Appendix A: Colorado School of Mines, Materials Research Science and Engineering Center in Renewable Energy

Renewable Energy Materials Research Science and Engineering Center
Colorado School of Mines
CHECRA Grant: $400,000 (per year for 6 years)

Summary: The Materials Research Science and Engineering Center (MRSEC) at the School of Mines, under the leadership of Dr. Craig Taylor, is focused on investigating emerging renewable energy materials, such as enhancing solar panels through nanotechnology and improving membrane technologies important to renewable energy applications, such as batteries, fuel cells and electrolyzers.

Description of the project, the principal persons or entities involved in the project, and the amount of funding allocated to each principal person or entity

With annual global energy consumption expected to increase to as much as 30 terawatts by 2050 and mounting concerns over oil reserve depletion, energy security, and global warming, meeting world energy demand will be one of the grand challenges of the 21st century. While renewable and alternative technologies have the potential to address the most serious concerns with fossil fuels, cost is a major obstacle to their widespread deployment. There has been remarkable progress, for example, in lowering the price of photovoltaic (PV) electricity generation, yet present costs remain higher than electricity produced from coal. Similar price differentials exist when comparing fuel cells with conventional electricity generators. Estimates based on historical trends give several decades before many renewable technologies become competitive. Transformative technological innovation is the key to accelerating this time line and fundamental advances in materials science will spearhead this process.

The MRSEC consists of two Interdisciplinary Research Groups (IRGs). IRGI is concentrating on materials of potential use in the next generation of PV devices, but the scope of this IRG will be much broader since the systems of interest have important properties in common with a wide range of other electronic and opto-electronic materials. The important questions this IRG is attempting to answer involve the scattering and relaxation mechanisms that govern electronic transport in semiconducting materials of use in PV applications, especially mechanisms that are altered in nanostructured environments. These nanostructures include quantum wires and quantum dots, which have potential for significant improvements in efficiency by tuning the optical and electronic properties through size, composition, and surface termination, and by uniquely quantum mechanical effects, which offer possibilities for collecting solar radiation that is lost in conventional cells. The long-term research directions of this IRG are aimed at producing transformative changes in PV technology through significant improvements in materials properties that result from development of fundamental concepts for more efficient carrier generation and collection.

The second Group (IRG2) is concentrating on advanced membranes for renewable energy applications, with the scope being also much broader since the systems to be studied include polymers, ionic solids, and hybrid systems. Solid electrolyte materials and membrane technologies are central to many processes in the conversion, utilization, and storage of energy. Very frequently, ionic transport is the "weak link" in electrochemical energy storage or conversion systems. At present, the myriad interactions that occur in ion

transport membranes- ion-ion, ion-solvent, and ion-electrode-are poorly understood. Fundamental research is crucially needed to provide the knowledge required for the intelligent design of novel transport membranes with highly optimized properties. IRG2 is fabricating novel transformative ion conducting materials by synergistically combining materials with dramatically different ionic transport characteristics.

An additional research group involves the evaluation of clathrate structures as potential materials for renewable energy applications, such as hydrogen storage, photovoltaics, and membranes for ionic transport. Energy storage, and in particular storage of hydrogen or methane produced from renewable resources, is another area of research in renewable energy where transformative research is critical. Clathrate hydrates, with as much as 164 volumes of gas contained per volume of clathrate hydrate, present a potentially attractive class of energy storage compounds. Center scientists and engineers have succeeded in making silicon clathrate materials in larger volumes for our experiments in using these materials in solar cells. Recently, thin films of clathrate silicon have been produced. This accomplishment is significant because thin films are necessary in order to use these materials in solar cells.

In addition to the two research groups, funds were used to support "seed" grants on promising but very preliminary research projects. Four projects funded in 2014 were entitled: (1) II-IV-N_2: Developing a new class of optoelectronic materials, Eric Toberer and Adele Tamboli, (2) Band gap tuning of Silicon quantum Dots by peripheral attachment of conjugated organic semiconductor ligands, Alan Sellinger and Mark Lusk, (3) Oil and Water? Mixing Protons and Electrons in Oxides, Ryan O'Hayre, (4) Revolutionary proton conducting polymer films, Andy Herring.

Principal Senior Investigators	**Funding from CHECRA**
P. Craig Taylor, Director	$40, 000
Reuben Collins, Associate Director and Head IRG 1	$120,000
Andrew Herring, Head IRG2	$120,000
Carolyn Koh, Head, Seed Grant Program and Head IRG3	$120,000

The manner in which each principal person or entity applied the funding in connection with the project

P. Craig Taylor: Discretionary funding of promising new research directions.
Reuben Collins: Funding for films of silicon nanodots imbedded in an amorphous silicon matrix for improved solar cell materials
Andrew Herring: Funding for organic-inorganic nanostructured membranes for fuel cell and battery applications
Carolyn Koh: Funding of novel approaches to new materials for photovoltaic applications or membrane technologies. Funding for development of clathrate materials for renewable energy applications.

Results achieved

The success of center scientists relies on studies of state-of-the-art nanostructures. In the last year center scientists have demonstrated how growth parameters can be used to optimize crystallinity of the plasma synthesized Si quantum dots used in the Center's research. The synthesis process involves nucleation and growth of silicon quantum dots from a dilute silane gas flowing continuously through a capacitively coupled plasma inside a tube reactor. Center scientists are also actively investigating silicon nanocrystals imbedded in an amorphous Si matrix, known as hydrogenated nanocrystalline Si. Studies of photoluminescence and electron paramagnetic resonance quenching in state-of-the-art, conventional, hydrogenated nanocrystalline silicon films prepared by Plasma Enhanced Chemical Vapor Deposition (PECVD) have led to the exciting and surprising discovery of hot carrier transfer from the amorphous matrix to the Si nanoparticles. The successful basic research on hot carrier collection from a hydrogenated amorphous silicon matrix has been transferred to a separately funded applied project to make proof-of-principle PV devices. In addition, organic surface functionalization of silicon quantum dots has been explored theoretically as a first step toward building larger assemblies leading to a new form of silicon quantum dot/organic semiconductor meso-material.

In the polymeric systems research in the Center, the nexus of theory, synthesis, and characterization has produced membranes (ionomer/heteropolyacid nanocomposites) that perform well under low hydration and elevated temperature. Two promising heteropoly acid (HPA) dopants are $H_3PW_{12}O_{40}$ (HPW) and $H_4SiW_{12}O_{40}$, (HSiW), which upon addition to the 3M ionomer, enhance the stability and performance of the polymeric system. At a molecular level the combined computational and experimental approach has resulting in an enhanced understanding of how heteropoly acids (HPA) interact with the solvent in the perfluorosulfonic acid proton exchange membranes. In the case of the mixed-phase ceramics component of toe research in the Center, large-grained electrolytes with uniquely-passivated grain boundaries have been developed using a new approach to perovskite synthesis utilizing solid-state reactive sintering (SSRS) in the presence of appropriate additives. These additives enhance sintering/grain development and under reducing conditions can lead to unique nanocomposite systems with exceptional conductivity. This approach, substantiated by continuum-level theory, has yielded nano-composite perovskite oxides with record-setting proton conductivity at temperatures below 400 °C.

Center scientists have been able to produce large quantities (grams as opposed to milligrams) of an open cage (clathrate) structure that is made from silicon. Originally, these clathrate silicon materials were being used to test how much hydrogen could be stored and how easily it could be extracted. Currently Center members are making larger samples of silicon

and silicon- germanium clathrates and testing them as materials for solar cell applications. In particular theoretical calculations indicate that these forms of silicon an silicon-germanium exhibit direct optical band gaps, which means that they absorb light much better than the diamond silicon structure that is commonly in use for today's solar cells. Recently center scientists have been able to make thin films of these clathrate materials. This accomplishment is important because any electronic device, such as a solar cell, will require thin film geometries.

Publications in 2014:

Seed Funding- Partial CHECRA Support

- D. Clark, J. Tong, A. Morrissey, A. Almonsoori, I. Reimanis, and R. O'Hayre, "Anomalous low-temperature proton conductivity enhancement in a novel protonic nanocomposite", *Phys. Chem. Chem. Phys.*, **16** (11), 5076 – 5080, (2014) http://pubs.rsc.org/en/content/articlelanding/2014/cp/c4cp00468j#!divAbstract

- Deml, V. Stevanovic, C. Muhich, C. Musgrave, R. O'Hayre, "Oxide enthalpy of formation and band gap energy as accurate descriptors of oxygen vacancy formation energetics", *Energy and Env. Sci.* **7**(6), 1996-2004 (2014) http://pubs.rsc.org/en/content/articlelanding/2014/ee/c3ee43874k
- T. Tauer, R. O'Hayre, and W. Medlin, "Ab-initio investigation of proton stability at $BaZrO_3$ interfaces, *Chem. Mater.* **26** (17), 4915-4924 (2014). http://pubs.acs.org/doi/abs/10.1021/cm500035e

- A. Deml, V. Stevanovic, A. Holder, M. Sanders, R. O'Hayre, and C. Musgrave, "Tunable oxygen vacancy formation energetics in the complex perovskite oxide $Sr_xLa_{1-x}Mn_yAl_{1-y}O_3$", *Chem. Mater.* **26**(22), 6595-6602 (2014). http://pubs.acs.org/doi/abs/10.1021/cm5033755

- Li, H., Z. Lin, M.T. Lusk and Z. Wu., Charge Separation at Nanoscale Interfaces: Energy Level Alignment Include Two-Quasiparticle Interactions, Journal of Chemical Physics 141 154701 (2014) doi:10.1063/1.4898155

- • Fields, J.D., S. McMurray, L.R. Wienkes, J. Trask, C. Anderson, P.L. Miller, B.J. Simonds, J. Kakalios, U. Kortshagen, M.T. Lusk, R.T. Collins, P.C. Taylor, Quantum confinement in mixed phase silicon thin films grown by co-deposition plasma processing,Solar Energy Materials and Solar Cells 129 7-12 (2014) doi:10.1016/j.solmat.2013.10.028

- • Li, H., T. Zhou, Z. Wu, A. Sellinger and M. T. Lusk, Tailoring the Optical Gap of Silicon Quantum Dots without Changing Their Size, Physical Chemistry Chemical Physics 16 19275 (2014) doi:10.1039/C4CP03042G

- Bagolini, L., Mattoni, A., Collins, R. T., and M. T. Lusk and M. T. Lusk, Carrier Localization in Nanocrystalline Silicon, Journal of Physical Chemistry C 118 13417-13423 (2014) doi:10.1021/jp5024586

- "Editorial: Nobel Prizes honor ground-breaking innovations in applied science," R. T. Collins, Applied Physics Letters**105**, 1 (2014). http://scitation.aip.org/content/aip/journal/apl/105/20/10.1063/1.4902755?TRACK=RSS

- "Evidence for Anisotropic Mechanical Behavior and Nanoscale Chemical Heterogeneity in Cycled LiCoO2"D. Diercks, ECS Digital Library. http://jes.ecsdl.org/cgi/content/abstract/161/11/F3039. DOI 10.1149/2.0071411jes

- N-bromosuccinimide-based Bromination and Subsequent Functionalization of Hydrogen-terminated Silicon Quantum Dots , Jacob P. Bell, Jacqueline E. Cloud, Jifang Cheng, Chilan Ngo, Suneel Kodambaka, Alan Sellinger, S. Kim Ratanathanawongs Williams, and Yongan Yang, *RSC Adv.*, **4** (93), 51105 – 51110 (2014). http://pubs.rsc.org/en/content/articlelanding/2014/ra/c4ra08477b#!divCitation

