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Analysis and synthesis of best practices in interdisciplinary social–environmental education in the United States

Abstract | Social–environmental (SE) issues often are complex and require an interdisciplinary approach for solutions. Currently, scientists and decision-makers trained in graduate programs do not have sufficient training in interdisciplinary tools and methods to achieve effective approaches to SE problems. In this paper, we characterize and analyze two interdisciplinary graduate programs in the western US to detail: i) characteristics of institutions and institutionalization; ii) (inter)disciplinary contributions; iii) past and current SE projects; iv) curriculum with signature methods, courses, ethics; v) thesis/dissertation requirements; vi) faculty and student characteristics, and vii) market for students. A final synthesis includes five lessons learned for a successful interdisciplinary education and research program: 1) effective leadership; 2) an institutional culture of collaboration; 3) resources; 4) institutional support and assistance in development of administrative structure compatible with the institution, and 5) internal and external communication.

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Keywords | graduate programs | characterization | interdisciplinarity | integrated methods

Introduction

Social–environmental (SE) issues often are complex and require an interdisciplinary approach for solutions (Newell 2001). Universities and research institutions have recognized the need for interdisciplinary approaches for some time (e.g., Luszki 1958; Bammer 2013). The National Academies Committee on Facilitating Interdisciplinary Research examined the scope of interdisciplinary research at US universities, and their report provided detailed conclusions and recommendations on how to achieve interdisciplinary research, the challenges to overcome, and the changes

Received: 17th of June, 2016. Accepted: 29th of July, 2016.

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needed (NAS 2005). In recent years, US universities have seen an increase in interdisciplinary degree programs in Environmental Sciences, Water Resources, and related themes (Benson *et al.* 2015; Chandramohan and Fallows 2009).

Faculty in US universities are engaged in integrated research projects funded by national level agencies (e.g., the National Science Foundation (NFS)). Some graduate programs started many decades ago (e.g. the Water Management MS at the University of Wisconsin at Stevens Point), some were initiated through funding such as the NFS–Integrative Graduate Education Research Traineeship (NFS–IGERT). Others began through faculty–led initiatives, in some cases facilitated by internal funding from the upper administration. By our estimate, well over 100 US universities now train scientists in the water and environmental areas through interdisciplinary programs. In other parts of the world, interdisciplinary graduate programs also have developed (Weingart and Padberg 2014). All these programs are in different stages of maturity, and require a methodology that characterizes them for synthesis of lessons learned. Those who are actively developing, coordinating, and sustaining such programs understand the rewards of training students and working across disciplines as well as the challenges to achieve success within their institutions. There are signs of institutional change as some universities have begun to perform structural transformations that institutionalize concepts of interdisciplinarity (Weingart 2014; Noorden 2015; Darbellay 2015; Crow and Dabars 2015).

In this paper, we characterize interdisciplinary water resources graduate programs at two universities, in Oregon (Oregon State University) and Idaho (University of Idaho). Both programs share a similar vision, and seek to integrate research, education, and outreach across various traditional boundaries (figure 1) through distinct programmatic elements. The authors have experience with these graduate programs as directors and faculty teaching and advising students, and grants in programs such as the NFS–IGERT programs. They have also participated in reviews of other interdisciplinary programs in water resources (e.g., the University of New Mexico and Texas A&M University) and draw on those experiences as well. The objectives of this paper are to develop a description of program dimensions (see Program Dimensions below) for the optimal environment in which interdisciplinary graduate education may occur; to characterize two existing interdisciplinary graduate programs; and to conduct a synthesis of the findings for improvement of current programs or initiation of new programs. Furthermore, the paper makes recommendations for continued analysis and synthesis of interdisciplinary education programs.

Program dimensions

Weingart (2014) and Crow and Dabars (2015) identified that obstacles to interdisciplinary approaches lie in the nature of disciplines as forms of knowledge production and institutionalized organizational structures like departments or faculties that cannot be changed easily. In this regard, understanding how knowledge is produced in interdisciplinary graduate programs is key to creating better conditions for interdisciplinary and SE program development. Understanding the production of SE knowledge implies giving meaning to academic practices and involves a shared communicative process.

Developing an interdisciplinary graduate program is not as simple as developing a curriculum and a set of degree requirements. In addition, there are core concepts related to the academic institution, disciplinary culture(s), and faculty and student communities. We identify a set of seven programmatic dimensions: i) characteristics of institutions and institutionalization; ii) inter- and disciplinary contributions; iii) past and current SE projects; iv) curriculum with signature methods, courses, ethics; v) thesis/dissertation requirements; vi) faculty and student characteristics (e.g., productivity and happiness), and vii) markets for students. These dimensions are discussed next.

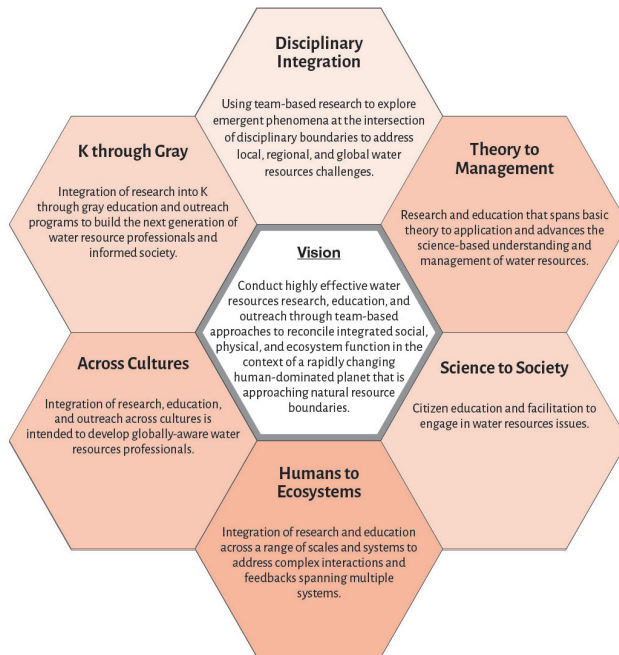


Figure 1. Water resources programs at OSU and UI share a common general vision and seek to integrate research, education, and outreach across traditional boundaries through distinct programmatic components.

