Center for Advanced Decision Support for Water and Environmental Systems (CADSWES)

UNIVERSITY OF COLORADO **BOULDER**

2018 Annual Report

CADSWES, founded in 1986, is a Research Center within the College of Engineering and the Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder. www.colorado.edu/cadswes

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1. Overview

CADSWES research focuses on natural resource management, particularly the sustainable management of multi-objective water resource systems for planning and operations, climate change adaptation, policy analysis, improved short and long term forecasting under hydrologic variability, and hydropower optimization.

CADSWES R&D is sponsored primarily by the Bureau of Reclamation, U.S. Army Corps of Engineers and the Tennessee Valley Authority for development of modeling techniques and decision support software products, research to improve management of large river and reservoir systems, decision-making for uncertain future conditions, hydropower optimization and applications.

Enhancements to, and applications of the RiverWare modeling system and associated software are the primary focus of CADSWES R&D. As the use of the tools expands, the need for more advanced capabilities evolves. The RiverWare software has become a widely used tool in the U.S. and has a growing number of users abroad. With increasing number of users, technology transfer continued to be a major part of the activities in 2018.

The Center's research and development emphasis continued to be a strong platform for graduate student education – building the next generation of sustainability focused natural resource researchers and practitioners. Projects in mid-term operational and long-term planning models and Streamflow forecast testbed for the Colorado River Basin, multi objective evolutionary algorithms for robust decision making under deep uncertainty and regionally relevant tradeoffs provided graduate student research.

CADSWES faculty, as part of the Department of Civil, Environmental and Architectural Engineering, participate in collaborative research and teaching within the Department and College.

2. Research Projects

The following research projects were carried out by graduate students with faculty affiliated with CADSWES.

Colorado River Basin Streamflow Forecast Testbed

Sponsor: Bureau of Reclamation Lower Colorado Region
Sarah Baker Ph.D. candidate, Principal Investigators B. Rajagopalan (CEAE) and E. Zagona (CEAE/CADSWES), A. Wood (NCAR) and J. Prairie (Bureau of Reclamation – UC)

A testbed was developed using Reclamation's Mid-Term Probabilistic Operations Model (MTOM) to assess streamflow forecasts and operational projections in the Colorado River Basin for a Master's Report project. The current uncertainty and error of out-year (lead times beyond current year) streamflow forecasts and operational projections were assessed. A testbed was then created to establish a protocol for testing the performance of streamflow forecasts and modeled operational projections. Operational forecasts such as ensemble streamflow prediction (ESP) and research-grade streamflow forecasts are now being evaluated in the testbed to determine the skill of alternative streamflow forecasts.

Colorado River Basin Decision Making Under Deep Uncertainty

Sponsor: Bureau of Reclamation Upper and Lower Colorado Regions
Elliot Alexander, M.S. Student, Principal Investigators: J. Kasprzyk (CEAE) and E. Zagona CEAE/CADSWES)
Bureau of Reclamation: C. Jerla and A. Butler (BOR-LC) and J. Prairie (BOR-UC)

Classical decision-making frameworks have aided water managers in selecting an optimal water resources plan. These methods are applicable when dealing with simple systems and well-understood uncertainties impacting the system. As water resources systems and models become more complex and the future climatic conditions are poorly known, the classical decision-making frameworks don't hold up. In deeply uncertain conditions, it is more appropriate to strive for multiple robust water resources plans rather than an optimal plan. The focus of this research is to create an adaptive planning framework that uses the Borg multi-objective evolutionary algorithm (MOEA) coupled with the Colorado River Simulations System (CRSS) RiverWare model to explore how possible policy alternatives meet multiple objectives and are robust to unknown future conditions.