- Colloidal Nanocrystals of Lithiated Group 14 Elements.Cloud, J. E., Wang, Y., Yoder, T. S., Taylor, L. W., & Yang, Y. *Angewandte Chemie International Edition*, ***53***(52), 14527-14532 (2014). http://onlinelibrary.wiley.com/doi/10.1002/anie.201408108/full

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- Interface for Light-Driven Electron Transfer by Photosynthetic Complexes across Block Copolymer Membranes, Liangju Kuang, Tien L. Olson, Su Lin, Marco Flores, Yunjiang Jiang, Wan Zheng, JoAnn C. Williams, James P. Allen, and Hongjun Liang J. Phys. Chem. Lett., **5,** 787-791 (2014). **DOI:** 10.1021/jz402766y http://pubs.acs.org/doi/abs/10.1021/jz402766y

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- *A simple and effective method for controllable synthesis of silver and silver oxide nanocrystals.* Jacqueline E. Cloud,[a] Lauren W. Taylor[a] and Yongan Yang, RSC Adv. **4,** 24551-24559 (2014). **DOI:** 10.1039/C4RA02882A http://pubs.rsc.org/en/content/articlelanding/2014/ra/c4ra02882a/unauth#!divAbstract

- *Composition Dependence of the Band Gap and Doping in Cu 2 O-Based Alloys as Predicted by an Extension of the Dilute-Defect Model,* V Stevanović, A Zakutayev, S Lany - Physical Review Applied **2,** 044005 (2014). http://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.2.044005

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- *Hidden spin polarization in inversion-symmetric bulk crystals.* X Zhang, Q Liu, JW Luo, AJ Freeman, A Zunger - Nature Physics **1o**, 387-393 (2014). doi:10.1038/nphys2933 http://www.nature.com/nphys/journal/v10/n5/abs/nphys2933.html

- *Control of the electrical properties in spinel oxides by manipulating the cation disorder,* P.F. Ndione, Y.Z. Shi, V. Stevanovic, A. Zakutayev, S. Lany, P.A. Parilla, J.D. Perkins, J.J. Berry, D.S. Ginley, and M.F. Toney,. *Advanced Functional Materials* **24**, 610-618 (2014). DOI: 10.1002/adfm.201302535

- *Control of doping in Cu2SnS3 through defects and alloying,* LL Baranowski, P Zawadzki, S Christensen, D. Nordlund, S. Lany, A. C. Tamboli, L. Gedvilas, D. S. Ginley, W. Tumas, E. S. Toberer, and A. Zajutayev, Chemistry of Materials **26**, 4951-4969 (2014). **DOI:** 10.1021/cm501339v

- *New insights into the properties determining oxygen vacancy formation energies in oxides,* AM Deml, Ph.D. Thesis, Colorado School of Mines (2014). http://digitool.library.colostate.edu/exlibris/dtl/d3_1/apache_media/L2V4bGlicmlzL2R0bC9kM18xL2FwYWNoZV9tZWRpYS8zNDEwNjU=.pdf

Education and Outreach - Partial CHECRA Support

- "Including Children with Disabilities in STEM: An Outreach Program for Dyslexic Students." , Wright, L. & Moskal, B.M., Proceedings of the Annual Meeting of the American Society for Engineering Education, Indianapolis, Indiana (2014).

- "Dyslexia and STEM." B. M. Moskal, Interview by Camp Spring Creek (December 2014), Available: https://campspringcreek.wordpress.com

- "STEM and Education." B. M. Moskal, Interview on the Blastercast (February 26, 2014), Available: https://itunes.apple.com/us/podcast/the-blastercast/id828697165

- "Earth, Energy and Environment." Moskal, B., Wempe, W., & Chan, K. (2014, April). Part of the ASEE K-12 division presentation at the U.S.A. Festival in Science and Mathematics, Washington, DC.

- "Physics, Dyslexia and Learning: A Collaboration for Disabled Students." Moskal, B. & Taylor, C. (2014). American Physical Society, Denver, Co, presentation. http://doit-prod.s.uw.edu/doit/nolan-and-physics-case-study-accommodating-learning-disabilities

- "Preparing the Next Generation of Material Scientists." Gallagher, L., Moskal, B., & Thurmer, C. (2014, April). Materials Research Society Spring Conference, San Francisco, CA.

In 2014 the REMRSEC supported over 50 postdoctoral research associates, graduate students, and undergraduate students. Through our summer teacher training workshops for K-12 teachers

in Adams County and Denver Public Schools the REMRSEC trained over 40 teachers to become proficient in delivering lessons on renewable energy topics that fit the state-mandated curriculum and are age appropriate for a specific grade. The Center also hosted 20 dyslexic students from grades 3-6 to enhance their proficiency in science and engineering concepts. This is particularly high aptitudes for mathematics and science subjects, but they often get left behind in a traditional learning environment. Finally, the REMRSEC ran a research experiences for undergraduates program that provided quality research experiences for 20 undergraduate students from around the country. This program is an excellent recruiting tool to attract the best and the brightest future scientist and engineers to finish their educations in Colorado and hopefully remain here to bolster the scientific workforce.

Appendix B: University of Colorado, Liquid Crystal Materials Research Center, 2014

Liquid Crystal Materials Research Center

University of Colorado – Boulder

CHECRA Grant: $400,000 (per year for 6 years)

SUMMARY

The Liquid Crystal Materials Research Center (LCMRC or the Center) has existed on the University of Colorado – Boulder campus since the early 1980s, with block funding from the NSF Division of Materials Research since September 1998. The LCMRC is currently funded as an NSF Materials Research Science and Engineering Center (MRSEC), one of an elite national network of advanced materials research programs.

DESCRIPTION OF THE PROJECT, THE PRINCIPAL PERSONS OR ENTITIES INVOLVED IN THE PROJECT

A major theme of materials science as we enter the 21st century is understanding and manipulation of the interactions between self-organizing complex molecules. It is precisely here that the study of liquid crystals has the greatest impact. Nowhere else are the requirements for understanding the delicate interplay between molecular architecture and its macroscopic manifestations more demanding than in the directed design of liquid crystals.

The Liquid Crystal Materials Research Center is one of the principal centers of liquid crystal study and expertise in the world, its research spanning the range from cutting-edge, basic liquid crystal and soft materials science to the development of enhanced capabilities for commercially important electro-optic, nonlinear-optic, chemical, biological, and other novel applications. The Center is a unique venue worldwide for research on key aspects of liquid crystal science and technology, chief among these the science and application of ferroelectric liquid crystals. The core Center research program is at the University of Colorado, Boulder.

The Center's research is organized within an Interdisciplinary Research Group addressing three major project themes: 1) understanding the relationship between molecular structure and macroscopic materials structure and properties of liquid crystals; (2) inventing new and useful ways of controlling liquid crystal behavior through interaction with surfaces; and (3) inventing and exploring new polymer materials possessing unique properties deriving from liquid crystallinity. Each of these research themes integrates *molecular modeling and design, chemical synthesis, physical studies,* and *applications development* into a multidisciplinary, collaborative research effort.

In 2014, the CHECRA funding was allocated to the three focus areas of the center described in this summary – research, industrial outreach, and education outreach.

FUNDING ALLOCATED TO EACH PRINCIPAL PERSON OR ENTITY

Research - The past year of MRSEC, with NSF funding supplemented by the CHECRA matching state funds, has continued in its role as CU Boulder's single most visible materials research group nationally and internationally. A summary of major research accomplishments is as follows:

The Ferromagnetic Nematic Phase - Observation of ferromagnetic nematic ordering in a colloidal suspension of magnetic nanosheets in an isotropic solvent. Observation of the ferromagnetic Fredericksz transition in a colloidal suspension of magnetic nanosheets in a nematic liquid crystal solvent. The magnetically induced molecular reorientation, coupled with the typical strong liquid crystal birefringence, produces the giant magneto-optical effect.

Room Temperature Ionic LCs - RTILs are low melting-temperature, organic salts, of great utility because of near-zero vapor pressure, fully tailorable solubility, high polarity, and non-coordinating nature. The Center is leading in the development of photopolymerized nanoporous materials having RTIL nanochannels **Figure 1.2** shows a Center atomistic computer simulation of a RTIL nanoporous lamellar phase made from the tri-imidazolium molecules indicated. Such RTIL liquid crystal systems will be pursued in the development of the polymerization of biphiphilic lyotropic nanoporous media for electrolytes and separations.

Industrial Outreach - *Electro-Optic Retroreflectors* - In collaboration with Lawrence Livermore National Laboratory we have developed a nematic liquid crystal electro-optic geometry that exhibits high contrast between voltage-on and voltage-off states in far field reflection. These cells are prototypes for active, smart retro-reflective particles for remote sensing that can be interrogated by long distance laser ranging.

The Center has been a major innovator in the field of ferroelectric liquid crystals (FLCs) for many years. Displaytech, Inc., a Colorado company founded by the Center PI and Co-PI, has successfully commercialized FLC in the form of microdisplays for camera viewfinders and hand-held picoprojectors. The Displaytech team continues to manufacture liquid crystals for its display products in Longmont.

Initial experiments, in which the photogenerated carrier lifetimes in HNF structures doped with C60 homolog PCBM have proven to be exceptionally exciting, with these composites exhibiting extremely long carrier lifetimes.

Education Outreach - *Materials Science from CU* delivered **90** classes to **3,400** Colorado K-12 children. The Center *Graduate Training Program in Liquid Crystal Science and Technology* received funding from the Department of Education *Graduate Assistantships in Areas of National Need* program for 5 additional graduate fellowships.

Diversity - During the past year the participation of graduate and undergraduate researchers that are either female or underrepresented minority has increased to over 55%. These students include five current Ph.D. students who are now UCB graduate students, entering through our Cal Poly Pomona and Metro State University Denver Partnerships.

Engineering Research Center in Extreme Ultraviolet Science and Technology
Colorado State University, University of Colorado

CHECRA Report for 2014

Director: Prof. Jorge J. Rocca. Colorado State University
Deputy Director: Prof. Margaret M. Murnane. University of Colorado
CHECRA Grant: $200,000 (2008, 2009), $400,000 (2010-2014)

Project Summary

The National Science Foundation Engineering Research Center in Extreme Ultraviolet Science and Technology is a partnership between Colorado State University and the University of Colorado. The Center is a world leader in the generation and application of light beyond the ultraviolet to challenging scientific and industrial problems that include nanotechnology, advanced materials, clean energy, and in the near future biology. *The funding provided by the Colorado Higher Education Competitive Research Authority (CHECRA) was crucial in assisting the Center to secure funding for $ 4.48 Million from several agencies during 2014.* Current Center funding includes a $0.8 Million grant co-funded by NSF and by one of Center's corporate members, Cymer Inc. to conduct research relevant to the lithography of the next generations of integrated circuits. During the past year, the Center also received ~$132 K in other industry funding, and a new grant for ~$336K from the National Science foundation to run a Research Experience for Undergraduates program for 2015-2017. The Center also has National Science Foundation funding to offer research experiences for high school teachers during the summers of 2014-2016. In May 2014 the Center hosted the 14th International Conference on X-ray Lasers, that was held in the campus of Colorado State University with the attendance of nearly 100 scientists from around the world.