Characteristics of institutions and institutionalization: The first dimension describes the characteristics of the academic institution (i.e., university) where the program is being administered. Descriptions focus on the following: the process that was followed to initiate the program, how the program is administered within the university structure, the level of administrative support from colleges and departments, connections to research institutes, and the resource base for the students. An underlying question is if the program is sustainable.

Inter- and disciplinary contributions: Interdisciplinary programs build on the strengths of the disciplines involved with the program. This is exemplified in the courses that students have access to for their depth and breadth elements, and the richness of interdisciplinary methods courses, student committees, and research projects.

Past and current SE projects: Each graduate program is characterized by the research and case study projects that graduate students engage in towards new knowledge production. New knowledge production is an important aspect of successful interdisciplinary programs to enhance their ability to clearly articulate the motivation for their existence. What is the value of an interdisciplinary program at an institution with strong disciplinary programs? What new knowledge is produced? We argue that interdisciplinary approaches are essential for both structuring research on SE systems and understanding and interpreting the results of such research.

Curriculum with signature methods, courses, ethics: Disciplinary and interdisciplinary course work, including courses (e.g., environmental ethics, environmental history, seminars) beyond the dominant discipline of the students are valuable in the training towards interdisciplinary research (Klein 2006; Newell 1994). Particularly important is student access to courses where they work in teams and practice interdisciplinary methods.

Thesis/dissertation requirements: In this dimension, the combined effects of the (inter)disciplinary contributions, SE projects, and interdisciplinary training in courses at the institution define the depth and breadth of the thesis research project.

Faculty and student characteristics (e.g., productivity and satisfaction): In addition to the disciplines contributing to the program, this dimension characterizes the degree of participation of the faculty both in terms of their teaching and research productivity, connectivity across campus, enjoyment and willingness to engage in collaborative groups, and leadership roles in the administrative and social aspects of the program. Student characteristics include their ability and interest in engaging in interdisciplinary education and research, and other programmatic elements such as organizing seminars or social activities.

Markets for students: The last dimension deals with SE “real-world” problems in terms of reflecting on employability of graduate students, and the employment of graduates in their field.

Characteristics of two interdisciplinary graduate programs

In this section, we describe two interdisciplinary graduate programs in water resources, characterized by the relevant program dimensions from our list of seven above.

Water Resource Graduate Program at Oregon State University

i) Characteristics of institution and institutionalization

Oregon State University (OSU) is a Land Grant, Sea Grant, Sun Grant and Space Grant institution, and a Carnegie Very High Research institution. Enrollment at OSU is nearly 30,000 (including about 4,400 graduate students) (OSU 2015). With over 80 faculty members actively engaged in water-related research and teaching, OSU has sufficient breadth of coursework and advising to offer three interdisciplinary degrees in Water Resource Engineering (WRE), Water Resource Policy and Management (WRPM), and Water Resource Science (WRS) as part of the Water Resources Graduate Program (WRGP). Since its inception in 2005, the WRGP has grown to over 150 graduates of the program and annual enrollment of about 65 students from 2011-2016. The institution plays an important role in water-related research, scholarship, and graduate education in the US and internationally.

Prior to 2005, faculty and courses relevant to water resources at OSU were spread across multiple colleges and departments, with little coordination of curriculum. The strength of OSU in water-related research and education was not visible outside the institution. In a grass-roots effort led by faculty and students from six colleges and multiple departments, OSU built the WRGP. Key to the development of the program was identifying a coordinated curriculum that could deliver the coursework for ID graduate degrees in WRE, WRPM and WRS, and showcase OSU’s strength in water resources research and education. The WRGP has two central objectives: 1) provide identifiable, marketable degrees that prepare graduates to address critical environmental issues and enhance scholarship in water-related fields, and 2) build on existing strengths to increase the number of graduate students coming to OSU to study water resources, thereby increasing the output of the faculty and helping to develop emerging strengths in water resources research and education. The Hydrophiles student group (local student chapter of the American Water Resources Association (AWRA)) on campus has greatly helped promote the WRGP.

The Hydrophiles group (with assistance from the WRGP) sponsors an annual Water Resources Research Symposium to highlight student research. Gender balance and diversity in the WRGP have improved over time. The current student body has equal numbers of male and female students in the WRE and WRS degree programs, and enrollment in the WRGP program is 75% female. Since 2011, about 15% of domestic students enrolled have been members of racial or ethnic minorities, and 15% of students have been international students.

Institutional support for the program includes half-time salaries for a director and administrative assistant, although recent program review notes that the director position requires full-time effort. Space allocations for students are provided by participating colleges and include offices and conference rooms. Students share classroom and computing facilities with departmental majors. At present, the program relies on individual faculty members who choose to allocate time and resources for advising students in the program. Research and teaching facilities are located in the participating departments and colleges.

The WRGP is strongly tied to the Institute for Water and Watersheds (IWW), established in 2005 through an internal OSU grant. The IWW is also funded by returned overhead, by funds from the OSU Research Office, and in part by the US Geological Survey Program for state Water Resources Research Institutes. The IWW has helped convene faculty and students around important interdisciplinary research concerns related to water in Oregon, and provides funds for bringing seminar speakers to Oregon.

