to simulate watershed and reservoir nutrient processes with progressive urbanization scenarios to evaluate the effects of forest land conversion on reservoir TOC concentrations. Resulting TOC concentrations from reservoir modeling are utilized to estimate the cost of TOC removal during drinking water treatment for a given forest-to-urban land conversion scenario. Differences between pre-and post-urbanization scenarios yield the municipal water treatment cost savings provided by forest ecosystems as a result of minimized in-reservoir TOC. The dollar value per km$^2$ savings provides an estimate of the monetary value of forest water purification ecosystem services through application of cost-based valuation. The methodology is recommended for use in future interdisciplinary modeling courses to assist other US municipalities struggling to reduce DBP while teaching interdisciplinary modeling skills.

## Study Area

Converse Reservoir, located near the Alabama-Mississippi border, supplies the majority of drinking water for the City of Mobile through the Mobile Area Water and Wastewater Service (MAWWS). Precipitation near the City of Mobile is some of the highest in the US, with a 48 year (1957-2005) median annual precipitation of 166 cm. Converse Reservoir receives inflow from seven major tributaries, as well as groundwater inflow. A firm-yield analysis of Converse Reservoir estimated ~5 percent of the total volume is from groundwater (Carlson and Archfield, 2008). Streamflow from the 3 major tributaries (Big, Crooked, and Hamilton creeks) has been monitored by USGS gauging stations since 1990. Converse Reservoir has two main branches, Big Creek, which becomes the mainstem of the reservoir, and Hamilton Creek (Figure 1). The drinking water intake is on Hamilton Creek 4.8 km from the mainstem of the reservoir.

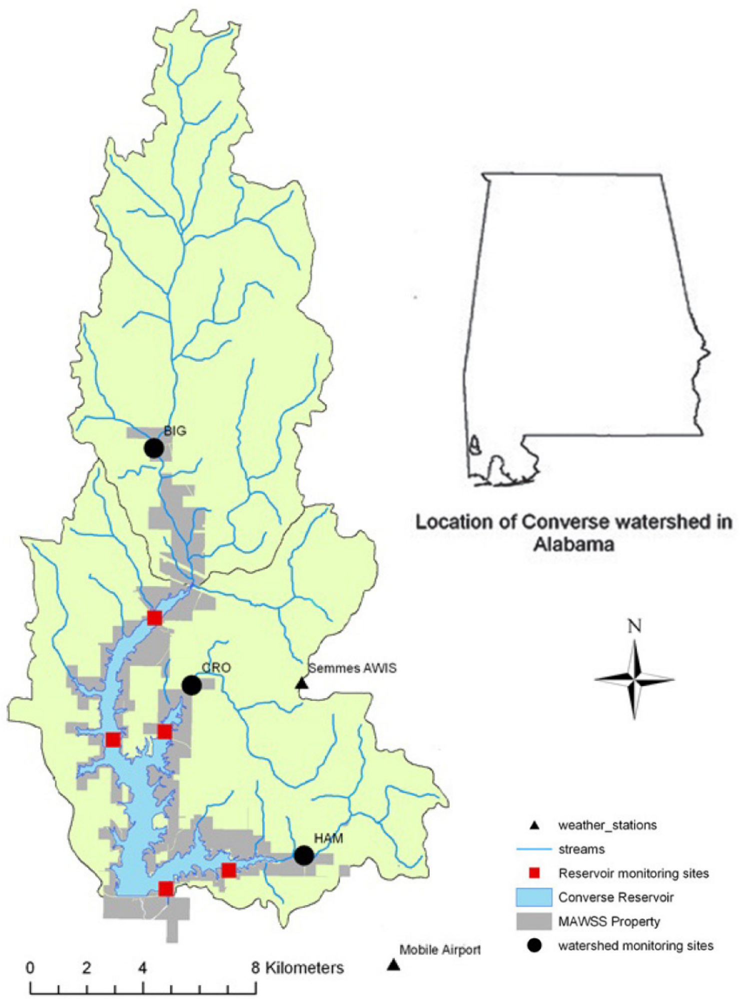

**Figure 2.** Monitoring locations, weather stations, and Mobile Area Water and Sewer Systems (MAWSS) property in Converse Watershed in southwestern Alabama. Watershed monitoring sites represent gauging and water quality monitoring locations.