Description of the project, the principal persons or entities involved in the project

The Engineering Research Center in Extreme Ultraviolet Science and **Technology** was created by the National Science Foundation in 2003 to advance the science and technology of light in the Extreme Ultraviolet (EUV) region of the spectrum (wavelengths approximately 1 to 50 nm) that is becoming a critical enabling technology in areas of great importance to the national economy that include the printing of the next generations of integrated circuits that, due to their small features, can no long be printed with longer wavelength light . Furthermore, exciting new opportunities in the materials, chemical, and biological sciences arise from the ability of EUV light to be focused into unprecedented small spot sizes, short pulse durations, and extremely high intensities. Further development of EUV technologies will open up a variety of new areas of research, including new tabletop probes of surface, chemical, cellular samples, nanostructures and materials, and the development of a new generation of nanoprobes.

The Center combines the complementary expertise of Colorado State University and the University of Colorado—leaders in compact EUV light sources and applications—with a set of collaborating institutions and industry, which includes a set of sixteen industrial corporate members. At Colorado State University, the Center faculty includes Profs. Jorge Rocca, Carmen Menoni, Mario Marconi, and Elliot Bernstein with affiliations to the Electrical Engineering,

Chemistry, and Physics departments. At the University of Colorado the Center Faculty includes Profs. Margaret Murnane, Henry Kapteyn and Ronguii Yang, with affiliations to the Physics Department, JILA, the Electrical and Computer Engineering and Mechanical Engineering Departments.

To realize the full impact of EUV technology in manufacturing and in scientific research, we are developing a new generation of compact coherent EUV sources with unique capabilities and we are combining them with advanced EUV optics to implement engineered systems designed to solve challenging engineering and scientific problems. Breakthroughs in new EUV lasers and in High Harmonic Generation sources have significantly expanded their spectral coverage, in some cases increasing the average power by orders of magnitude. By integrating the new compact sources with advanced EUV optics, we have developed a new set of microscopes, materials modification stations, and spectrometers with unique capabilities for a broad range of applications in industry and science. These include compact EUV microscopes with sub-38 nm resolution, a laser ablation testbed capable of producing sub-100 nm holes, an EUV photoacoustic metrology testbed to characterize thin films, a lensless microscope with 20 nm spatial resolution and elemental sensitivity, a single photon ionization spectrometer for the study of nanoclusters and a table-top workstation for the patterning of arrays of nanostructures.

Impact on Education

This Center makes an important contribution to education in Colorado, ranging from graduate and undergraduate education to elementary school. We are addressing the shortage of engineers and scientist with expertise in EUV technology by training a large number of students and young scientists, with many joining industries in Colorado. As the result of a proposal the Center wrote in 2014, it just received a new NSF grant for ~$336 K to offer Research Experience for Undergraduate (REU) students during 2015-2017. Our Research Experience for Undergraduate program (summer and year-round) has already mentored more than 200 students, with a significant fraction of the summer participants from under-represented minority groups. The new NSF grant will offer research opportunities for 30 additional undergraduate students during the next three years. In the summer of 2014, the Center also started to make use of a $ 318 K grant from the NSF to offer summer Research Experience for high school Teachers (RET) for 2014-2016. The teachers conduct research at the Center and develop curriculum material they can take back to the classroom. Optics teaching kits containing materials and curriculum for standards-based hands-on activities were distributed to over 100 K-12 teachers.

During 2014, the Center supported 20 undergraduate students to conduct research at CSU and CU. We have also developed a successful set of workshops for K-12 students and teachers. In 2014 we continued to hold the annual "Optics After School" Lab program for High School Students. This five-day event has affected nearly 250 High School students since the Center started. The Center also supported High School student researcher interns during the summers. During the summer of 2014, we provided research experiences for 5 High School students. The Center continued to work to increase the participation of under- represented groups, and during 2014 student interns included several members of under-represented groups and several women, including one from Colorado College.

The amount of funding allocated to each principal person or entity, manner in which each entity applied the funding in connection with the project, and results achieved

The $400 K in state matching funds to the Center for 2014 were distributed in equal parts betweem Colorado State University and the University of Colorado to support graduate students and young scientists who work to develop new sources and applications of EUV laser light and to equip new laboratories to conduct research and train students in this area.

At Colorado State University, the CHECRA matching funds for the NSF EUV ERC are used to young research scientists, and contributed to making operational a new laboratory to conduct research in this area. At the end of 2013 CSU completed a new building for Center research and in 2014 two of the major experimental setups were moved into the new laboratory that is specifically designed for laser research. The two laser systems moved into the new building are both now operational and are enabling a broad scope of research. During 2014 we continued to make significant advances in the development of extreme ultraviolet and soft x-ray lasers. Results were published about the demonstration of the first table top lasers able to operate at high average power in the sub-20 nm wavelength region. The high average power of these lasers allows applications such as the error-free printing of nanostructures. We also use this new laser infrastructure to conduct experiments in collaboration with industry to develop techniques for printing the future generation of integrated circuits. Successful experiments were also conducted to using the EUV lasers developed at the Center to demonstrate a new EUV nanoscale imaging technique that combines holography and microscopy. Finally, we continued to make progress in the development of a highly sensitive technique that uses the interaction of EUV light with materials in combination with mass spectrometry to map in 3-dimensions the chemical composition of samples with nano-scale resolution. In a collaboration with infectious decease specialists, the ultimate goals is to develop an instrument that will be capable of mapping the composition of a tuberculosis bacillus in 3-D. Carmen Menoni was elected University Distinguished Professor at CSU, one of 14 professors with that distinction among the more than 1000 faculty at CSU.

The University of Colorado used their $200K State Matching funds for the EUV ERC to support a postdoctoral researcher and two graduate students. These young scientists worked on key technologies of the Center – the development of compact laser and x-ray sources with wavelengths less than 1 nanometer, and also the development of new microscopy and nanometrology techniques. Major advances continued in 2014, with high quality nanoscale imaging and metrology of materials. These new capabilities attracted interest from industry. Many applications of these technologies are being implemented in collaboration with NIST Boulder Labs, industry and other collaborators including: the development of new microscopes capable of high-resolution nanoimaging of thick materials samples; characterization of interfaces and thin films of interest to the semiconductor and data storage industries; measurements of heat transport in nanostructures of interest to electronics and photovoltaics; and understanding and optimizing magnetic materials on nanoscale dimensions for applications in data storage. [see references] Past work on laser and x-ray sources has already been commercialized and has led to a 38-person spin-off company in Boulder. [KMLabs link:www.kmlabs.com.] The current work on advanced microscopes is also being commercialized. Henry Kapteyn and Margaret Murnane were named CU Boulder Inventors of the Year.

Summary to Benefits to the State of Colorado

- During 2014 the Center generated $4.48M in funding from Federal Agencies for Colorado State University and University of Colorado.
- The Center attracted $131,725 in new funding from industry during 2014.
- The Center supported 75 graduate and undergraduate students and faculty in Colorado
- The Center continued to graduate numerous students with PhD or MS degrees who were hired by Colorado high technology companies.
- Continued assisting Colorado companies in bringing new products to the market (e.g., KM laboratories, XUV Lasers)
- Provides research experiences for undergraduate students (20 students at CSU and CU during 2014)
- Reached ~500 K-12 students and 25 teachers with science workshops and demonstrations during 2014.
- Continued to provided summer research experiences for High School teachers, 7 during 2014
- Offered research experiences for High School students, 5 high school students during the summer of 2014.
- Hosted the 14th International Conference of X-Ray Lasers on the campus of Colorado State University during May, 2014, attended by nearly 100 scientist from institutions around the world.
- Increased the National and International reputation of Colorado as a leader in advanced technology and science.

Center Peer Review Journal Publications for 2014

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Engineering Research Center Reinvention of the Nation's Urban Water Infrastructure (ReNUWIt)
Colorado School of Mines
CHECRA Grant: $400,000 (per year for 5 years)
Reporting Period: January 1 - December 31, 2014

Summary: The Engineering Research Center (ERC) for Reinventing the Nation's Urban Water Infrastructure (ReNUWIt) at the Colorado School of Mines, under the leadership of Dr. John E. McCray, is a collaborative effort among four research universities: CSM, Stanford University, University of California at Berkeley, and New Mexico State University. The ERC was established on August 1, 2011 and is the first center to focus on civil infrastructure ever funded by the National Science Foundation.

Cities are facing a mounting water crisis from climate change, population expansion, ecosystem demands and deteriorating infrastructure that threatens economic development, social welfare, and environmental sustainability. Without relatively large investments this crisis will only deepen through the 21st century. Accordingly, the goal of this ERC is to advance new strategies for water/wastewater treatment and distribution that will eliminate the need for imported water, recover resources from wastewater, and generate rather than consume energy in the operation of urban water infrastructure while simultaneously enhancing urban aquatic ecosystems. While many existing approaches could be used to transition urban water infrastructure to this more sustainable state, their implementation currently is limited by uncertainties about their long-term performance, life cycle costs, institutional impediments and public concerns about unfamiliar technologies.

Description of the project, the principal persons or entities involved in the project, and the amount of funding allocated to each principal person or entity

To meet the challenges described above, ReNUWIt has launched key research projects within three research thrust areas. These research thrust are defined as follows:
(1) **Efficient Engineered Water Systems:** Decrease reliance on inefficient centralized treatment systems by employing distributed treatment systems that embrace water conservation, local use of alternative supplies, energy management, nutrient recovery, and that integrate with existing infrastructure;
(2) **Natural Water Infrastructure Systems:** Integrate managed natural systems into water infrastructure to fully realize the potential benefits that natural systems can provide with respect to water storage and improvement of water quality, while simultaneously rehabilitating urban hydrology and aquatic habitat;
(3) **Urban Systems Integration and Institutions:** Support the reinvention and restoration of urban water systems through the development of decision-making tools that account for economic, environmental and social factors and development of approaches that can circumvent impediments to change posed by regulations, laws, jurisdictional fragmentation, financing and public perception.

Water resource planners are hesitant to integrate new types of engineered treatment systems into their water portfolio due to uncertainties about cost, reliability, public health risks, and overall impacts on system performance. Thus, a mechanism for technology assessment is

needed at scales ranging from the laboratory to the full-scale service area. Such capabilities do not exist in the public, private, or academic sectors, and as a result, many good ideas are not brought into practice. To facilitate the integration of new technologies into urban water systems, tools like life-cycle assessment for decision-making are being advanced and research on engineered systems that support the concept of tailored water for distributed non-potable and potable water reuse, energy-positive wastewater treatment and nutrient recovery, concentrate management, and enhanced water recovery is being conducted.

The goal of the *Efficient Engineered Systems* research thrust is to characterize the viability of existing but underutilized technologies at different scales by assessing their economic, environmental, and social costs and benefits. The specific aims of this thrust are: (i) to identify the most efficient scale of implementing more sustainable engineered water systems; (ii) to provide new, resilient technologies leading to energy-positive wastewater treatment and recovery of nutrients; (iii) to develop technologies that provide water tailored to meet specific needs including alternative water delivery systems; and, (iv) to develop energy-efficient hybrid systems for concentrate management and enhanced water recovery.

The thrust area on the use of *Natural Water Infrastructure Systems* will bring a much-needed quantitative approach to an area that has not previously been subjected to rigorous engineering analysis. Research at CSM will employ advances in fundamental understanding of natural systems to remove impediments to integrating natural systems into water infrastructure by making the complex processes that affect water transport, quality and ecosystem function in natural systems predictable and manageable. The goals are to: (i) develop tools for manipulating natural systems to enhance water quality; (ii) integrate managed aquifer recharge into urban settings using reclaimed water leading to drinking water augmentation; and (iii) harvest stormwater and infiltrate in urban settings to augment local supplies.

Within the *Urban Systems Integration and Institutions* thrust, research focuses on the development of integrated regional water models. These models will serve as decision-support tools for water resource and urban planners and managers to test the performance of treatment and supply options developed in the Natural and Engineered Systems thrusts.