Mid-term operational and Long- term planning for the Colorado River

Sponsor: Bureau of Reclamation UC through a Pathways appointment for Conor Felletter.
Conor Felletter, M.S. Student, Principal Investigators: J. Prairie (BOR-UC), E. Zagona (CEAE/CADSWES) and B. Rajagopalan (CEAE)

This project develops a protocol for comparing the performance of two of the Bureau of Reclamation's (Reclamation) mid-term models of the Colorado River Basin (CRB) and applies it at two reservoirs along the Green River. The protocol assesses the current skill and reliability of inflow ensembles used to drive the models and the accuracy of operational projections generated by the models. The project quantifies performance with two sets of metrics, hydrology metrics and operational metrics. Results from the comparison are used to make initial recommendations about updates to the model's operational rule logic. Future work will extend this protocol to the entire CRB and provide guidance about which models' operational projections should be used for Reclamation's mid-term projections.

Flexibility Analysis for Hydropower Systems

Sponsor: CADSWES Research Initiatives
Sumi Thapa, M.S. Student, Principal Investigators: T. Magee (CADSWES) and E Zagona (CEAE/CADSWES)

Hydropower systems – river and reservoir systems with multiple hydropower plants – typically must provide some operating reserves to the grid for correcting energy and demand imbalances. But these systems may also seek to maintain some additional flexibility in order to sell extra energy if prices are high, or to avoid producing energy that they would have to sell at a disadvantage. This operational flexibility of the hydro system must comply with other operating objectives such as spill constraints and forebay target elevations. This study aims to analyze the effects of typical hydropower system operating policies and system characteristics on operational flexibility that could be used for increasing net power revenues.

Robust Operations for Klamath River Basin

Funded by Bureau of Reclamation Technical Services Center Policy Office
Mitchell Frischmeyer, M.S. Student; Principal Investigator: E Zagona (CEAE/CADSWES), and David Neumann (CADSWES); in collaboration

Due to changing hydrologic conditions as well as changing demands and environmental regulations, river basins in the Western US and elsewhere need to revise their operating policies and implement new types of policies that are robust to uncertain future changing conditions. Further, water managers need decision support tools for planning and operating the systems, and for communicating operations and policies to stakeholders. This project seeks to assess existing tools and management strategies used by water managers in the Klamath Basin Area Office (KBAO), and extend the tools and findings of the Pilot Study and Basin Study by further developing and testing the existing RiverWare model so that it may be used for daily operations. The work involves understanding the current operations including changes for the 2013 Biological Opinion, and in collaboration with TSC and KBAO, develop a model, test results and explore alternative operations, and develop methods and tools for communicating model results with the stakeholder community.

3. Decision Support Software

A major activity of CADSWES is research and development of decision support software, funded by water management agencies, and used widely by the water management community. RiverWare is the flagship product and other DSS tools extend the capabilities in various ways.

RiverWare

RiverWare®, a river and reservoir modeling tool for operational scheduling and forecasting, basin planning, policy evaluation and other operational analysis and decision processes, has been developed at CADSWES since 1993, funded by the Bureau of Reclamation, the Tennessee Valley Authority and the U.S. Army Corps of Engineers. Each year, sponsors fund new enhancements. Additional software upgrades, releases and maintenance are supported through the license revenues. See riverware.org for detailed description of the software.

Three major RiverWare releases 7.2, 7.3 and 7.4 and 9 patch releases were issued in 2018. Notable enhancements included:

- Groundwater-surface water modeling was enhanced to include deep groundwater aquifer interactions. This adds to the previous shallow groundwater interactions that influence surface water dynamics in many river basins. The deep groundwater model can be used in lieu of coupling a groundwater model such as MODFLOW.
- Computational timestep sizes were extended to include 5-minute and 15-minute increments, this in support of real time hydropower optimization applications by utilities on the Middle Columbia River. Previously the timestep sizes ranged from hourly to yearly.
- Collaborative modeling efforts were further supported by the development of model comparison tools that allows different versions of models and policy logic to be compared and merged.
- A scripting dashboard was developed to allow specification of modeling tasks for use by operators or others who must complete multiple steps in data loading, date adjustments, model execution, output processing, etc.

Integration of RiverWare with other Software and Modeling Platforms

The Corps Water Management Systems (CWMS) is a database and modeling platform developed and used by the U.S. Army Corps of Engineers (USACE) for real time flood control management. A RiverWare plugin allows Corps modelers to use RiverWare for reservoir management in the suite of models.