The Graduate School is currently the administrative home for interdisciplinary programs such as the WRGP. However, in 2013, it was proposed that the Graduate School serve only as an incubator of interdisciplinary programs, and that once established, successful programs would be moved to disciplinary colleges. A recent Task Force consisting of faculty and students, appointed by the Provost produced a report recommending that all interdisciplinary programs at OSU be housed in a school of Interdisciplinary Studies within the Graduate School, administered by an Associate Dean of the Graduate School with administration and a budget model for funding similar to that for Colleges and Departments, including a baseline budget for operations and additional funding supplied in proportion to program productivity with respect to number of graduates and student credit hours taught in the courses with the WRP, WRS or WRE designators. These recommendations are currently under consideration by OSU's central administration.

While enrollment has grown at OSU and the WRGP, resources available to the institution and the program have not kept pace with that growth. Program participating departments and individual advisors strive to support graduate

students on research grants, teaching assistantships, fellowships and scholarships. Student financial need, however, often exceeds the available resources. WRGP's ability to recruit students is sometimes limited by the lack of financial support.

ii) Inter- and disciplinary contributions

Signature areas of strength at OSU in water-related research and education include hydrology in natural resource areas in the Colleges of Agriculture, Earth, Ocean and Atmospheric Sciences, Engineering, Forestry, Liberal Arts, and Science. Faculty interact across college and departmental boundaries to collaborate on large, interdisciplinary research grants. Other interdisciplinary initiatives at OSU include the Environmental Sciences Program, Marine Resource Management Program, a Humanitarian Engineering Program, the new Environmental Humanities Program, and the Marine Studies Initiative. Disciplinary expertise and depth along with interdisciplinary breadth and willingness to collaborate and learn together on interdisciplinary projects is a hallmark of the faculty involved in the wrgp at OSU.

iii) Past and current SE projects

Graduate students have been involved in new knowledge produced through interdisciplinary research including improved understanding of interactions among social and biophysical attributes of water systems. In these projects, identification of important thresholds and vulnerabilities that are influenced not only by the physical and biological components of these systems, but also by human context including, but not limited to, demographics, culture, power relationships, institutions and governance. Improved understanding that emerges from interdisciplinary research provided guidance for decision-making that incorporates biophysical, socioeconomic and socio-ecological aspects of the system. For example, Brown *et al.* (2009) produced a model (IDAM) applied to dams in China that incorporated geopolitical, socio-economic and biophysical attributes to help characterize the context for decision-making and understanding the impacts that dams will have in a region. Studies of farmer adoption of new agricultural practices to help conserve water revealed interactions between landscape change and water policy in China (Ingman *et al.* 2015). Integrated assessments of how alternative management of agricultural land in the US Corn Belt could influence water quality, biodiversity, informed by farmer perceptions of best practices, provided important guidance for development of farm policy (Santelmann *et al.* 2004). Studies of water sustainability in a major river basin (Santelmann *et al.* 2013) were used to identify attributes that make

watersheds vulnerable or resilient to water scarcity in the face of climate change. While interdisciplinary systems research is in its infancy, only by studying these systems as SES can we reasonably hope to identify thresholds and interactions among the drivers of system processes.

These examples and additional major projects by faculty at OSU, and particularly the faculty members who have been leaders within the WRGP and the IWW, are shown in table 1. These projects include funds for research assistantships for students in the WRGP and opportunities for students to experience research collaboration across disciplines first-hand.

iv) Curriculum with signature methods, courses, ethics

The WRGP offers Ph.D. and MS degrees in WRE and WRS, and a MS degree in WRPM, with a newly developed concentration in Water Cooperation and Peace as a Joint Educational Programme with UNESCO-IHE in Delft, the Netherlands and University for Peace in Ciudad Colón, Costa Rica. Students can also apply to

Table 1. Major funding for research and student support at Oregon State University with titles of funded projects and names of water program faculty leadership who were principal investigators, co-investigators, or collaborators.

Program	Project title and faculty names
Internal Funding from Institution	Provost’s Office, Colleges, Graduate School.
USGS WRRI	Institute for Water and Watersheds (Campana, Jarvis, McDonnell, Lach).
NSF/EPA Water-Watersheds Program	Modeling effects of alternative landscape design and management on water quality and biodiversity in Midwest Agricultural Watersheds (Santelmann); Developing methods and tools for watershed restoration (Bolte, Santelmann, Smith).
NSF Biocomplexity in the Environment	Sustaining multiple functions for urban wetlands (Santelmann, Bolte, Huber, Lach).
NSF IGERT	Ecosystem informatics (Jones).
NSF Coupled Human Natural Systems	Bridging communities and scale through a global mountain transdisciplinary sustainability network s (Nolin).
NSF Decision-making Under Uncertainty	Interdisciplinary research and methods for assessing dams as agents of change in China (Tullos, Tilt, Wolf).
NSF Water Sustainability and Climate	Anticipating water scarcity and informing integrative water system response in the Pacific Northwest (Nolin, Haggerty, Bolte, McDonnell, Santelmann).
NSF Science, Technol., Eng. & Math Scholarships	Meeting national needs for hydrologists and water resource engineers (Santelmann, Haggerty, Tullos).
NSF Sustainability Research Networks	Transitioning toward sustainable urban water systems (Haggerty).

and enroll concurrently at the School of Law at the University of Oregon to earn a Juris Doctor (J.D.) degree. All students in the WRGP take at least six credits of required courses in common: the core course WRP 524 Sociotechnical Aspects of Water Resources (3cr); WRP, WRS or WRE 505 Journal Club (1 cr); and two seminars (WRP, WRS or WRE 507 Water Resources Seminar (1 cr). Each degree program also has program-specific curriculum requirements for each area of specialization within the degree. Students work with their advisor and committee to tailor their program of study to their needs, taking into account undergraduate coursework and experience. We have also developed a capstone course in Applied Field Problems for the WCP program, which can also be taken by students in other degree programs within the WRGP.