Within the ReNUWIt framework described above, fourteen projects were funded in 2014:

- Tools to support decision making for nested, spatially-scaled, integrated urban water infrastructure (U1.2);
- Regional Demand Forcasting (U2.4);
- Denver Stormwater Planning (U2.5);
- Tailored water for distributed non-potable reuse using sequencing batch/membrane bioreactor hybrid systems (E1.1);
- Point-of-entry water treatment for potable reuse (E1.3 - formerly E1.4);
- Sustainable landscape irrigation with reclaimed water (E1.5 - formerly E1.3);
- Microalgae for wastewater treatment and recovery: A new approach to onsite wastewater treatment (E2.2);
- Anaerobic digestion as primary treatment at WWTPs (E2.4);
- Design of unit process wetlands to optimize chemical contaminant removal (N1.2);
- Managed aquifer recharge and recovery: Simulation, modeling and operation (N2.1 - formerly N3.1);
- Improving water quality during managed aquifer recharge (MAR) (N2.2 - formerly N3.2)
- Aquifer storage, treatment, and harvesting of stormwater for distributed reuse: coupled modeling, laboratory and field studies (N3.1 - formerly N4.1);

- Methodologies, models, and materials for predictable removal of chemicals from stormwater during distributed recharge (N3.3 - formerly N4.3); and
- Hyporheic zone management for water quality improvement (N3.4- formerly N2.3).

Principal Investigators	Funding from CHECRA
John McCray, CSM Principal Investigator	
Center Lead	$21,962
Project Lead, Denver Stormwater Planning, U2.5 (Fall project start)	$8,459
Project co-Lead, Point-of-Entry Treatment, E1.3	$12,220
Project Lead, Hyphorheic Management, N3.4	$7,268
Tzahi Cath, Engineered System Thrust Leader	
Project Lead, Decision Support Tools, U1.2	$19,498
Project Lead, Tailored Water, E1.1	$43,982
Project Lead, Microalgae Wastewater Treatment, E2.2	$21,837
Linda Figueroa	
Project Lead, Anaerobic Digestion, E2.4	$15,013
Christopher Higgins	
Project Lead, Subsurface Purification, N3.3	$28,017
Terri Hogue	
Project Lead, Regional Demand Forecasting, U2.4 (Fall project start)	$1,383
Reed Maxwell	
Project Lead, Coupled Modeling, N3.1	$71,702
Barbara Moskal	
Education Lead	$12,430
Junko Munakata-Marr	
Project Lead, Sustainable Irrigation, E1.5	$47,218
Jonathan Sharp	
Project Lead, Unit Process Wetland, N1.2	$2,465
Project Lead, Unit Process Recharge, N2.2	$55,653
Kathleen Smits	
Project Lead, Aquifer Management, N2.1	$9,044
TOTAL SPENDING (Jan-Dec 2014)	***$378,151***

Within the ReNUWIt projects, full or partial support was provided to:

- 14 Doctoral students
- 5 Master's of Science Thesis students
- 4 Hourly Graduate Students, Non-thesis Master's Students
- 10 Hourly Undergraduate students
- 7 REUs ~ a 10 week summer program designed to provide research experience for undergraduates
- 1 RET ~ 10 week summer program designed to provide research experience for K-12 teachers. In 2014, the RET was from the Englewood School District.
- 5 Post Doctoral Fellows
- 3 Assistant Research Faculty
- 2 Research Staff
- 10 Faculty ~ 3 Assistant Professors; 4 Associate Professors; and 3 Professors

Participant		Project(s)
I. Avila *	Hourly Undergraduate Student	E1.5
T. Baird *	Hourly Undergraduate Student	N3.4
U. Chen	Hourly Undergraduate Student	E2.4
A. Heldmyer *	Hourly Undergraduate Student	E1.5
T. Kalin	Hourly Undergraduate Student	Education & Outreach
C. Marks	Hourly Undergraduate Student	N3.3
C. Panos *	Hourly Undergraduate Student	U2.4
K. Percival *	Hourly Undergraduate Student	N3.3, N3.4
S. Stokes *	Hourly Undergraduate Student	N1.2
C. Weller *	Hourly Undergraduate Student	E2.2
B. Bader *	Hourly Graduate Student	N3.4
V. Billings *	Hourly Undergraduate / Graduate Student	E1.1, E2.2
M. Guyader *	Hourly Graduate Student	N3.4
E. Im *	Hourly Graduate Student	N3.3
C. Carandang	MS Thesis	U2.4
L. Cherry *	MS Thesis	U2.5
J. Cochran *	MS Thesis	E1.5
J. Coontz	MS Thesis	E1.1
Z. Drumheller	MS Thesis	N2.1
M. Danglmayr	PhD	Education & Outreach
T. Fry *	PhD	N3.1
M. Hahn *	PhD	E2.4
S. Herzog	PhD	N3.4
R. Holloway *	PhD	E1.1
J. Johnson	PhD	Education & Outreach
Z. Jones	PhD	N1.2
K. Kazor *	PhD	Education & Outreach
J. Miorelli	PhD	Education & Outreach
D. Ramey *	PhD	E2.2
P. Roa *	PhD	E1.3
B. Ulrich	PhD	N3.3
D. Vuono	PhD	E1.1
V. Zhiteneva	PhD	Education & Outreach
A. Blaine	Post Doctoral Fellow	Education & Outreach
S. Lopez *	Post Doctoral Fellow	N3.1
L. Robbie *	Post Doctoral Fellow	E1.1, E2.2, E2.4
S. Roberts *	Post Doctoral Fellow	N3.3
P. Schulte	Post Doctoral Fellow	N2.1
M. Geza (*	Assistant Research Professor	U1.2
D. Li *	Assistant Research Professor	N2.2
J. Regnery	Assistant Research Professor	N2.1, N2.2
K. Lowe	Senior Research Associate	Administration
M. Veres	Research Associate	Test Site Manager

* These students and Staff were funded directly with CHECRA funds. However, all students and staff benefited in some way from CHECRA funds via research materials and supplies.

The manner in which each principal person or entity applied the funding in connection with the project

John McCray, Professor: Discretionary Center funding for supporting new research directions; design and installation of new testing apparatus; and travel support for students and faculty. Partial salary support was for ReNUWIt Center management and student advising and mentoring. Funding for one graduate student who is developing a prototype using ceramic nanofiltration membrane coupled with UV oxidation for point-of-entry drinking water treatment (E1.3). One graduate student is studying water quality improvements in the hyporheic zone to develop management strategies for urban stream restoration (N3.4). Tuition and stipend support for this student is from an NSF Scholarship. CHECRA Funding supported one non-thesis graduate student and an undergraduate hourly research student (N3.4). Nominal funding was also used for materials and supplies for construction of field testing apparatus (N3.4). A new project was started in Fall 2014 to evaluate Denver stormwater planning with one graduate student. Tuition and nominal materials were supported by CHECRA funds while student salary was contribured in-kind by Denver Water (U2.5).

Tzahi Cath, Associate Professor: Partial salary support for an Assistant Research Faculty member to develop a decision support tool to aid tailoring water treatment for specific beneficial use (U1.2). Funding for one graduate student focused on energy optimization and tailored non-potable reuse (E1.1). Partial funding for one graduate student focused on gasification for energy recovery from wastewater solids (E2.2). Partial salary support was provided for one post doctoral fellow to conduct life cycle assessments (E1.1, E1.3, E2.2, and E2.4). Nominal funding used to cover an hourly undergraduate student for bench scale testing of nutrient and energy recovery from wastewater using specific target microalgae (E2.2). NSF funds supported one student focused on tailored non-potable reuse (E1.1), materials and analyses, three REU students, and partial support for faculty student advising and mentoring. Supplemental funds from CSM provided partial salary support for research staff to operate and maintain the Mines Park Test Site.

Linda Figueroa, Associate Professor: Tuition support for a graduate student who is developing a pilot-scale reactor for methane recovery in cooperation with Plum Creek Wastewater Authority, Castle Rock, CO (E2.4). Partial faculty salary support was provided for student advising and mentoring. Nominal funding was used for analysis of samples from the pilot scale anaerobic bioreactor at Plum Creek Wastewater Authority. In-kind support was provided by Plum Creek Wastewater Authority for student salary and analysis.

Amanda Herring, Assistant Professor: Partial funding for one graduate student to conduct statistical evaluations for multiple projects remaining support for this graduate student was provided through a CSM fellowship.

Christopher Higgins, Associate Professor: One graduate student is developing special adsorbants to remove chemical contaminants in stormwater during distributed recharge (N3.3). Support for the graduate is through a NSF Scholarship. CHECRA funds supported two hourly students (one non-thesis graduate student and one undergraduate student) and partially supported one post doctoral fellow to assisting chemical analysis using liquid chromatography tandem mass spectrometry (LC-MS/MS). Partial faculty salary support was provided for student advising and mentoring.

Terri Hogue, Associate Professor: A new project was started in Fall 2014 to evaluate regional demand forecasting (U2.4). One undergraduate student was supported for hydrologic data gathering and synthesis that will contribute to modeling and statistical studies for water

consumption and stormwater modeling studies. One graduate student and nominal materials were supported with NSF funds.

Reed Maxwell, Professor: Salary support for one post doctoral fellow to develop watershed-scale models to locate distributed stormwater recharge facilities focusing on the Cherry Creek watershed (N3.1). One graduate student was also supported looking at water quantity impacts of converting pervious areas to low impact development in urbanized watersheds (N3.1). Specifically looking at the impacts associated with converting 15%, 25%, 35% and 50% of existing pervious areas under different design storms (2-Yr, 5-Yr, 10-Yr, 50-Yr, 100-Yr) on flooding. Partial faculty salary support was provided for student advising and mentoring. This study is currently focusing on the Cherry Creek watershed in Denver.

Barbara Moskal, Professor: Nominal support for classroom materials in support of the Bechtel Summer Teacher Workshop. Two graduate students received tuition and stipend support from NSF funds to focus on education and outreach for K-12.

Junko Munakata-Marr, Associate Professor: Funding for one graduate student and two hourly undergraduate students for operation and maintenance of test cells for soil treatment of irrigated reclaimed water (E1.5). Nominal funding for materials, supplies, and analysis needed for monitoring of the test cells. Supplemental NSF funding also supported an undergraduate student via a Veteran Research Supplement and an REU student to conduct microbial assessments.

Jonathan Sharp, Assistant Professor: Funding to cover one undergraduate student, supplies and materials to study the biocommunity diversity in unit processes wetlands to better understand key boundary conditions for the attenuation of trace organic chemicals (N1.2). NSF funds supported one graduate student (N1.2) with additional supplemental NSF funds sponsored a REU student working with the graduate student. Partial salary support was provided to one post doctoral fellow to evaluate attenuation of trace organic chemicals in managed aquifer recharge systems (N2.2). Support for a second post doctoral fellow, nominal materials, and analyses was provided through NSF funds.

Kathleen Smits, Assistant Professor: Funding for one graduate student who designed and constructed a 3-D intermediate-scale tank experiment to simulate fate and transport processes of artificial recharge and recovery facilities (N2.1). Partial support was provided to Tissa Illangasekare (Professor) for faculty student advising and mentoring. NSF funds supported one student focused on managed aquifer recharge (N2.1), materials and analyses, and partial support for faculty project direction and student advising and mentoring.

Results Achieved

Center scientists and engineers continued field research at Colorado School of Mines campus test bed that utilizes and treats municipal wastewater (~7,000 gal/day) to support both the *Efficient Engineered Water Systems* and *Natural Water Infrastructure Systems* thrusts. The demonstration-scale treatment unit allows effluent qualities to be tailored to various reuse applications (i.e., urban landscape irrigation; streamflow augmentation; groundwater recharge) and continues to be supported through collaborations with manufacturers and start-up companies within Colorado. Strategies for optimization of generating on-demand effluent qualities with elevated levels of nitrogen while simultaneously optimizing energy demands continue. A second season of irrigation, analyses of leachate, and soil samples collection was

completed to assess using tailored water for irrigation to reduce potable use, reduction of mineral fertilizers, and minimize nitrate leaching to groundwater. Energy recovery and thermochemical extraction of energy from wastewater biosolids are being explored.

Demonstration scale anaerobic baffled reactors have been operating at the Plume Creek Water Reclamation Authority (PCWRA) in Castle Rock for two years to evaluate a treatment configuration that hinders lateral migration of solids along the length of the reactor, and enhances contact with the biomass, with minimal energy input. Based on the positive results, PCWRA is planning to construct a demonstration scale mainstream anaerobic treatment system. The demonstration will consist of primary and secondary anaerobic treatment reactors. Each tank will be approximately 10 cubic meters in volume to enable integration of anaerobic mainstream treatment upstream of their oxidation ditches. In addition, CSM and PCWRA partnered on a proposal to the National Science Foundation on enhancing our understanding of the fundamental processes in a pilot system with primary and secondary anaerobic treatment stages to be constructed and operated at the Mines Park Test Bed Facility (award outcome is pending until May 2015). Finally, project researchers have been solicited by water reclamation utilities in Western States to explore testing and upscaling of the anaerobic mainstream treatment.

Activities within the natural water infrastructure systems thrust included the upscaling of testing at the field scale. In N.3, CSM investigators helped to design an open water wetlands cell constructed at Prado by the Orange County Water Department, and installed a new testbed to install water treatment features in streambeds for treating storm-water pollutants and promote cleaner water leaving our cities. These modules were termed "Biohydrochemical Stream Water Treatment (BEST)" modules and an invention disclosure has been filed at CSM. In N.3, researchers are working with Aurora Water to develop smarter, more efficient methods for infiltrating recycled water for aquifer storage while simultaneously improving water quality. The technology is termed SMART (smart managed aquifer recharge technology). In N.4, new geomedia is being researched for potential to remove stormwater pollutants during infiltration in engineered low-impact development (LID features). In addition, a high-resolution spatial model was developed for the south Denver area to simulate the many interacting effects of storm water and water supply including the potential impacts of new water infrastructure.

Within the *Urban Systems Integration and Institutions* thrust, CSM center scientists have developed a conceptual model that couples supply options with demand while also considering water treatment/distribution as well as wastewater collection and treatment. The model will also allow characterization of water and energy inefficiencies in the current system. Two new projects were initiated focusing on urban systems and the coupling between humans and water-energy cycling (U2.4) and Denver stormwater planning (U2.5).

Summary of Benefits to the State of Colorado

- Received $830,000 NSF core funds in 2014. These funds in combination with CHECRA funds and $324,541 CSM matching funds supported 19 PhD and masters graduate students, 10 undergraduate students, 10 faculty, 5 post doctorial fellows, 3 assistant research professors, and 2 research staff.
- Professor McCray started a new project with the City and County of Denver (U.2.5) that is jointly funded by the City and ReNUWIt (~ $150,000 coming from the City and $200,000 from ReNUWIt over 2 years). A new M.S. student Lisa Cherry is working on this project, which is a technical, economic, and legal feasibility study for beneficial stormwater use in a west Denver neighborhood. Development trends in Denver are expected to result in additional storm-water runoff over the next 25 years, and Denver's

population is expected to increase significantly over that time, placing great stress on water providers. The goal of this project is to collect stormwater in a centralized facility, treat the stormwater for better water quality using innovative ReNUWIt technologies before discharging into the South Platte River system, and use the storm-water for urban irrigation on City Parks and Recreation facilities (that would also serve as a public education facility). Ideally, the facility would also be part of a water-quality credits trading system that would facilitate sustainable urban development in Denver.

- Based on outcomes from E2.4, Plum Creek Water Reclamation Authority is planning to construct a demonstration scale mainstream anaerobic treatment system.
- Bi-monthly seminars organized and sponsored by the ReNUWIt students. Seminar speakers and topics include a range of student research, industry partners, and experts.
- Delivered a Water Treatment Short Course at the Bechtel Summer Teacher Workshop.
- Delivered Dyslexic Camp for dyslexic students (grades K-7) providing the opportunity to experience success in science.

Publications and Presentations in 2014 (funded wholly or in part with CHECRA funds):

Thesis and Dissertations:

Cochran, J. (2014). Effects of Turfgrass Irrigation with Tailored Reclaimed Water on Turfgrass Visual Quality, Rootzone Salinity, Nitrogen Species, and Denitrifying Microorganisms in the Vadose Zone. M.S. Thesis. Civil and Environmental Engineering, Colorado School of Mines, Golden, CO.

Vuono, D.C. (2014). Mechanisms of Diversity Maintenance, Resilience, and Niche Differentiation in Activated Sludge Microbial Communities. Ph.D. Dissertation. Civil and Environmental Engineering, Colorado School of Mines, Golden, CO.

Publications:

Betancourt, W.Q., M. Kitajima, A.D. Wing, J. Regnery, J.E. Drewes, I.L Pepper, and C.P.Gerba (2014). Assessment of virus removal by managed aquifer recharge at three full-scale operations. *J. of Env. Sci. and Health Part A (Toxic/Hazardous Substances and Environmental Engineering)* 49: 1685–1692.

Cameron, D., R. Knight, J. Regnery, and J. McCray. The use of a geostatistical method to characterize flow paths at an aquifer recharge site. In review. *Groundwater.*

Condon, L.E. and R.M. Maxwell (2014). Feedbacks between managed irrigation and water availability: Diagnosing temporal and spatial patterns using an integrated hydrologic model. *Water Resources Research*, 50(3): 2600-2616.

Condon, L.E. and R.M. Maxwell (2014). Groundwater-fed irrigation impacts spatially distributed temporal scaling behavior of the natural system: A spatio-temporal framework for understanding water management impacts. *Environmental Research Letters*, 9(3): 034009.

Condon, L.E., A.S. Hering, and R.M. Maxwell. Quantitative assessment of groundwater controls across the continental US using a multi-model regression algorithm, In Revision *Advances in Water Research*.

Herzog, S., C.P. Higgins, and J.E. McCray. Engineered streambeds for induced hyporheic flow: Enhanced removal of nutrients, pathogens, and metals from urban streams. Submitted July 2014, *J. Env. Eng.*

Herzog, S., C.P. Higgins, and J.E. McCray. Biohydrochemical enhancement structures for stormwater treatment (BEST): Induced hyporheic flow and potential for enhanced

contaminant biodegradation, In revision, *J. Env. Eng.*

Holloway, R.W., J. Regnery, L.D. Nghiem, and T.Y. Cath (2014). Removal of trace organic compounds and performance of a novel hybrid ultrafiltration-osmotic membrane bioreactors, *Env. Sci. & Tech.*, 48(18): 10859-10868.

Holloway, R.W., A.S. Wait, A. Fernandes-da-Silva, J. Herron, M. Schutter, K. Lampi, and T.Y. Cath. Long-term pilot scale investigation of novel hybrid ultrafiltration-osmotic membrane bioreactors, In press, *Desalination.*

Jasper J.T., Z.L. Jones, J.O. Sharp, and D.L. Sedlak (2014). Nitrogen removal in shallow open-water treatment wetlands. *Env. Sci. & Tech.,* 48(19): 11512-20.

Jasper J.T., Z.L. Jones, J.O. Sharp, and D.L. Sedlak (2014). Biotransformation of trace organic contaminants in open-water unit process treatment wetlands. *Env. Sci. & Tech.,* 48(9): 5136-44.

Kazor, K., R. Holloway, T. Cath, and A.S. Hering. Comparison of linear and nonlinear dimension reduction techniques for automated process monitoring of a decentralized wastewater treatment facility, Submitted to *Journal of Bioresource Technology.*

Kirsch, B. and R. Maxwell. Water Markets to Minimize Drought-Induced Economic Losses in California, *J of American Water Works Association.* In press.

Lin, L., X. Xu, C. Papelis, T.Y. Cath, and P. Xu (2014). Sorption of metals and metalloids from reverse osmosis concentrate on drinking water treatment solids, *Separation and Purification Technology*, 134: 37-45.

Lumley, N.P.J., R.J. Braun, T.Y. Cath, A.L. Prieto, D.F. Ramey, and J.M. Porter (2014). Techno-economic analysis of wastewater sludge gasification: A decentralized urban perspective, *Bioresource Technology*, 161: 385-394.

Miller-Robbie, L., B. Ulrich, D. Ramey, K.S. Spencer, S. Herzog, T. Cath, J. Stokes, and C.P. Higgins (2014). Life Cycle Assessment of the Co-Production of Biosolids and Biochar for Land Application. *Journal of Cleaner Production.* 91: 118-127.

Mitrano, D.M., J.F. Ranville, A. Bednar, K. Kazor, A.S. Hering, and C.P. Higgins (2014). Tracking dissolution of silver nanoparticles at environmentally relevant concentrations in laboratory, natural, and processed waters using single particle ICP-MS (spICP-MS), *Environmental Science: Nano*, 1: 248-259.

Parsekian, A.D., J. Regnery, A. Wing, R. Knight, and J. Drewes (2014). Geophysical and geochemical identification of flow paths with implications for water quality at an ARR site. *Groundwater Monitoring & Remediation,* 34: 105-116.

Ramey, D.F., N.P.G. Lumley, A.L. Prieto, J.M. Porter, and T.Y. Cath (2014). Evaluating air blown gasification for energy recovery from wastewater solids: impact of biological treatment and point of generation on energy recovery, *Sustainable Energy Technologies and Assessments*, 9: 22-29.

Regnery, J., D. Vuono, D. Li., R. Holloway, Z. Jones, and J. Drewes. Differential expression of small-subunit rRNAs reveals niche differentiation of activated sludge microorganisms and their potential for trace organic chemical removal. In review. *Water Research.*

Regnery, J., A. Wing, M. Alidina, and J. Drewes. Biotransformation of trace organic chemical attenuation during groundwater recharge: How useful are first-order rate constants? In review. *Journal of Contaminant Hydrology.*

Sinthusith, N., A. Terada, M. Hahn, P. Noophan, J. Munakata-Marr, and L.A. Figueroa (2014).

Identification and quantification of bacteria and archaea responsible for ammonia oxidation in different activated sludge of full scale wastewater treatment plants, *J. of Env. Sci. and Health Part A*, 50(2): 169-175.

Vuono, D.C., J. Benecke, J. Henkel, W.C. Navidi, T.Y. Cath, J. Munakata-Marr, J.R. Spear, and J.E. Drewes. Disturbance and temporal partitioning of the activated sludge metacommunity, Accepted *International Society for Microbial Ecology Journal* (advance online publication August 15, 2014).

Vuono, D.C., J. Munakata-Marr, J.R. Spear, and J.E. Drewes. Disturbance opens recruitment sites for bacterial colonization in activated sludge, Accepted *Environmental Microbiology*.

Xu, X., L. Lin, C. Papelis, M. Myint, T.Y. Cath, and P. Xu (2014). Use of drinking water treatment solids for arsenic removal from desalination concentrate, *Journal of Colloid and Interface Science*, 445: 252-261.