RiverWare is tightly integrated with the graphical user interface, execution and databases. In 2018 additional native RiverWare user interface features were made available in the CWMS interface.

USACE RTS – Real Time Simulation – is the public version of CWMS. A RiverWare plugin was developed and released for RTS in 2018.

USACE HEC-WAT – Hydrologic Engineering Center Watershed Analysis Tool is the USACE modeling framework for integrated multi-disciplinary water resources studies. In 2018 CADSWES designed a plugin to integrate RiverWare into WAT.

FEWS – the Deltares Flood Early Warning System – is a database, modeling and graphical interface platform widely used by the National Weather Service and major RiverWare users such as Bonneville Power Administration and Tennessee Valley Authority. In 2018 enhancements were made to correctly and automatically account for daylight savings time changes during RiverWare simulations within FEWS.

Borg-RiverWare Wrapper – "The Borg Multiobjective Evolutionary Algorithm (MOEA) is a state-of-the-art optimization algorithm developed by David Hadka and Patrick Reed at the Pennsylvania State University. It captures the tradeoffs between many conflicting performance objectives, providing decisions makers with detailed insight into their problem characteristics." (borgmoea.org). Coupling RiverWare with Borg provides a powerful multi-objective simulation-based optimization that can inform decisions on infrastructure and operating policies. In 2018 a software wrapper was developed to allow researchers to apply the techniques in several studies.

Other Software DSS Tools

RiverSMART – the RiverWare Study Manager and Research Tool – is an integrated set of tools and techniques to facilitate large planning studies the consider multiple future hydrologic and demand scenarios, possible future operating policies to identify possible strategies to address long term supply demand imbalances and other challenges. Developed with funding from the Department of Interior's WaterSMART Program, this software has been used extensively by Reclamation for the federally mandated Basin Studies. In 2018 enhancements supported the use of these tools by two Reclamation-funded research projects at CADSWES primarily to facilitate scenario management.

Demand Input Tool – DIT – manages all the demand data for the Colorado River Basin. In addition to the official demands, it allows users to create alternative demand scenario for the future, organizing the data by geographic location and sector (agriculture, energy, etc.). The Excel based tool can automatically populate Reclamation's Colorado River Simulation System, the long-term planning model of the basin. In 2018, the Excel DB was converted to MS Access and a new relational data schema was developed in preparation for future software transition away from Excel to a database centered implementation.

RiverWISE –the RiverWare Interactive Scenario Explorer – was designed and the prototype developed and tested in 2018. This tool allows stakeholders without a RiverWare license or training to easily change inputs and run and compare scenarios, and share these with others.

RiverWare User Community

RiverWare has been licensed through the CU Technology Transfer Office since 1998. In 2018 RiverWare was used by TVA River Operations in Knoxville, TN, by 26 offices of the Bureau of Reclamation, 13 offices of the Army Corps of Engineers, and 100 other entities including federal agencies, states, cities, water districts, utilities, NGOs, academic institutions, consulting companies and foreign entities from the

countries of Canada, Egypt, England, Ethiopia, India, Germany, Mexico, Sri Lanka and Sudan and Tajikistan. 18 new entities acquired the RiverWare software during the year.

4. Presentations, Conferences, Visitors and Outreach

Presentations:

February 1 and 2, CADSWES hosted the 2018 RiverWare User Group Meeting. 19 presentations were given by members throughout the RiverWare user community as well as by CADSWES members. The list of presenters and links to abstracts are available on the RiverWare website here.

CEAE Classes: Dr. Zagona and David Neumann assisted Professor Kasprzyk in teaching CVEN 5423 Water Resource Engineering during the 2018 spring and fall semesters, including providing support and guidance to students on class projects using RiverWare.

Mitch Clement presented at the 2nd International Meeting on Decision Support Processes for Participatory Water Management: building capabilities in Europe, Latin America and the Caribbean, April 17 – 19 in Valencia Spain. Mitch's presentation, "The use of RiverWare as a decision support tool in basins with a variety of operational objectives," was well received. He also taught a 3 day workshop on RiverWare to attendees, professional water managers, university faculty and students.