Students take ethics courses through the Office of Research Integrity, and ethics are addressed in the core course, Sociotechnical Aspects of Water Resources. The Graduate School and several departments also offer specific courses and seminars in ethics, and seminars on research ethics are held and promoted during the year.

v) Thesis/dissertation requirements

Graduates are required to have disciplinary depth as well as interdisciplinary breadth. Each student's program of study for the WRE and WRS degree must demonstrate that the student meets certification criteria established by the American Institute of Hydrology (AIH) for the Professional Hydrologist certification exam and for WRE, are consistent with the basic math and science requirements for the Fundamentals of Engineering and Professional Engineer exams. The WRPM students take fundamental coursework in public policy as well as specific methods courses. To earn an M.S. degree, students in the WRS degree program must earn a minimum of 45 credits and complete and defend a thesis, whereas students in the WRE and WRPM degree programs must earn a minimum of 45 credits and must complete and defend either a research project paper or thesis. For the Ph.D. degree, students in the WRE and WRS programs must complete 108 credits, successfully pass qualifying exams, and complete and defend a dissertation.

vi) Faculty and student characteristics

About 70 faculty members have been approved to advise students in the WRGP. These faculty are most active in the program, and another 10 to 20 occasionally serve on committees or teach courses taken by students in the program. The active graduate faculty members have been productive in the past decade as research faculty, publishing more than 1,740 scholarly articles and generating over US \$150M from 2005-2014. It is interesting to note that

the greatest number of publications and highest amount of funding has been generated by faculty members who advise students in more than one degree program. These faculty members are those whose research interests and advising span multiple disciplines and who tend to attract graduate students interested in interdisciplinary research.

Faculty in the WRGP have earned recognition from a number of professional organizations, including election as a Fellow of the American Geophysical Union, selection as Darcy Lecturers by the National Groundwater Association, and recognition as Diplomate, Water Resources Engineer (D.WRE) of the American Academy of Water Resources Engineers (AAWRE). Faculty members have received awards such as the John Hem Award for Excellence in Science and Engineering, Hollis Dole Professorship in Geosciences, the Dubach Professorship in Public Policy, and the prestigious Heinz Award. Several faculty members have served as Editor or Associate Editor for the journal *Water Resources Research*, *Hydrologic Processes*, as well as for other journals related to water such as *Water Policy*, and *Ecosphere*. Faculty have also been recognized for service to professional organizations, serving as President of the American Water Resources Association, and Treasurer for the International Association for Landscape Ecology. The WRGP provides delegates to the University Council for Water Resources (UCOWR).

vii) Markets for students

Data collected by the program in exit interviews indicate that ~ 95% of the students completing the WRE degree have either been employed in their field within six to twelve months of degree completion or have gone on to further education. These estimates are consistent with the results of a survey of alumni conducted for a ten year program review in Fall 2014 in which 100% of respondents reported that they were employed within a year of graduation; and all Ph.D. respondents were employed within six months. Among Ph.D. graduates to date, five are assistant professors at public universities; others are employed by consulting firms or state/Federal agencies.

Nearly all of the WRPM graduates have either been employed in their field within six months of degree completion (64%) or have gone on to Ph.D. or J.D. programs (27%). The survey of alumni for our ten year review in Fall of 2014 found that most WRPM respondents were employed in their field of study, though three were employed in other professions. Most often, WRPM graduates are employed either in environmental consulting or government agencies. Several have gone on to Ph.D. or J.D. programs, and several work for non-governmental organizations in the US or internationally.

Nearly all of the M.S. students completing the wrs degree have either been employed in their field within six months of degree completion or have gone

on to Ph.D. or J.D. programs. Among respondents to a survey of alumni, 71% of M.S. alumni found jobs in the first six months, another 15% were employed within a year of graduation.

Every respondent (100%) to our alumni survey, including all degree programs, reported that they would recommend the program to others, and reported a relatively high degree of satisfaction with advising, mentoring, and coursework, with average scores on a five-point scale across all categories ranging from 4.2 to 5 across the degree programs, where 1 = unsatisfied and 5 = very satisfied. For students in the WRPM degree program, the lowest levels of satisfaction were reported in the level of financial support (3.3) and faculty advising (3.7), and the highest level of satisfaction was in professional relationship with the committee (4.4) and overall satisfaction with the program (4.5). For the WRS and WRE alumni, the lowest satisfaction was related to availability of diverse coursework (3.6) and the highest satisfaction was for major professor mentoring and resources available for research.

Water Resources Program at University of Idaho

i) Characteristics of institutions and institutionalization

The University of Idaho (UI) is a public university and serves the State of Idaho as the land-grant and primary research institution. About 9,100 undergraduate students and 2,200 graduate students are enrolled in disciplinary programs housed in nine Colleges offering 88 M.S. and 32 Ph.D. degree options. The Water Resources (WR) Program is one of four interdisciplinary academic programs at UI, and the only program in the state of Idaho with both M.S. and Ph.D. offerings in Water Resources.