Presentations:

Beardsley S.E., Z.L. Jones, J.O. Sharp, and D.L. Sedlak (2014). Optimizing vegetated treatment wetlands for the transformation of trace organic compounds. Environmental Sciences: Water Gordon Research Conference. June 22-27, 2014, Holderness, NH.

Cath, T.Y. (2014). Engineered Osmosis: Multi-Barrier Approach to Direct Potable Reuse and Nutrient Recovery, A seminar given at the Southern Nevada Water Authority, March 10, 2014, Las Vegas, NV.

Cochran, J., V. Roux, E. Sevostianova, M. Serena, J. Munakata-Marr, and B. Leinauer (2014). Nitrate leaching from turfgrass irrigated with tailored effluent water from a subsurface drip system. Poster presentation, Rocky Mountain Water Reuse Workshop, August 14, 2014, Golden, CO.

Cochran, J., V. Roux, E. Sevostianova, M. Serena, J. Munakata-Marr, and B. Leinauer (2014). Nitrate leaching from turfgrass irrigated with tailored effluent water from a subsurface drip system. Poster presentation, AWWA Sustainable Water Management Conference, March 31-April 2, 2014, Denver, CO.

Coolidge, E. (2014). Anaerobic nitrifier denitrification for energy recovery. Renewable Energy Materials Research Science and Engineering Center Research Experience for Undergraduates Symposium, July 24, 2014, Golden, CO.

DiPalma, M., T. Rauch-Williams, J. Fraser, and J. Munakata-Marr (2014). Operational strategies for promoting nitrogen elimination in centrate sidestream treatment. Poster presentation, WEFTEC, September 27 - October 1, 2014, New Orleans, LA.

Drumheller, Z.W., J. Regnery, J. Lee, T.H. Illangasekare, P. K. Kitanidis, and K.M. Smits (2014). Integrating predictive modeling with control system design for managed aquifer recharge and recovery applications. Poster. American Geophysical Union Fall Meeting, December 2014, San Francisco, CA.

Esteban M., S. Herzog, Z. Jones, and J. Sharp (2014). Hyporheic zone management: nitrate removal for treated wastewater effluent using an engineered hyporheic zone as a bioreactor. AGU fall meeting, December 15 - 19, 2014. San Francisco, CA.

Esteban, M., Z. Jones, S. Herzog, J. McCray, and J. Sharp (2014). Microbial denitrification in a pilot-scale engineered BEST hyporheic zone, July 2014, Golden, CO.

Hahn, M. (2014). Plum Creek Water Reclamation Authority Anaerobic Treatment of Municipal

Wastewater at Ambient Temperature Rocky Mountain Water Environment Association Biosolids Annual Workshop, November 13, 2014. Castle Rock, CO.

Herzog, S., C.P. Higgins, and J.E. McCray (2014). Streambed hydraulic conductivity structures: Enhanced hyporheic exchange and contaminant removal in model and constructed stream. Oral presentation at AGU Fall Meeting, December 15-19, 2014, San Francisco, CA.

Herzog, S., C.P. Higgins, and J.E. McCray (2014). Streambed hydraulic conductivity structures: Enhanced hyporheic exchange in model and constructed stream. Oral presentation at NGWA Groundwater Summit, May 4-7, 2014, Denver, CO.

Herzog, S., C.P. Higgins, and J.E. McCray (2014). Biohydrochemical enhancement structures for streamwater treatment (BEST): Enhanced biodegradation in the hyporheic zone. Oral presentation at Colorado School of Mines Conference on Earth and Energy Research, February 27-28, 2014, Golden, CO.

Holloway, R.W., J. Regnery, L.D. Nghiem, and T.Y. Cath (2014). The ultrafiltration-osmotic membrane bioreactor – Potable reuse and nutrient recovery, GRS 2014, July 5-6, 2014, New London, NH.

Holloway, R.W., J. Regnery, L.D. Nghiem, and T.Y. Cath (2014). The UF-osmotic membrane bioreactor: Trace organic compounds removal and nutrient recovery, 24th Annual Meeting North American Membrane Society, June 3, 2014, Houston, TX.

Holloway, R.W., J. Herron, K. Lampi, and T.Y. Cath (2014). The UFO-MBR for potable, indirect potable, and nutrient recovery – rejection of TOrCs, Proceedings of the AWWA/AMTA 2014 Membrane Technology Conference and Exposition, March 10-14, 2014, Las Vegas, NV.

Homme C.L., D. Li D, and J.O. Sharp (2014). Impact of biofiltration and dissolved organic carbon on nitrosamine biotransformation. ISSM-International Symposium on Subsurface Microbiology (ISSM), October 5-10, 2014, Pacific Grove, CA.

Jones Z.L., J.T. Jasper, S.E. Beardsley, R. Almstrand, D.L. Sedlak, and J.O. Sharp (2014). Diatomaceous dissimlatory nitrate reduction to ammonium supporting anammox organisms in a shallow open water cell of a unit process wetland. ISME15-International Society for Microbial Ecology, August 22-29, 2014, Seoul, South Korea.

Lopez, S.R., R.M. Maxwell, and N.B. Engdahl (2014). Using high performance computing and an ultra-high-resolution domain to evaluate best management practices within urban environments, International Conference on Computational Methods in Water Resources (CMWR), June 10 – 13, 2014, Stuttgart, Germany,

Lopez, S.R. and R.M. Maxwell (2014). Particle tracking within urban systems: using high performance computing and an ultra-high-resolution domain to evaluate best management practices within urban environments, American Geophysical Union, December 15 - 19, 2014, San Francisco, CA.

McCray, J.E. (2014). Reinventing the Nations Urban Water Infrastructure: The Role of Water Reuse. WateReuse Association, Water Reuse Colorado, 2014 Workshop, Panel Discussion on Integrated Water Planning with Larua Belanger, PE, Western Resource Advocates; John McCray, PhD, CSM; Dave Little, Director of Planning, Denver Water, August 14, 2014, Golden CO (**invited**).

McCray, J.E. (2014). Resiliency of the Nation's Urban Water Infrastructure, Resilience Week 2014, August 19, 2014, Denver CO (**invited**).

McCray, J.E., C.P. Higgins, T.Y. Cath (2014). Reinventing the Nation's Urban Water Infrastructure, Opportunities for Municipal Water Utilities, City of Aurora, Aurora Water, April

2014, Aurora CO (**invited**).

Ramey, D.F., N.P.G. Lumley, J.M. Porter, and T.Y. Cath (2014). Air blown gasification for energy recovery from solids in decentralized water reclamation facilities, Poster in Conference on Earth & Energy Research (CEER), February 27-28, 2014, Colorado School of Mines, Golden, CO.

Vuono, D., J. Munakata-Marr, J. Spear, and J. Drewes (2014). Quantifying the roles of immigration and regrowth during secondary succession, Platform presentation, ISME15, August 24-29, 2014, Seoul, South Korea.

Vuono, D., J. Regnery, J. Munakata-Marr, J. Spear, and J. Drewes (2014). Temporal dynamics of active microbial populations and function in batch-fed activated sludge treatment system, Poster presentation, ISME15, August 24-29, 2014, Seoul, South Korea.

Vuono, D., J. Regnery, D. Li, and J. Drewes (2014). Diversity, dynamics and function of active microbial populations transforming organic micropolluants in activated sludge treatment systems. 248th ACS National Meeting, August 10, 2014, San Francisco, CA.

Vuono, D., J. Regnery, J. Munakata-Marr, and J. Drewes (2014). Diversity, dynamics and function of active microbial populations in batch-fed activated sludge treatment systems. IWA Specialized Conference Activated Sludge – 100 Years and Counting, June 12-14, 2014, Essen, Germany.

Center for Mulitscale Modeling of Atmospheric Processes (CMMAP)

Colorado State University
Principal Investigators:
Center Director: David A. Randall, Colorado State University
Deputy Director: Chin-Hoh Moeng, The National Center for Atmospheric Research, Boulder, Colorado
Director for Education and Diversity: A. Scott Denning, Colorado State University
Director for Knowledge Transfer: Steve Krueger, University of Utah
Director for Cyberinfrastructure: John Helly, University of California, San Diego

Project Description

The Center for Multiscale Modeling of Atmospheric Processes (CMMAP) is one of seventeen current Science and Technology Centers (STCs) sponsored by the National Science Foundation. Up to this time, CMMAP is the only STC ever awarded in the state of Colorado. CMMAP is a partnership of research and educational institutions, government agencies, and industry.

CMMAP's activities are divided into three areas: (1) research, which is focused on developing a new kind of global atmospheric model; (2) education, outreach and diversity, which seeks to educate and train a diverse population (specifically women, underrepresented minorities, and individuals with disabilities) in climate and Earth System Science; and (3) knowledge transfer, through the sharing of information with other modeling centers and the Colorado Governor's Energy Office. CHECRA funding is being used to support all three of these focus areas.

The Center's research is focused on improving the representation of cloud processes in climate models. Cloud processes are central to the Earth Sciences. Changes in cloudiness can either amplify or damp climate change. In addition, cloudiness and precipitation are key elements of any weather forecast. Clouds are central components of the water cycle. Chemical transformations occur inside clouds and feed back to affect the properties of the clouds. Last but not least, the biosphere is highly dependent on cloud processes. Progress in all of these disciplines is being held back by our limited ability to understand and simulate global cloudiness.

CMMAP's vision is to take advantage of rapidly increasing computer speed to achieve major advances in our ability to understand and predict the effects of clouds on weather and climate, through a revolutionary new approach called the "multi-scale modeling framework" (MMF), in which high-resolution cloud models are coupled to lower-resolution global models. CMMAP's research team includes climate modelers, cloud modelers, and experts on turbulence, radiation, cloud physics, and observations.

CMMAP also has major activities in the areas of Education and Diversity. CMMAP's graduate students are immersed in the Center's culture. They see, and some of them participate in, the training of high-school science teachers and the teaching and mentoring of diverse

undergraduates. The students work collaboratively with faculty, solving problems together. Through "the Center experience," these future leaders are gaining a broad and deep perspective on what it means to be a scientist. In years to come, the larger U.S. society will benefit from this.

The Center's research, education, and diversity missions have the potential to feedback positively on each other. Through its outreach and education work, CMMAP has built credibility with diverse communities. This credibility invites those communities to consider how CMMAP's science mission can serve their priorities. CMMAP's experience in knowledge transfer provides strategies for moving from the basic research to practical knowledge that the communities can use. Finally, the broad experiences of CMMAP graduate students prepare them to link research, education, and diversity. This a positive feedback loop that enriches the research, attracts diverse communities and students, and transfers knowledge to users, all based on the connections that are forged within the Center.

How the CHECRA funding was used

CHECRA is providing CMMAP with $150,000 per year, total of five years, for a total of $750,000. CMMAP will use the full $150,000 of CHECRA funds allocated for the current year.

The CHECRA funds are partially supporting one administrative professional and three research scientists at Colorado State University. The administrative personnel provide essential operational support for CMMAP, including financial management and the organization of a broad range of research and educational activities. The three research scientists who are receiving partial salary support from CHECRA are Ross Heikes, Celal Konor, and Minoru Chikira. They are developing new mathematical methods to represent weather and climate processes, and doing theoretical work on the role of water vapor in the tropical atmosphere.

In addition, some of the CHECRA funds are being used to support components of a computer cluster including two RAIDs (Redundant Array of Inexpensive Disks) which serves as an expansion of disk storage for extensive cloud modeling data as well as computer modeling workstations. The Science and Technology Center requires high capacity workstations for data collection, processing, and model integrations. CMMAP's super parameterizations cloud modeling projects involve exclusive model output that is highly specialized and intended primarily for analysis by the project team.