Concerns about the quality of Converse Reservoir as a supply source for drinking water led to various scientific investigations (ADEM 1996, 2003; Bayne et al. 1998; Journey et al. 1995; Journey and Gill 2001; Gill et al. 2005). Tributary and reservoir water quality data have been collected by the United States Geological Survey (USGS), Auburn University (AU), and MAWSS under various sampling programs and intervals from 1990 to 2005.

Urban growth within the watershed is likely to occur. The eastern watershed boundary extends to within 500 m of Mobile, Alabama, city limits. The Mobile Metropolitan Planning Organization (MMPO) Transportation Plan (2000 to 2030) depicts a new freeway loop bisecting the eastern portion of the watershed (MMPO 2005). Future forecasts of urbanization in the Southeastern U.S. reported by the Southern Forest Resource Assessment (Wear and Greis 2002) indicated that major urbanized centers will be concentrated in three large areas, one of which encompasses the Converse Watershed. The Forests on the Edge project (FOTE, Stein et al. 2005) evaluated urbanization at a national scale and depicted increased population and urban housing densities within the Converse Watershed every 10 years between 1990 and 2030. Local, regional and national urbanization studies described above concur that the Converse Watershed will likely experience significant urbanization in the coming decades.

## Methods

Results from watershed and reservoir hydrologic models were utilized to estimate the value of forested landscapes for potential reservoir TOC regulation. In-reservoir TOC concentrations resulting from watershed pre-and post-urbanization forest to urban land use conversions were utilized. A cost-based economic analysis method was used to estimate the value of the forested landscape for water quality maintenance using costs associated with additional drinking water treatment options available in lieu of watershed management.

### Watershed Modeling

The Loading Simulation Program in C++ (LSPC) (USEPA 2010a), which can simulate TOC and provide input for a widely used reservoir model described below, was selected as the watershed model for this project. LSPC was used to simulate pre-urbanization land use scenario, as well as post-urbanization scenarios estimated using Forest on the Edge (FOTE) housing density projections for 2020 (Stein et al. 2005; Stein et al. 2006). Base and future scenarios were paired and compared with one another to evaluate the influence of estimated forest to urban land conversion on simulated total N (TN), total P (TP) and TOC concentrations and loads to Converse Reservoir between 1991 and 2005 using actual atmospheric conditions. While our economic analysis focuses on TOC, analysis of TN and TP were necessary since these nutrients support algae growth, simulated during reservoir modeling, which is a form of C important to the overall TOC budget.

Hydrologic calibration of the watershed model consisted of comparisons between predicted streamflow at Big Creek (USGS station number 02479945), Hamilton Creek (02480002) and Crooked Creek (02479980) to observed corresponding daily, monthly and yearly streamflow from 1 January 1991 to 31 December 2000. Grab samples of TN, TP and TOC concentrations collected by the USGS were extrapolated to monthly loads using the USGS load estimator (LOADEST) regression model for Big, Crooked and Hamilton creeks (Runkel, Crawford, and Cohn 2004). LOADEST estimates loads in rivers by utilizing measured streamflow and concentration data to develop a regression model. Monthly loads estimated by LOADEST were compared with simulated LSPC monthly loads statistically using Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and ratio of the root mean square error to the standard deviation of measured data (RSR) to evaluate model performance (Elias et al. 2011).

**Table 1.** Raw Water Volume from Converse Reservoir from 1992 to 2005.

| Year | Raw Water Volume (cubic meters) |
|---|---|
| 1992 | 30,238,000 |
| 1993 | 30,162,000 |
| 1994 | 30,230,000 |
| 1995 | 29,753,000 |
| 1996 | 30,859,000 |
| 1997 | 41,479,000 |
| 1998 | 34,141,000 |
| 1999 | 32,982,000 |
| 2000 | 35,965,000 |
| 2001 | 33,611,000 |
| 2002 | 33,766,000 |
| 2003 | 32,097,000 |
| 2004 | 32,645,000 |
| 2005 | 32,948,000 |

### Reservoir Modeling

Daily flows and loads (kg) from watershed modeling were used to simulate base and future scenarios in the Environmental Fluid Dynamics Code (EFDC) hydrodynamic and water quality reservoir model. Reservoir model simulations were used to calculate the daily difference in TOC concentration at the drinking water intake. These daily increases in TOC following urbanization were used to estimate differences in treatment cost.

### Economic Analysis

The change from forested to urbanized land use along with the resultant change in reservoir TOC concentrations were valued with a cost-based method using the cost of removing carbon to minimize

**Table 2.** Total Flow, Direct Runoff, and Baseflow of Big Creek, Hamilton Creek, and Crooked Creek.

| Recommended Criteria[1] | $R^2$ | NSE > 0.5 | RSR <=0.7 | PBIAS +/- 25% |
|---|---|---|---|---|
| **Big Creek** | | | | |
| **Total Flow** | | | | |
| 1991-2000 | 0.75 | 0.71 | 0.54 | 13.9 |
| 2001-2005 | 0.69 | 0.59 | 0.64 | 3.1 |
| **Direct Runoff** | | | | |
| 1991-2000 | 0.65 | 0.52 | 0.69 | 35.8 |
| 2001-2005 | 0.70 | 0.45 | 0.74 | 16.2 |
| **Baseflow** | | | | |
| 1991-2000 | 0.84 | 0.83 | 0.41 | 0.6 |
| 2001-2005 | 0.63 | 0.61 | 0.62 | -4.2 |
| **Hamilton Creek** | | | | |
| **Total Flow** | | | | |
| 1991-2000 | 0.67 | 0.60 | 0.63 | 14.5 |
| 2001-2005 | 0.72 | 0.69 | 0.56 | 2.5 |
| **Direct Runoff** | | | | |
| 1991-2000 | 0.62 | 0.56 | 0.66 | 33.1 |
| 2001-2005 | 0.81 | 0.63 | 0.61 | -4.7 |
| **Baseflow** | | | | |
| 1991-2000 | 0.71 | 0.63 | 0.61 | 7.2 |
| 2001-2005 | 0.67 | 0.62 | 0.62 | 4.7 |
| **Crooked Creek** | | | | |
| **Total Flow** | | | | |
| 1991-2000 | 0.71 | 0.67 | 0.57 | 6.6 |
| 2001-2005 | 0.7 | 0.61 | 0.62 | -1.3 |
| **Direct Runoff** | | | | |
| 1991-2000 | 0.72 | 0.57 | 0.66 | 29.6 |
| 2001-2005 | 0.73 | 0.52 | 0.69 | 19.2 |
| **Baseflow** | | | | |
| 1991-2000 | 0.67 | 0.64 | 0.60 | -6.2 |
| 2001-2005 | 0.66 | 0.54 | 0.68 | -10.4 |

[1] Statistics presented include the coefficient of determination ($R^2$), Nash-Sutcliffe efficiency (NSE), ratio of the root mean square error to the standard deviation of measured data (RSR), and percent bias (PBIAS).

human health risk from carcinogens as mandated by the Stage 2 DBP Rule (USEPA 2005b). The amount of land converted from forest (52 km$^2$) was linked to higher costs for TOC removal as urbanization increased. The difference in additional powdered activated carbon (PAC) treatment costs divided by the area changed from forest to urban land use provided a cost per km$^2$ estimate for forest water quality services related to reservoir TOC concentrations. A cost-based method was selected as a straightforward application of previously determined costs for additional water treatment with PAC used to value forest-water related services. The benefit of this approach is that it attaches an actual dollar value to ecosystem services. The drawback is that it relies upon estimates of increased treatment costs, which may change with changes in regulations or PAC costs.

**Table 3.** Median Total Nitrogen, Phosphorus, Organic Carbon Concentrations At Drinking Water Intake on Converse Reservoir.

| Scenario | Units | TN | TP | TOC |
|---|---|---|---|---|
| | | 0.38 | 0.006 | 2.59 |
| **Base Future** | mg/L | 0.59 | 0.010 | 3.65 |
| **Difference** | mg/L | 0.21 | 0.004 | 1.1 |
| **Percent Change** | mg/L % | 55 | 67 | 41 |
| **Difference/km$^2$** | mg/L per km$^2$ | 0.004 | 0.0001 | 0.02 |

n = 4,292 days

Total Nitrogen (TN), Total Phosphorus (TP), and Total Organic Carbon (TOC)

Based upon previous monitoring data, MAWSS has established TOC and water temperature levels above which disinfection byproduct formation is more likely in the water distribution system. Operational thresholds are defined as a finished water TOC concentration exceeding 1.5 mg/L when the water temperature at the treatment plant exceeds 27ºC (May to October). TOC at the drinking water intake was evaluated daily from May to October using 2,042 days from 1992 to 2004, excluding 2000 and 2001. The decline in water level during the drought of 2000 hampered reservoir simulation by decreasing water level to the point of cell 'drying,' which was not computationally feasible in the version of EFDC used in this research. Reservoir water TOC is currently treated with powdered activated carbon (PAC) to minimize DBP formation. The cost for PAC in April 2010 was \$1.72 per kg (\$0.78 per lb) and was used in base and future scenario economic analysis. This is a conservative estimate since PAC cost by 2020 is projected to range from \$4.25 per kg (\$1.93 per lb) to \$5.82 per kg (\$2.64 per lb) (Volkert 2010).

The least and highest total raw water flows treated between May and October were used to define the upper and lower possible additional treatment cost between 1992 and 2005 (Table 1). The maximum volume treated between May and October was 9,501 million gallons in 2000, a severe drought year. The minimum volume treated between May and October was 7,860 million gallons in 1995. The treatment volume for 1995 and 2000 was used in cost analyses.

The total daily treatment volume in 2020 was expected to be 7.5 percent higher than 2005 (personal communication, MAWSS). To calculate an estimated future treatment volume for comparison with base scenarios, the 7.5 percent increase was applied to the mean daily treatment volume from selected years having the least and highest treatment volume (1995 and 2000, respectively).

MAWSS has found that a finished water TOC concentration of 1.5 mg/L or less reduces the formation of DBPs. The drinking water treatment process at MAWSS typically removes 45 percent or more of the reservoir water TOC. Assuming a TOC removal of 45 percent during water treatment and a finished water goal of 1.5 mg/L TOC, the reservoir water TOC concentration above which additional treatment is necessary was 2.7 mg/L. The work rate is the ratio of TOC reduction (mg/ L) to PAC dose (mg/L). A work rate of 0.063 for TOC removal with PAC was calculated by MAWSS. Equation (1) identifies the PAC dose necessary for a specified TOC reduction.

$$\frac{\text{TOC reduction required (mg L-1)}}{0.063} = \text{PAC required (mg/L)} \qquad (1)$$

To calculate the daily cost for additional water treatment, assuming the daily simulated TOC concentration at the drinking water intake was > 2.7 mg/L, additional treatment cost for base and future scenarios was computed by subtracting the 2.7 from the simulated concentration to derive the TOC reduction requirement. PAC required (Equation 1) was multiplied by the daily treatment volume to derive the mass of daily PAC required. The daily PAC requirement multiplied by \$1.72 per kg gives the daily cost for PAC treatment.

**Table 4.** Additional Annual Treatment Costs and Costs Per Area Urbanized for Powdered Activated Carbon (PAC) for Converse Reservoir**.**

| | **Base Scenario Max. Volume Treated** | **Base Scenario Min. Volume treated** | **Post-Urban** | **Increase in annual treatment cost following urbanization** | | **Increase in annual treatment cost per km$^2$ following urbanization** | |
|---|---|---|---|---|---|---|---|
| | | | | Max.Volume | Min. Volume | Max. Volume | Min. Volume |
| 1992 | 9,830 | 12,470 | 925,750 | 913,750 | 913,750 | 915,920 | 17,610 |
| 1993 | 96,950 | 112,810 | 740,880 | 628,070 | 643,930 | 12,080 | 12,380 |
| 1994 | 17,380 | 21,850 | 752,090 | 730,240 | 734,710 | 14,040 | 14,130 |
| 1995 | 417,570 | 502,840 | 1,175,440 | 672,610 | 757,870 | 12,940 | 14,570 |
| 1996 | 268,450 | 320,390 | 1,107,290 | 786,900 | 838,840 | 15,130 | 16,130 |
| 1997 | 47,070 | 57,130 | 1,356,780 | 1,299,660 | 1,309,720 | 24,990 | 25,190 |
| 1998 | 288,200 | 352,470 | 1,153,160 | 800,690 | 864,960 | 15,400 | 16,630 |
| 1999 | 37,630 | 46,580 | 1,131,570 | 1,085,000 | 1,093,950 | 20,870 | 21,040 |
| 2002 | 74,960 | 93,330 | 806,560 | 713,230 | 731,600 | 13,720 | 14,070 |
| 2003 | 708,020 | 844,850 | 1,776,760 | 931,920 | 1,068,740 | 17,920 | 20,550 |
| 2004 | 316,150 | 381,910 | 1,391,340 | 1,009,430 | 1,075,190 | 19,410 | 20,680 |
| Mean $/y | 204,470 | 249,690 | 1,119,780 | 870,090 | 912,310 | 16,730 | 17,540 |
| Max. $ y$^{-1}$ | 708, | 844,850 | 1,776,760 | 1,299,660 | 1,309,720 | 24,990 | 25,190 |
| Min. $ y$^{-1}$ | 9,830 | 12,470 | 740,880 | 628,070 | 643,930 | 12,080 | 12,380 |