The launch of the WR graduate program in 2007 was preceded by substantial informal organizational efforts by a group of enthusiastic faculty from multiple colleges. The formal launch of the program was part of a five-year, internal US \$1.6M grant from the University administration to develop the innovative, cross-cutting research and education program Waters of the West, which partially supported the program for the first five years. Programmatically, the program has undergone a number of administrative changes since inception. Initially an independent administrative structure of the Waters of the West combined the interdisciplinary research and graduate programs. Starting in 2011, administration of the degree program was consolidated with two other university-wide programs: the Professional Science Masters (PSM) and Environmental Science (ENVS) programs. WR continued as an independent degree program. In 2015, as part of a statewide program prioritization process (called Focus for the Future Initiative at UI), WR, ENVS, and PSM were disentangled and their administration moved to individual colleges.

In the new structure, the WR program is administered by a single college: the College of Agricultural & Life Sciences. The intent was to retain WR as a university-wide program, but to realize efficiencies in the administrative structure. The program is currently undergoing a faculty-driven refocusing effort to ensure the long-term sustainability of the successful graduate program, an effort that has received the support of the President, Provost, Vice President for Research and Economic Development, and Colleges with faculty members in the program. A parallel effort to organize and focus student activities was initiated by a group of highly motivated students with the formation of the H2IdahO water resources student club in 2015. The club is a formal chapter of the International Association for Hydro-Environment Engineering and Research (IAHR) and students have applied to be joint chapter of the AWRA. Student activities to date have been the organization of a statewide seminar series, social gatherings that have been coordinated with recruiting and fundraising events, and informal collaborations with other nearby student chapters.

Degrees are offered in WR Engineering & Science, WR Science & Management, and WR Law, Management, and Policy at both the M.S. and Ph.D. levels. Students also have the option of completing a concurrent J.D. degree in Law. The program's focus is on teaching students interdisciplinary approaches to understanding and solving integrated water resources problems. WR is a university-wide program with an enrollment of approximately 40 students in any given year. The WR Program has no directly appointed faculty members, rather participating faculty in the program are self-selected and drawn from eight different Colleges across the University.

Institutional support for the program includes a part-time director and administrative staff as well as a common office and conference room. The program relies exclusively on voluntary contributions of faculty time and resources for programmatic activities. Research and teaching facilities are spread across the University as a result of the interdisciplinary nature of the program's curriculum and faculty. The long-term viability of these physical resources is tied to the university as a whole. As a campus-wide program, WR relies on voluntary faculty participation and their grant productivity to enroll graduate students. In addition, core courses for the program are taught by affiliated faculty without direct support through WR. Currently 57 faculty from eight colleges self-identify with the WR program although the level of involvement between faculty members varies greatly. Because the program itself has no financial resources to support student stipends or faculty contributions, the motivation for faculty to be involved is a combination of egoism, altruism, collectivism and principlism. Institutionally there are very

few restrictions for faculty involvement. For example, students advised in the WR program are double counted with WR and the home unit of the advising faculty, and grants and publications obtained through interdisciplinary activities are generally recognized. However, the level of encouragement or disincentivization in interdisciplinary activities such as the WR program varies widely with the institutional home units of participating faculty, and is mostly determined by the viewpoints of individual faculty member's direct supervisors (department heads and deans).

Enrollment is limited primarily by external funds. Graduate students have been funded through a combination of SE grants, including the NSF GK-12 and NSF IGERT, and through funding obtained by major advisors (see table 2). A limited number of students have been supported through disciplinary college or departmental research and teaching assistantships, and some students have partially carried the educational costs themselves.

ii) Inter- and disciplinary contributions

The UI WR Program is focused around strengths in food, biophysical and human systems research. Research at the food-water nexus includes strengths in

Table 2. Major funding for research and student support at the University of Idaho with titles of funded projects and names of water program faculty leadership who were principal investigators, co-investigators, or collaborators.

Program	Project title and faculty names
Internal funding from institution	Waters of the West (Blue Ribbon, 2006).
USGS Northwest Climate Science Center	Projecting climate change effects on aspen distribution and productivity in the central and northern Rockies by coupling hydrological and landscape-disturbance models (Link).
USGS	Lewiston Orchards Projects (Kennedy).
EPA	Program 319: Lapwai Creek (Cosens, Boll, Strand).
Palouse Basin Aquifer Committee (PBAC)	Development of the Palouse Basin Participatory Model (Fiedler, Cosens, Beall, Boll).
NSF IGERT	Adaptation to change in water resources (Boll, Link, Cosens, Kennedy, Tracy).
NSF GK-12	GK-12 project in water resources for middle and high schools in rural northern Idaho and eastern Washington (Boll, Williams, Allen).
USDA-NIFA	Synthesis and analysis of 13 CEAP projects (Boll, Brooks, Wulfhorst, Mahler).
NSF Funded National Socio-Environmental Synthesis Center	Social-Ecological System Resilience, Climate Change and Adaptive Water Governance (Cosens, Fremier and others from throughout the United States)

aquaculture, the demand, design and water quality associated with irrigated agriculture, and growing strength in the development of water re-use and treatment technology. Research in the biophysical system includes fish population dynamics, the linkage between physical and ecological processes, and growing strength in the application of climate science to regional water supply predictions and development of natural resources management challenges. Researchers in the human systems cluster generally collaborate with faculty in the food and biophysical system clusters. With the unique inclusion of a law school in the program, research strengths include the integration of law and science to develop models for water law reform to account for ecosystem dynamics, climate change, and drought.

iii) Past and current SE projects

Two initial integrated projects of the Waters of the West program were used to develop team-based research methodology between faculty and WR students. The first project was on management of the water supply for the entities relying on a declining aquifer, the Palouse Basin Aquifer, serving the University of Idaho, Washington State University, and surrounding communities. This problem used a participatory systems approach to characterize the long-term behavior of a basalt aquifer, and evaluated aquifer stabilization based on water conservation and new source development (Beall *et al.* 2011). Graduate students and faculty used population and hydrogeologic data to conceptualize the problem, conceptual engineering design of new surface water sources, conservation methods, and social science data on public attitudes toward conservation. The second project was on anadromous steelhead trout (*Oncorhynchus mykiss*) recovery efforts on Lapwai Creek, a tributary to the Clearwater River within the Nez Perce Indian Reservation in north-central Idaho. The problem required integration of quantitative and qualitative information across multiple disciplines. Students used GIS to compare diverse datasets, and analyzed floodplain dynamics and steelhead habitat. Both projects became case study examples in the Interdisciplinary Methods in Water Resources course (described under dimension *iv*).

Building on these initial projects, the NSF-IGERT project titled “Adaptation to change in water resources: Science to inform decision-making across disciplines, cultures and scales” provides training to 25 Ph.D. students in the WR Program on team-based integrated research. The visions for the traineeships are to prepare doctoral students to be effective at research integration and to enter the workforce trained in professionalism and work ethic, communication, collaboration and teamwork, and critical thinking and problem-solving skills. The overall project goal is to train future scientists to

address complex interactions and feedbacks in physical, ecological, and social systems resulting from the combined impacts of climate change and human population dynamics, and to use collaborative skills to develop adaptation strategies. Adaptation scenarios will evaluate short- and long-term effects of climate change and population dynamics on water supply and demand, while assimilating feedbacks such as future changes in infrastructure, legal and institutional structures, and ecological responses. The IGERT Program will institutionalize innovative training components as part of the WR program to increase and sustain the impact of the program after the grant ends in 2019.

A synthesis project on law and science through the National Socio-Environmental Synthesis Center (SESYNC) (Cosens and Gunderson 2013) has resulted in a publication of six water basin resilience assessments (Cosens *et al.* 2014), and synthesis articles on the project including the role of law in adaptation are currently in review for a special issue in ecology and society (Cosens *et al.* 2016). These and additional major projects supporting interdisciplinary water resources research and training are listed in Table 2.

iv) Curriculum with signature methods, courses, ethics.

In 2007, the faculty started to teach the program's signature course Interdisciplinary Methods in Water Resources (Cosens *et al.* 2011). The course is designed to introduce students to the disciplinary building blocks of water resources and methods of integration across these disciplines to solve emerging water problems. In the disciplinary portion of the course, students learn a concept from Repko (2011) termed "disciplinary adequacy." This is the minimum an interdisciplinary researcher must know in a secondary discipline to achieve effective integration whether alone or with a team. Introductory disciplinary lectures in the course are a starting point towards reaching disciplinary adequacy by providing an introduction to the methods, values, viewpoints, and emerging questions of a particular discipline, as well as introducing students to the faculty who teach and do research in that area. The interdisciplinary methods section of the course has been developed with the recognition that there is no single methodology, tool, cookbook, or approach to interdisciplinary research, and focuses on the steps that can be taken to improve the process of integration. Students are introduced to "tools" that include concept mapping, the development of cross-disciplinary integrating questions, systems modeling, and dialogue methods. Because the UI WP Program focuses on team-based research and many research projects involve interaction with stakeholders, the interdisciplinary methods section of the course includes exercises in cross-disciplinary communication (Eigenbrode *et al.* 2007; Looney *et al.* 2014), and ways to manage meetings, conflict, and group dynamics. The course is currently

being used to test a module focused on ethics related to stakeholder based research under an NSF grant in which Cosens and Boll are participants (O'Rourke 2013) Students apply these concepts in two team-based projects developed from aspects of faculty/student research within the program. Group reports and presentations must include not only a solution or steps toward a solution to the problem presented, but the methodologies used by the team for integration and reflection on the challenges faced.

As noted above, the program offers degrees in: Engineering & Science, Science & Management, and Law, Management & Policy. Each option area requires students to complete a set of common core courses in addition to degree requirements specific to the chosen option area. Given the emphasis on depth in a water resource subject area and breath in interdisciplinary areas, both M.S. and Ph.D. degrees have higher credit requirements for course work than those of the College of Graduate Studies. In addition, students may pursue a concurrent J.D. with either an M.S. or Ph.D. degree. The Engineering & Science curriculum option area meets certification criteria established by AIH for the Professional Hydrologist certification exam and are consistent with the basic math and science requirements for the Fundamentals of Engineering & Professional Engineer exams. Curriculum requirements for the Science & Management area are consistent with certification criteria established by the US Office of Personnel Management for qualification standards for the Hydrology Series (GS-1315). Curriculum requirements for the concurrent J.D. degrees are consistent with the requirements to sit for a state bar exam and equivalent to the general requirements for a J.D. from the UI College of Law.

v) Thesis/dissertation requirements

Water resources thesis and dissertations reflect integration beyond a single discipline. Integration can be achieved throughout the thesis/dissertation, or through a separate interdisciplinary chapter that specifically integrates methods and/or information from at least two distinct disciplines to advance the argument(s) in the thesis/dissertation. All chapters are to be integrated into a coherent whole. Each student evaluates the interdisciplinarity of their thesis/dissertation, at the proposal stage by completing the Interdisciplinary Thesis/Dissertation Proposal Approval form, and prior to the final defense by completing the Interdisciplinary Thesis/Dissertation Approval Form. One distinctive aspect of UI theses and dissertations is that interdisciplinary chapters may be co-authored by two or more students. The interdisciplinary chapter may therefore be lead authored by a student other than the primary author of the thesis/dissertation, provided that the student was substantively involved in the research and that the graduate committee approves of the inclusion of the chapter in the final document.