Summary of Benefits to the State of Colorado

- CMMAP was renewed by the National Science Foundation through July 2016, through an award of $17,991,000 to Colorado State University, much of which is used to pay the salaries of staff and graduate students who live in Colorado.
- CMMAP reached over 20,000 K-12 students and teachers through the activities of the Little Shop of Physics (LSOP) in more than 40 school visits, science workshops and the LSOP annual open house.
- CMMAP provided an intensive week long training to 36 teachers, elementary through high school with the Teaching Weather and Climate Summer Teacher Course.

- CMMAP supported the Windows to the Universe website, which had 6,158,872 page views from 4,050,930 visitors.
- CMMAP supported 16 CSU graduate students and 12 undergraduate summer interns. Several of these interns are expected to attend graduate school at CSU.
- CMMAP has hosted team meetings in Fort Collins annually bringing about 40 visitors per year to Colorado.
- CMMAP supported the 2014 LSOP Weather and Science Day which was held at Coors Field in Denver, CO on April 23, 2014. This educational event provides an interactive presentation that incorporates physics, math, and meteorology into unique science experiments and reaches an audience of ~15,000 middle and high school students. The number of students participating qualified this for the Guinness Book of World Records: Breaking the world record for the largest practical science lesson.
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Journal Publications for 2014

1. Arnold, N., M. Branson, M. A. Burt, D. S. Abbot, Z. Kuang, D. A. Randall, and E. Tziperman, 2014: Significant consequences of explicit representation of atmospheric convection at high CO_2 concentration. Submitted to *Proc. Nat. Acad. Sci.*
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Appendix F: School of Mines, Water Quality and Supply Impacts from Climate-Induced Insect Tree Mortality

Integrated GroundWater Modeling Center (IGWMC)
Colorado School of Mines
CHECRA Grant: $75,000 (per year for 5 years)
Reporting Period: January 1-December 31, 2014

Summary: IGWMC received $2.3 million from the National Science Foundation to examine the impact of the pine beetle devastation on vital watersheds in the Rocky Mountain west. The project is led by the Colorado School of Mines in collaboration with research partners from Colorado State University. The study examines the potential water resource changes resulting from the mountain pine beetle epidemic by examining changes in climate, forested ecosystems altered by pine beetle impacts, biogeochemical processes and resource management practices.

(a) A description of the project, the principal persons or entities involved in the project, and the amount of funding allocated to each principal person or entity;

Mountain headwaters in the western United States provide drinking water for more than 60 million people, as well as a broad range of agricultural, ecological, tourism, and industrial water users. The Platte and Colorado River basins alone provide water to more than 30 million residential users and 1.8 million acres of irrigated agriculture. A warming trend in the region has been accompanied by unprecedented tree mortality associated with the ongoing mountain pine beetle (MPB) epidemic, and the ramifications of this event on our water resources are not well understood. The goal of our proposed work is to determine potential water resource changes resulting from the MPB epidemic by defining feedbacks between climate change, insect driven forest disturbance, biogeochemical processes and management practices. This is accomplished with laboratory and field studies that feed fully-coupled, regional hydrologic and climatic models to interpret observations and assess management options that are developed through engaging stakeholders.

In addition to directly affecting the hydrologic cycle, climate change increases ecosystem susceptibility to stressors. Warmer winter minimum temperatures and persistent drought conditions have contributed to the ongoing MPB epidemic in the Rocky Mountains that has affected an estimated 4 million acres of lodgepole pine forests. Subsequent insect-induced stressors, such as the emerging engraver and twig beetle populations threatening young trees, are evidence of the long-term nature of this issue. Large-scale forest disturbances due to beetle-killed forests, as well as forest management practices, can significantly alter watershed hydrology, including evapotranspiration, infiltration, runoff, and surface energy fluxes in a region where snowpack is a critical water storage component. We address these land cover perturbations to the hydrologic cycle across a range of scales (hillslope, watershed and regional) using a combination of integrated hydrologic models, hydrologic-atmospheric models and observations.

Just as importantly, soil-vegetation disturbances from beetle-killed forests or forest management may also impact water quality by increasing particulate transport through erosion, increasing nitrification rates and organic carbon fluxes, which can cause decreased soil solution pH, and increasing mobilization and subsequent leaching of metals and metalloids. Similarly, increases in dissolved organic carbon (DOC) in the water supply may lead to increased formation of drinking water disinfection byproducts such as U.S. EPA regulated compounds trihalomethanes, haloacetic acids, and nitrosamines. These potential impacts of climate change, beetle-killed forests, and management practices on water quantity and quality pose significant threats to public health and the regional economy. In order to accurately assess anthropogenic impacts on hydrology and water resources in mountain watersheds an integrated approach must be taken that accounts for

interactions and feedbacks not just within the hydrologic cycle but also between the natural (climate, hydrologic, ecological, and biogeochemical) and human (water and forest management) factors that influence water quantity and quality. To directly address the impacts of changing land cover on the fate and transport of metal and organic compounds we employ field and laboratory studies and reactive transport simulations.

Principal Investigators	Funding from CHECRA
Reed Maxwell, Director and Project Lead for Coupled Modeling	$3,851
Jonathan Sharp	$0
John McCray	$28,302
Alexis Navarre-Sitchler	$0
Total Spending (Jan. – Dec. 2014)	$46,067

Students and Postdocs (*funded through CHECRA)

Name	Affiliation	Work
Nick Engdahl	CSM postdoctoral research fellow	Multi-scale modeling of the effects of landscape and climate changes on integrated hydrologic systems
Colin Penn*	CSM graduate student	Modeling work to incorporate distributed MPB specific parameters into the vegetation aspects of Common Land Model (CLM)
Jennifer Jefferson*	CSM graduate student	Modeling an idealized domain with homogeneous forest land cover and a heterogeneous subsurface representation of a Rocky Mountain watershed
Moira Pryhoda	CSM graduate student	Pine needle leachate chemistry from a mountain pine beetle infested watershed in Summit County, CO
Kristin Mikkelson	CSM postdoctoral research fellow	Bark beetle infestation impacts on nutrient cycling, water quality and interdependent hydrological effects
Lindsay Bearup	CSM postdoctoral research fellow	Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds
Sophia Seo	CSM graduate student	Sensitivity analysis on the land surface model parameters
Brent Brouillard	CSM graduate student	Drinking water quality impacts
Nicolas Jeangros	CSM graduate student	Modeling future impacts of forest insect infestations on the carbon cycle in streams and groundwater
Mary Michael Forrester	CSM graduate student	Modeling groundwater age resulting from transpiration loss in beetle-infested areas
Nicole Bogenschuetz	CSM undergraduate student	Field characterization of soil mineralization
Andrew Maloney	CSU undergraduate student	Stakeholder outreach and surveys
Adam Mitchell	CSU undergraduate student	Stakeholder outreach and surveys

(b) The manner in which each principal person or entity applied the funding in connection with the project

Reed Maxwell: Partial tuition and stipend support for two graduate students at CSM: Colin Penn (MS student, HSE) and Jennifer Jefferson (PhD Student, HSE). Colin is conducting high-performance computer modeling work to understand the impacts of the mountain pine beetle infestation on snowpack and runoff in the Big Thompson Watershed in Rocky Mountain National Park. Jennifer is conducting high resolution hillslope modeling for a site in Breckenridge, CO, to understand how heterogeneous forest land cover and a heterogeneous subsurface interact with selective beetle-killed trees to impact hydrology (snowpack and runoff). Partial summer salary was also provided to Prof Maxwell who is supervising students Bearup, Jefferson, Penn and co-supervising Mikkelson and supervising Dr. Engdahl.

Alexis Navarre-Sitchler: Partial summer salary to the Assistant Professor. Prof. Sitchler is supervising graduate student Pryhoda and co-supervising Bearup and Mikkelson who work on metals transport using field observations and laboratory experiments to better understand stream water quality as a result from the pine beetle infestation in Colorado's Rocky Mountains.

John McCray: Dr. McCray is supervising and giving partial tuition and stipend support to graduate student Nicolas Jeangros, who is working on modeling the future impacts of forest insect infestations on the carbon cycle in streams and groundwater.

(c) The results achieved by the project

This past year has included laboratory, field and data analysis to further research the impact the pine beetle infestation has on water quality in the Rocky Mountain West. Column experiments were run to determine the impact pine needle leachate has on metal mobility, along with the gathering of field soil water samples under beetle impacted trees. The soil-water samples were used to determine if correlations existed between different metals and DOC content. These results were analyzed and published (see Mikkelson et al 2014).

Isotope data analysis was completed, including an end-member mixing study to determine the change in contributions to streamflow with bark beetle infestation. In this study, we hypothesized that MPB-induced changes in transpiration would impact flow partitioning differently than changes in interception or ground evaporation and would be reflected at the watershed scale as increased groundwater contributions to streamflow. Our analysis indicates increased groundwater contributions in the more heavily and recently impacted watersheds. Furthermore, water budget analysis suggests these changes are consistent with expectations of flux changes from transpiration loss. This work was published in Nature Climate Change (Bearup et al 2014a). The results of our analyses improve our understanding of the flow paths transporting carbon and metals to the streams, and if the MPB is impacting water sources and residence times in these high mountain systems. These findings help inform water management decisions from both a water supply and quality perspective in addition to advancing our knowledge of tree water use as part of the water budget at the watershed scale. The main focus of this research over the remainder of the project is to complete any isotope analysis and use hydrologic models to provide additional interpretation of the isotope results.

Appendix F: School of Mines, Water Quality and Supply Impacts from Climate-Induced Insect Tree Mortality

Sequential extractions on soils collected in 2012 were completed to determine changes in metal partitioning and mobility in MPB-impacted forests. Additional modeling analysis was also conducted in order to further interpret the lab/field results. This work found that changes in organic complexation and soil organic matter is the primary driver of the difference in metal mobility under trees during different stages of attack (see Bearup et al 2014b). Also, we used batch experiments to determine the leachate chemistry of pine needles from trees in three stages (the green, red and gray stages) of MPB infestation from Summit County, CO, a watershed currently experiencing the MPB impact on water quality and ultimately groundwater geochemistry.

This past year's modeling activities included development, testing, and refinement of integrated numerical models for the pine beetle impacted study site(s). The large scale ParFlow-CLM model (1km resolution ~300km2) with impacted and unimpacted scenarios has been completed for the years 1995 through 1998. The remaining years (up to 2010) are being run sequentially and should be completed soon. The model outputs are currently being analyzed and post-processed in preparation for the first publication associated with the Colorado wide domain. This analysis will also provide a direct comparison to the Big Thompson and East Inlet model domains. A smaller scale model (20m resolution) of a watershed within Rocky Mountain National Park has also been constructed and is being used to investigate how environmental tracers may be used to identify changes in the distribution of water in beetle impacted watersheds (Engdahl and Maxwell, 2014).

A model of the Big Thompson watershed has been completed and used to determine estimates of beetle-impact on hydrology across a range of scales (stand to watershed) for an average climatological year (Penn, MS thesis; Penn et al 2014). Findings show that while the model accurately represents small-scale observations, larger scale behavior is affected by many compensating factors that mute the response signal yielding only a 10% change in watershed streamflow response. This response is smaller than inter-annual variability and would thus be difficult to detect in a noisy streamflow observation record.

We also have worked on the relationship between subsurface and surface characteristics, and surface fluxes like evapotranspiration (ET), one aspect that is significantly altered as a result of the mountain pine beetle infestation. We used ParFlow (PF), coupled with the Common Land Model (CLM), to model an idealized domain with homogeneous forest land cover and a heterogeneous subsurface representation of a Rocky Mountain watershed. Several scenarios with varying surface slopes and subsurface conditions were modeled to obtain annual ET distributions that were spatially-averaged at different resolutions. The average ET magnitude remained the same for each scenario regardless of the model resolution, while the standard deviation decreased with decreasing resolution. The relationship between hydraulic conductivity and ET was also found to vary with subsurface heterogeneity, anisotropy and conductivity magnitude; understanding these details, as well as the respective equations within PF-CLM that influence these relationships, is the focus of current research efforts.

Professor John McCray and PhD Student Nicolas Rodriguez are working on developing watershed and regional scale models that can efficiently simulate current impacts and predict future impacts of forest insect infestations on the carbon cycle in streams and groundwater, and eventually other important components of the biogeochemical cycle (i.e., N, P, O), as well as contaminants of interest (e.g., metals). However, watershed-scale hydro-chemical models require numerous input parameters, many of which may be correlated with each other, or the model is not sensitive to many of the input parameters. Under these circumstances, even a rigorously calibrated model may not produce unique results, and thus is not likely to be valid for future periods outside of the period

wherein calibration data was collected. Thus, the first step in this research is to conduct rigorous geospatial statistical studies to better understand the primary variables and input parameters that are most important to include in a watershed-scale hydro-chemical model wherein carbon cycling is a primary component. Three primary activities were performed during the reporting period:

- Literature review about the effect of insect infestations on the composition of dissolved organic matter including how those alterations affect metal mobility (write up in progress).

- Comparison of different statistical methods, including ordinary kriging, universal kriging, and top-kriging, for estimation of dissolved organic carbon (DOC) in streams using MPB infestations, elevation, slope, land cover, and precipitation.

- Identification of covariates that affect the carbon cycle in MPB affected forests in western Colorado using a simultaneous autoregressive (SAR) model (In progress).

(d) Education and outreach activities

In addition to publications in peer-reviewed journals, presentations at conferences, as noted below, two Pine Beetle Cafes were conducted directed at stakeholders, water providers and consultants in the Rocky Mountain West, and a number of press activities targeted a non-scientific public.

The pine beetle cafe were held at the American Water Works Association Rocky Mountain Section Annual Meeting held in September, 2013, and the Sustaining Colorado Watersheds Conference held in October, 2014 in Avon, CO. These meetings target water resources professionals (providers, regulators and consultants) over the entire Rocky Mountain region. The outreach occurred in two segments: a traditional presentation format where five presentations from this NSF pine beetle WSC project were delivered by project PIs. The second component was a "world-cafe" style discussion on stakeholder perceptions of beetle issues with approximately 21 in attendance over the two conferences. The goals of this activity were to determine previous stakeholder knowledge, enhance stakeholder communication, elicit unforeseen stakeholder concerns, to discover stakeholder perceptions of water quality and to further public communication and general education. The activity was very successful; in addition to better education of stakeholders around beetle impacts, several stakeholder priorities were discovered clustered around several main areas including: water quality, water quantity, streamflow, and increased fire risk.

Additional K-12, university, and professional education outreach activities resulting from this project include:

- Bearup LA. "Ecohydrology and Streamflow Generation Processes" 1-credit course focusing on streamflow generation processes, residence time distributions, and the role of vegetation in catchment response. 8 graduate students enrolled in the course. Delivered in Fall 2014

- Bearup LA, JL Jefferson, NB Engdahl, and RM Maxwell, Math and science events at three local elementary schools (4/18/13 Shelton Elementary; 9/26/13 and 9/23/14 Mitchell Elementary; 11/19/13 Dennison Elementary) – At these events, we teach students elements of the water cycle and how water and contaminants move through the natural environment using a variety of visual and interactive activities.

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- Bearup, Maxwell, Mikkelson, Sharp Judged two Elementary Science Fair – 2/1/13 Evergreen Country Day & 1/30/14 Mitchell Elementary

- Mikkelson KM, N Engdahl and JE McCray. Ecohydrological impacts from climate-induced changes in land cover and vegetation in mountain environments, Co-chaired a session at the 2013 GSA annual meeting (October)

- J. Sharp. "Biogeochemical Impacts on Water Sustainability" 1-credit course focusing on biogeochemistry of the mountain pine beetle and feedbacks into water quality. 14 graduate students enrolled in the course. Delivered in Fall 2013

Publications:

- Bearup, LA, RM Maxwell, DW Clow, JE McCray. (2014a). Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds. Nature Climate Change. **4**:481–486 (2014). doi: 10.1038/nclimate2198

- Bearup LA, Mikkelson KM, Wiley JF, Navarre-Sitchler AK, Maxwell RM, Sharp JO, McCray JE (2014b) Metal partitioning and mobilization mechanisms in soils under back beetle-killed trees. In review. Science of the Total Environment.

- Engdahl, N.B. and R.M. Maxwell (2014) Approximating groundwater age distributions using simple streamtube models and multiple tracers. Advances in Water Resources, ADWR2158, DOI: 10.1016/j.advwatres.2014.02.001

- Engdahl, N.B. (2014), Equivalence of the Time and Laplace Domain Solutions for the Steady-State Concentration of Radiometric Tracers and the Groundwater Age Equation, Water Resources Research, 50, doi: 10.1002/2014WR015413.

- Mikkelson, KM, LA Bearup, AK Navarre-Sitchler, JE McCray, JO Sharp. (2014) Changes in metal mobility associated with bark beetle-induced tree mortality. Environmental Science: Processes & Impacts 16 (6):1318-1327. doi: 10.1039/C3EM00632H

- Mikkelson KM, Bearup LA, Maxwell RM, Stednick JD, McCray JE, and Sharp JO (2013) Bark beetle infestation impacts on nutrient cycling, water quality and interdependent hydrological effects. Biogeochemistry. 115,1-21.

- Mikkelson KM, Dickerson E, McCray JE, Maxwell RM, Sharp JO (2013) Water-quality impacts from climate-induced forest die-off. Nature Climate Change 3, 218-222.

- Mikkelson KM, Maxwell RM, Ferguson I, McCray JE, and Sharp JO (2013) Mountain pine beetle infestation impacts: Modeling water and energy budgets at the hill-slope scale. Ecohydrology 6, 64-72.

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Presentations:

- Bearup, LA, RM Maxwell. Using particle tracking to link changing streamflow contributions to transpiration loss in bark beetle infested watersheds. International Conference on Computational Methods in Water Resources; Stuttgart, Germany, 10-13 June 2014.

- Bearup, LA, RM Maxwell. Changing stream water sources in insect-infested forests: a combined field and modeling analysis. European Geosciences Union General Assembly; Vienna, Austria, 27 April - 2 May 2014.

- Bearup LA, RM Maxwell, C Penn, DW Clow, JE McCray. Connecting increased groundwater contributions to transpiration losses in bark beetle infested watersheds. AGU Fall Meeting, San Francisco, Calif., 9-13 December 2013.

- Bearup LA, KM Mikkelson, AK Navarre-Sitchler, RM Maxwell, JE McCray, JO Sharp. Metal Mobility in Bark Beetle-Infested Forests. GSA Annual Meeting, Denver, Colorado, 2013 Oct 27-30.

- Bearup LA, C Penn, RM Maxwell, DW Clow, JE McCray, JO Sharp. Unraveling the interconnection between hydrology and geochemistry in mountain pine beetle infested watersheds using stable isotopes and modeling. Poster at MODFLOW and More, Golden, Colorado, 2-5 June 2013.

- Bearup LA, RM Maxwell, DW Clow, JE McCray, JO Sharp. Interpreting watershed scale hydrological alterations from widespread mountain pine beetle infestation using stable isotopes. Poster at Hydrology Days, Fort Collins, Colorado, 25-27 March 2013.

- Brouillard B, E Dickenson, and J Sharp. Seasonal Variations in Water Quality from Mountain Pine Beetle Induced Forest Die-Off. 2014 annual AWRA symposium in Golden, CO.

- Engdahl, NB, Maxwell, R.M., and Lopez, S.R. (2014) Urbanization effects on groundwater residence time distributions, 20th conference on Computational Methods in Water Resources (CMWR), June 10-14, 2014, University of Stuttgart, Stuttgart, Germany.

- Engdahl NB, and Maxwell, R.M. (2013) Realistic modeling of environmental tracer migration and composite age distributions in a pine beetle impacted watershed, Poster presentation H53F-1490, American Geophysical Union, Fall Meeting, December 9-13, 2013, San Francisco, CA.

- Engdahl, N.B., and Maxwell, R.M. (2013), Multi-scale modeling of the effects of landscape and climate changes on integrated hydrologic systems, Oral presentation T43-309-3, Geological Society of America, Annual Meeting, October 27-30, 2013, Denver, CO

- Jefferson JL, RM Maxwell. Understanding impacts of subsurface and surface heterogeneity on evapotranspiration in mountain pine beetle infested watersheds. Poster at AGU Fall Meeting, San Francisco, Calif., 9-13 December 2013.

- Jefferson JL, RM Maxwell. Understanding impacts of subsurface and surface heterogeneity on evapotranspiration in mountain pine beetle infested watersheds. GSA Annual Meeting, Denver, Colorado, 2013 Oct 27-30.

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- Mikkelson KM, LA Bearup, AK Navarre-Sitchler, JE McCray and JO Sharp. Changes to subsurface metal mobility in a bark beetle-impacted forest. 2014 annual NGWA conference in Denver, CO.

- Mikkelson KM, Will the bark beetle infestation affect water quality at water treatment plants in the Rocky Mountain West?, June 11th, 2013 AWWA conference in Denver, CO.

- Mikkelson KM , Will the bark beetle infestation affect water quality in the Rocky Mountain West?, May 14th, 2013 at the RMSWAWWA/RMWEA student conference at CSM, Golden, CO

- Mikkelson KM, Will the bark beetle epidemic impact water quality? Results from Colorado municipal water treatment facilities, February 18th, 2013 at the Institute of Arctic and Alpine Research, Boulder, CO.

- Navarre-Sitchler A, Pryhoda M, Dickenson E, Bearup L, Mikkelson K, Maxwell R, Sharp J, McCray JE. Changing soil chemistry in Rocky Mountain forests impacted by the mountain pine beetle. Goldschmidt 2014. Sacramento, CA. June 8-13, 2014

- Penn CA, RM Maxwell, NP Engdahl, DW Clow. Effects of bark beetle infestation on hydrology and land-energy feedbacks in mountain headwaters. American Geophysical Union Fall Meeting, San Francisco, CA, 9-13 December 2013

- Pryhoda MK, AK Navarre-Sitchler, E Dickenson. Pine needle leachate chemistry from trees in three stages of mountain pine beetle attack. MODFLOW and More, Golden, Colorado, 2-5 June 2013.

- Pryhoda MK, AK Navarre-Sitchler, E Dickenson. Pine needle leachate chemistry from a mountain pine beetle infested watershed in Summit County, CO. GSA, Denver, Colorado, 27-30 October 2013.

- Pryhoda MK, AK Navarre-Sitchler, E Dickenson. Impact of pine needle leachate chemistry from a mountain pine beetle infested watershed on groundwater geochemistry. AGU, San Francisco, California, 9-13 December 2013.

- Sharp JO, Mikkelson KM, McCray J, Maxwell R, Dickenson E. The Apple Doesn't Fall Far from the Tree: Applying Estuarine Principles to Watershed Biogeochemistry. Ocean Sciences Meeting. Honolulu, Hawaii. Feb 23-28, 2014.