**Table 5.** Studies Reporting Ecosystem Services Related Fresh Water Provisions.

| **Author** | **Year** | **Ecosystem Change** | **Valuation Method** | **$ per ha per yr** |
|---|---|---|---|---|
| This Study | 2010 | Forest to urban land use change influence on total organic carbon water treatment cost | Cost-based | $123.80 to $251.90 |
| Boyer and Polasky | 2004 | Water filtration from wetlands | Willingness to Pay | $15.22 to $31.22 |
| Nunez et. al | 2005 | Forest provisions of fresh water supply | Production Function | $61.20 to $162.4 |
| Constanza et al. | 2006 | Forest provision of fresh water | Benefit Transfer | $3.64 to $65.96 |
| Turner et al.* | 1988 | Value of water provision in the Chattahoochee and Oconee national forests | Cost-benefit Analysis | $245 |
| Postel and Thompson | 2005 | Average purchase price of land surrounding watersheds in the Catskills/Delaware watersheds for the NYC project | Natural land purchased for watershed protection | $6,745 |

* Adapted from US Department of Agriculture Forest Services 1985. *Proposed land and resource management plan*. 1985 revision. Chattahoochee-Oconee National Forests, Washington, D.C.

The mean daily and annual costs for additional PAC treatment were reported, along with a range of costs for the base scenarios provided, by using the minimum and maximum treatment volume in calculations. The mean cost for additional treatment for base scenarios was subtracted from the corresponding cost for future treatment to estimate an increase in cost per day and year due to forest to urban land conversion. The mean annual costs were calculated using minimum and maximum treatment volume to provide a range of expected increased treatment costs due to simulated urbanization.

The dollar value for forested land ecosystem services related to TOC concentrations was reported based upon the necessary increased treatment cost. To simulate urbanization between 1992 and 2020, forest to urban land conversion occurred on 52 km$^2$. The average increase in treatment cost between May and October was divided by the area urbanized to yield cost per km$^2$ per day.

## Results and Discussion

### Watershed Model Results

Watershed model results are dependent upon the simulated spatial distribution of urbanization in the Converse Watershed. As such, a spatially explicit regional growth model was used to provide the best estimate of urbanization by subwatershed. From 1992 to 2020 simulated urban and suburban growth of 52 km$^2$, which is an increase in total urban area from 3 to 22 percent (Stein et al. 2006), resulted in an increase of $> 50$ percent in TN and TP total loads (kg) to Converse Reservoir. TN and TP loads increased by 109 and 62 percent, respectively. LSPC watershed model total flow, direct runoff and base flow calibration and validation NSE and RSR performance ratings ranged from "satisfactory" to "very good" for all streams in the watershed (Table 2). Nutrient PBIAS performance ratings for calibration and validation were "fair" to "very good" (Moriasi et al. 2007). See Elias et al. (2011) for more detailed watershed modeling results.

Results indicated simulated urban growth generally increased monthly flows by 15 percent, but resulted in 2.9 percent lower flows during drought months. An increase in flow following simulated forest to urban land conversion resulted in a 26 percent increase in TOC loads, despite lower future TOC concentrations (16 percent). Simulated forest to urban land conversion led to significantly higher TOC loads during June, July and August of the critical period (May to October) for DBP formation in drinking water supplied by Converse Reservoir.

### Reservoir Model Results

Forest to urban land conversion resulted in elevated median TOC concentrations at the MAWSS drinking water intake. Median future TOC concentration increased by 1.1 mg/L (41 percent) over median base TOC concentration (Table 3). Higher TOC concentration simulated by the reservoir model, despite lower future TOC concentrations from the watershed model, is a result of increased nutrient (N and P) loading following urbanization supporting increased reservoir algae growth. Simulated forest to urban land use change caused monthly median predicted TOC concentrations at the source water intake between May and October to increase by between 33 to 49 percent. The largest increase occurred in August to October. TOC concentrations between May and October are important since additional drinking water treatment is positively related to elevated water temperatures.