vi) Faculty and student characteristics

A poll of students regarding how the program assisted them in helping to reach their goals varied widely, with answers focusing on the interdisciplinary nature of the program being most common. Program strengths included: the ability to develop technical depth in the latest sciences, polish teamwork abilities, and use cutting edge technology. Some students have already had success finding employment before graduating, while others stated that their current education is greatly improving their future prospects. Excellent faculty and the interdisciplinary nature of the program were the most common strong points mentioned by students. Others mentioned UI's location, the range of people and talents in the program, and the program's recent word of mouth recruiting of other high caliber talent. Current perceived weaknesses of the WR program were the lack of diversity in students and faculty and disruptions due to internal administrative changes. Noted needs included more curriculum choices, updated course offerings in-line with current science, better cross-listing of courses, better degree planning, more social cohesiveness and coordination and expansion of experiential learning, teaching, and research opportunities within the program.

vii) Markets for students

Graduates of the program have consistently secured gainful employment in academia, federal and state agencies, private consulting, Native American tribes, law firms, and non-profit organizations. In several cases, graduates were hired because of the interdisciplinary training in the water resources field. A network of graduates of this program exists, showing continued cohesion beyond the life of the program.

Synthesis

We have found that the benefits of strong interdisciplinary programs are multi-fold. These programs attract highly motivated, engaged students and faculty members with a passion to integrate their scholarship with pressing societal needs. As a result, effective programs can produce practitioners trained in professionalism and work ethic, communication, collaboration and teamwork, and critical thinking and problem-solving skills. The development of such programs can be challenging due to institutional inertia, therefore we conclude this paper with a synthesis of lessons learned from our collective programs and a suggestion for future directions to learn from previous programmatic challenges and successes. Our experiences over the past decade have identified five key elements of a successful interdisciplinary program: 1) effective leadership; 2) an institutional culture of collaboration; 3) resources; 4) institutional support and

assistance in development of administrative structure compatible with the institution, and 5) internal and external communication. Absence of any one of these components makes the program vulnerable and at risk in terms of program sustainability.

Leadership

Not only our own experiences, but our experiences as external reviewers of other programs underscore the importance of energetic, passionate leadership for successful interdisciplinary programs. Faculty involved in leadership of interdisciplinary programs and initiatives are not merely gifted administrators, though administrative ability is an important shared attribute. The faculty leadership in successful interdisciplinary programs also help create and fund opportunities for interdisciplinary research and education through collaboration with colleagues on collaborative grants. However, leadership must be shared by the faculty (with Associate Directors and committee involvement of the regular faculty) to prevent “burnout” and to help maintain a high level of engagement among the faculty participating in the program.

Institutional culture of collaboration

For interdisciplinary programs to flourish, there must be interdisciplinary research projects for students to experience interdisciplinary research. Such projects emerge from and then foster a culture that values collaboration at the institution. Collaboration in development of university-wide curriculum can help promote efficiency in delivery of coursework by eliminating redundancy in course offerings and helping courses that are taught to achieve sufficient enrollment. Conceptual models for the OSU degree program in WRE, and for the UI WR programs are shown in figures 2a and b, respectively. Departments and colleges deliver their own departmental degrees and collaborate to deliver the interdisciplinary degree in WRE with course offerings, advising, and service on student committees across colleges. Faculty collaboration can be facilitated through strategic hiring where active members of interdisciplinary programs are deliberately recruited to serve on relevant faculty search committees to evaluate applicants and communicate the collaborative culture of an institution. This serves to both identify potential hires who will actively engage in interdisciplinary programs and encourage desired applicants to accept a position offer. Institutions can also create a culture of collaboration at the student level which can train students in methods of collaboration and integration to be effective interdisciplinary team members post-graduation (Pinter *et al.* 2013). The acceptance of co-authored thesis and dissertation chapters by the UI College of Graduate studies is one example of how an institutional culture of collaboration was developed.

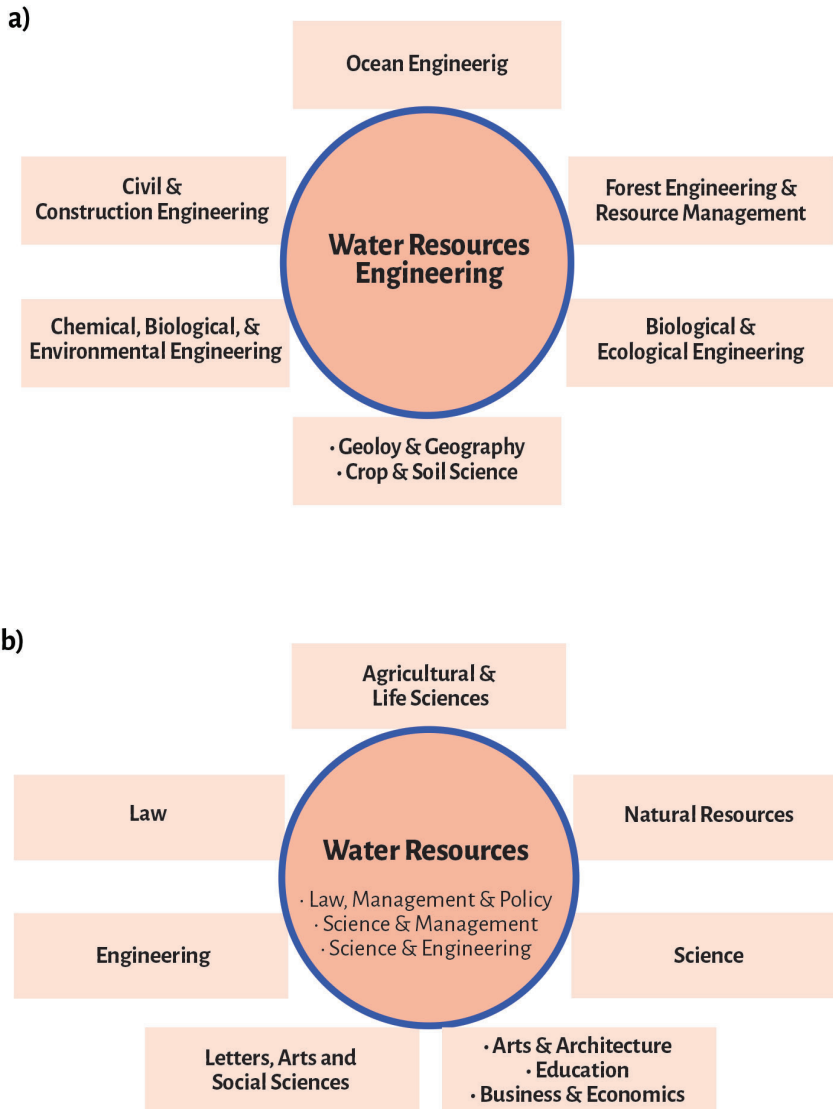


Figure 2. a) Conceptual model of the collaboration across units at OSU whose faculty advise and teach students in engineering degree programs for delivery of both the interdisciplinary Water Resource Engineering degree (WRE) and their disciplinary graduate degrees (in boxes). Similar models exist for the WRS and WRPM degrees. b) Conceptual model of the collaboration across colleges at UI whose faculty advise and teach students in the Water Resources degree programs. A key feature of both programs is that each department shares in the delivery of the WRE degree but does not “own” that degree, and that the breadth of faculty experience and coursework available for the WRE degree is enhanced by participation among units.

Resources

Financial resources are required for support of the program administration and to support students and faculty efforts in interdisciplinary teaching and research. Most programs receive some central institutional support for administration as well as space allocation and access to scholarships and assistantships for students. Such financial support is critical. Without resources and commitment from the institution to continue to support successful interdisciplinary programs, these programs can simply become, as one colleague put it “a treadmill for the naive”.

Institutional support

Financial support is only one aspect of institutional support. The recognition of an interdisciplinary program as a valuable component of the university or institution is essential. The reward system within colleges and promotion and tenure for faculty actively involved in interdisciplinary programs must be aligned with the value system at the institution. For example, at UI annual position descriptions were modified to include a section for faculty members to describe and formally receive credit for their engagement with interdisciplinary activities which is especially important for pre-tenure faculty members (Benson *et al.* 2015). When college and departmental leadership value and support interdisciplinary programs, they look out for those programs during times of institutional change, and can be creative in developing administrative and budgeting structures that are not in conflict with departments and other units. Without such commitment, when resources become scarce the interdisciplinary programs are simply unfunded or merged into other entities and wither away.

Communications

The four key elements identified above are necessary but not sufficient for successful interdisciplinary programs. Ongoing efforts must also be made for “inreach” – communication within the institution to highlight the value of the interdisciplinary program. One must be able to answer the question “What’s in it for me?” for those involved at all levels —students, faculty, departments and units, and the university itself, to sustain a thriving program—. Efforts at outreach are also important to inform future employers and colleagues at other institutions of the program and the success of its faculty and students. Likewise, it is critical to engage external stakeholders so that information about critical needs can be used to adapt and evolve programs to maintain a high level of societal relevancy. Communicating the value of interdisciplinary research, for example, the improved understanding of social-ecological systems that can

provide guidance for decision-making, is an important motivation for developing and sustaining interdisciplinary educational programs.

Future recommendation: Database for interdisciplinary graduate programs

In addition to the two graduate programs in this paper, many programs in the SE sciences exist each with characteristic program dimensions. The National Council for Science and the Environment has previously compiled information on curriculum and leadership of environmental programs (see NCSE 2016; Vincent 2010, 2013) including undergraduate and graduate programs. We are aware of additional graduate programs in water resources in the US and Canada (see CUAHSI 2016; UCOWR 2016). We recommend that further information on the seven program dimensions for similar programs throughout the world be compiled in a database to facilitate sharing of information on lessons learned and how challenges and barriers towards interdisciplinary education programs are being solved in similar programs. Such an effort could greatly facilitate the development of new programs and sustainability of existing programs by providing suggestions for how to effectively address common sets of challenges that are encountered by interdisciplinary SE programs.

Conclusions

Seven program dimensions characterized elements of two interdisciplinary graduate degree programs in the US. These programs are located in land-grant universities with strong research, education, and outreach missions with more or less stable administrative homes related to existing water centers and colleges. Each university provided the disciplinary depth in terms of course work and faculty expertise for the programs to create interdisciplinary breadth with new courses and experiences through SE projects. A high percentage of graduates from these programs found jobs or continued on in academic training at a higher degree level.

Our experiences with these programs over many years also identify elements needed for long-term success of interdisciplinary programs. These include the need for strong and energetic leadership, a strong culture of collaboration at the institutional level, financial resources for program administration and student/faculty efforts to engage in interdisciplinary research and teaching, and institutional support in rewarding participation and securing a stable and supportive administrative home. Finally, the value of interdisciplinary programs must be communicated continually within and outside the university to maintain the levels of participation and support, nurture relationships with stakeholders, and maintain societal relevancy. ■

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