Dr. Zagona was invited to give several presentations in China during the 60th Anniversary celebration of the China Institute of Water and Hydropower Research (IWHR) in Beijing in October, giving a keynote address for the International Symposium on Water System Operations, as well as at the Chinese Hydraulic Engineering Society in Nanchange.

Dr. Zagona attended the AGU Fall 2018 conference in Washington DC, December 10 – 14. MS student Elliot Alexander and PhD student Sarah Baker both presented their research work at the conference. Use this link to see their presentations.

Visitors and Outreach:

- January22, NCAR scientist Tom Hopson and guests from Ethiopian Construction Works Group and the Hydrology and Hydro Department visited CADSWES. A demo of RiverWare capabilities was provided.
- January 31, CADSWES hosted the annual RiverWare Sponsor's research and development meeting. 2017 accomplishments were reviewed and plans made for 2018. The meeting was attended by 20 people from the Bureau of Reclamation, US Army Corps of Engineers, and TVA, the three RiverWare sponsoring agencies, as well as 10 people from CADSWES.
- February 9, 3 Engineers from Grant County Public Utility District (Washington) visited to discuss the scope of work for the next phase of their project to develop a new hydropower optimization model to manage their resources on the Mid-Columbia River.
- May 1-3, 4 Water managers and engineers from Chelan County PUD visited CADSWES to discuss their RiverWare hydropower optimization model and scope of work to be done for the new project initiated at that time.
- June 22, Tom Hopson, from NCAR brought 3 representatives from Bihar India to get a demo of RiverWare capabilities.
- September 18, two members of Aqualytics Inc in Los Angeles CA came for a RiverWare demonstration and to discuss their modeling needs.

- September 20, 5 researchers from Escuela Superior Politecnica del Litoral (ESPOL) in Guayaquil Ecuador came for a demonstration of RiverWare and to share their goals.
- October 24, a representative from the State of UT came to discuss work to be done with RiverWare for a large state wide study.

5. Publications

Journal Articles

Basheer, M., Wheeler, K., Ribbe, L., Majdalawi, M., Abdo, G., & Zagona, E. (2018). Quantifying and Evaluating the Impacts of Cooperation in Transboundary River Basins on the Water-Energy-Food Nexus: The Blue Nile Basin, *Science of The Total Environment*, Volume 630 (15 July 2018), 1309-1323, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2018.02.249 (https://www.sciencedirect.com/science/article/pii/S004896971830648X).

Wheeler, K. G., J. W. Hall, G. M. Abdo, S. J. Dadson, J. R. Kasprzyk, R. Smith, and E. A. Zagona, (2018). Exploring Cooperative Transboundary River Management Strategies for the Eastern Nile Basin, *Water Resources Research*, 54, 9224–9254. (https://doi.org/10.1029/2017WR022149).

Master's Thesis:

On July 26, Elliot Alexander successfully defended his M.S. Thesis Searching for a Robust Operation of Lake Mead, Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO.

Published Abstracts and Conference Paper Presentations

Wheeler, K. G., Hall, J. W., Abdo, G. M., Dadson, S. J., Kasprzyk, J. R., Smith, R., &Zagona, E. A. (2018), Negotiating coordination within transboundary rivers: The Nile and the Grand Ethiopian Renaissance Dam, Abstract H13F-06 presented at the 2018 Fall Meeting, American Geophysical Union, Washington D.C., December 10-14.

Alexander, E., J. Kasprzyk, E. Zagona, J. Prairie, C. Jerla, A. Butler (2018), Generating and identifying Robust Lake Mead Operating Policies Using many Objective Robust Decision Making, Abstract G52F-03, presented at 2018 Fall Meeting, American Geophysical Union, Washington D.C., December 10-14.

Baker, S., J. Prairie, C. Jerla, A. Butler, E. Zagona, B. Rajagopalan, A. Wood (2018), A Testbed to Analyze Colorado River Streamflow Forecasts and Operational Projections, presented at the 2018 Fall Meeting, American Geophysical Union Fall Meeting, Washington D.C., December 10-14.