Additional drinking water treatment is necessary when raw water TOC concentration was > 2.7 mg/L between May and October. Using 1992 pre-urbanized land use, additional drinking water treatment with PAC was necessary on 47 percent of the days since TOC concentrations exceeded 2.7 mg/L. Simulated urbanization in the Converse Watershed caused additional drinking water treatment to be continuously necessary.

### Ecosystem Services Valuation Results

Forest to urban land conversion substantially increased in-reservoir TOC and water treatment cost in the Converse Watershed. Table 4 shows the base and future annual treatment cost, as well as the increase in annual treatment cost, for PAC addition. No additional water treatment with PAC was necessary until raw water concentrations exceeded 2.7 mg/L. The mean annual cost for additional treatment with PAC using base 1992 land use during simulations was between $207,000 to $250,000 per year depending upon volume treated (Table 4). The mean annual cost for treatment with PAC following simulated urbanization was $1,120,000, with a range of $740,000 to $1,777,000 per year.

The mean increase in annual treatment cost (n=11 y) was $870,090 to $912,310 per year (Table 4). The increase in annual treatment cost ranged from $628,070 to $1,309,720. The mean increase in annual treatment cost per km$^2$ urbanized was $16,730 to $17,540 per km$^2$. The increase in annual treatment costs ranged from $12,080 to $25,190 per km$^2$ per year ($120.80 to $251.90 per ha per year). Thus, the value of forest TOC regulation services lost following simulated urbanization was within the values for forest water provision of $61 to $162 per ha reported by Nunez, (2005) and $245 per ha reported by Turner et al (1988), but substantially higher than the $4 to $66 per ha estimated by Costanza et al. (2006). Since previous estimates encompass all water provision services from the forest and our estimate focused on only one water quality parameter, the total water provision services from forested catchments would likely be larger than both our current estimate and previous estimates.

## Future Research

This research provides a methodology to determine a specific cost-based value of forested watersheds for public water supply protection based upon land use change. This methodology can be applied using different land use shifts to incorporate other changes such as a shift from forest to agricultural land. Suresh et al. (2012, under review) document the influence of climate change and the El Nino Southern Oscillation on increased spring TOC at Converse Reservoir and this preliminary information should be further evaluated in terms of the cumulative impacts of climate change and urbanization. Finally, this methodology should also be applied to other watersheds in other regions to document regional differences in land use change in TOC concentration, possibly within the framework of an interdisciplinary modeling course.

## Conclusions

This interdisciplinary study focused on the value of one water quality variable, TOC, to estimate the economic benefits of forest cover in a source water catchment. Watershed model results, which are dependent upon the spatial distribution of urbanization in the watershed, indicated that urbanization increased TN, TP and TOC loads to Converse Reservoir. Reservoir model results indicated future median TOC concentration increased by 1.1 mg/L. Between May and October, urbanization increased monthly median TOC concentrations by 33 to 49 percent. With 1992 pre-urbanized land use, additional treatment was necessary 47 percent of the days between May within the range of previous values provided for all water provision ecosystem services from a forested catchment, suggesting that previous estimates may need to be increased to incorporate the value of forested catchments for water quality regulation.

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# WATER SYSTEMS, SCIENCE, AND SOCIETY UNDER GLOBAL CHANGE 2014 UCOWR / NIWR / CUAHSI CONFERENCE

**June 18-20, 2014**

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**Water Systems, Science, and Society**
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Water problems pose interdisciplinary challenges as evidenced by the tremendous diversity of interests within the three organizations sponsoring this conference – UCOWR, NIWR, and CUAHSI. Former U.S. Secretary of State, Hillary Rodham Clinton, put it eloquently when she stated on March 22, 2011, that:

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Global changes in climate, population, land use, biodiversity, and infrastructure continue to pose enormous challenges to our ability to effectively manage our water resources. UCOWR, CUAHSI, and NIWR invite you and your colleagues to join leading water managers, educators, researchers, and other professionals from across the country to the first joint conference of these national organizations to address some of the most compelling and important challenges facing our profession.

Two national university community organizations, UCOWR and CUAHSI, have similar missions, yet this is their first joint conference. This conference is unique because it is both a scientific conference and an exploration of how universities organize themselves to meet societal goals concerning water resources. A central theme to be addressed will be:

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# Interdisciplinary Modeling, Research, and Education

## Issue Editors

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