6. Technology Transfer

CADSWES held 8 3-day RiverWare training classes at CADSWES in 2018: 4 Introduction to Simulation, 2 Rulebased Simulation and 2 Water Accounting training classes. They were attended by 86 people, 36 from sponsoring agencies (Reclamation and Corps of Engineers) and 50 from other organizations including city and state water management agencies, consulting companies, research labs and utilities.

CADSWES facilitated 3 onsite specialty classes for 51 attendees in 2018:

1. US Army Corps of Engineers in Albuquerque NM sponsored 29 people from the surrounding area agencies and academia to improve modeling capabilities. US International Boundary Water Commission in El Paso TX hosted the two day training session February 7 – 8.
2. Mahaweli Water Security Investment Program in Colombo Sri Lanka sent 5 of their previously trained modelers for a customized 5 day "Advanced River System Modeling" session at CADSWES February 26 – March 2. Their consultant from Lahmeyer International also joined them.
3. Bonneville Power Administration in Portland OR had a customized training session for 16 members of 3 of their power generation groups, Short Term, Long Term and Real Time planning, May 15 – 17.

7. Personnel

The CADSWES R&D team includes:
Director: Edie Zagona, Research Professor, CEAE
Affiliated Faculty: CEAE Professor Balaji Rajagopalan and Assistant Professor Joe Kasprzyk
Research Associate: Tim Magee, Operations Research Analyst
Senior Professional Research Assistant: David Neumann, P.E., Water Resources Engineer
Senior Professional Research Assistant: Mitch Clement, P.E., Water Resources Engineer

Professional Research Assistants:
Robynn Balduf – Software Developer
Jessica Lee – Software Configuration
Patrick Lynn, PhD. – Software Developer
Bill Oakley – Software Developer
Jim Pasquotto – IT and Documentation Support
Nancy Stevens – Science Writer

Graduate Students:
Sarah Baker PhD student
Mitchell Frischmeyer M.S. student
Sumi Thapa M.S. student
Sarah Baker PhD student
Elliot Alexander MS Student (Reclamation Pathways program)
Conor Felletter MS Student (Reclamation Pathways program)

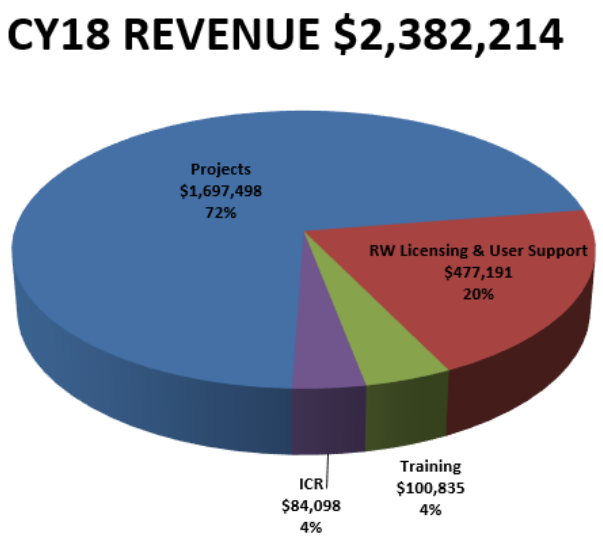
Exempt Professional Staff:
Kathryn Baack – Financial Coordinator
Gwen Miller – Tech Transfer Coordinator

The Bureau of Reclamation Boulder Duty Station shares space with CADSWES. Reclamation employees at this duty station are Alan Butler, Carly Jerla, Jessica Khaya, Rebecca Smith and Student Engineers in training Sarah Baker of the Lower Colorado Region. Jim Prairie, Elliot Alexander and Conor Felletter of the Upper Colorado Region.

8. Financials

CADSWES receives most of its funding through contracts and grants. Additional revenues are from the Technology Transfer Office as distributions for RiverWare software licenses, from payments for training classes provided to the users of our software tools, and from indirect cost return from the College of Engineering and Applied Science. Following are revenues and expenses for 2018.

Revenues



Expenses: