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14. ABSTRACT
This project made advances in data assimilation and modeling capabilities for predicting soil moisture states and fluxes at the sub-watershed scale by using calibration information from a network of high-quality observation sources at a range of scales including remote sensing data and field sites. The sub-watershed is the semiarid mountain front above Boise, Idaho which has two well-characterized field sites (Boise Hydrogeophysical Research Site, BHRS, a riparian setting at the base river boundary of the block, and Dry Creek Experimental Watershed,

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19a. NAME OF RESPONSIBLE PERSON
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19b. TELEPHONE NUMBER
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Report Title

Final Report on Measuring and Modeling Hydrologic Fluxes and States from Aquifer to Atmosphere at Multiple Scales

ABSTRACT

This project made advances in data assimilation and modeling capabilities for predicting soil moisture states and fluxes at the sub-watershed scale by using calibration information from a network of high-quality observation sources at a range of scales including remote sensing data and field sites. The sub-watershed is the semiarid mountain front above Boise, Idaho which has two well-characterized field sites (Boise Hydrogeophysical Research Site, BHRS, a riparian setting at the base river boundary of the block, and Dry Creek Experimental Watershed, DCEW, spanning open to forested slopes to the crest of the block). We have added instrumentation and monitored saturated and partially saturated moisture behavior between river, aquifer, vadose zone, and atmosphere at the BHRS to quantify fluxes and support direct and non-invasive geophysical (especially radar and electrical) method development for measuring moisture and physical properties and their spatiotemporal variations at high resolution. Similar activities have taken place at the DCEW as well as model developments and assessments of DCEW data on the ground and from satellites for validation and verification in data assimilation including downscaling of fractional snow cover and slope-aspect moisture regimes. Students and collaborators (within Boise State and extramural) are involved in all aspects of this project.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
05/21/2012	38	Jennifer L. Pierce, Alejandro N. Flores, Michael J. Poulos, Shawn G. Benner. Hillslope asymmetry maps reveal widespread, multi-scale organization, Geophysical Research Letters, (03 2012): 0. doi: 10.1029/2012GL051283
05/21/2012	39	M. Cardiff, W. Barrash, P. K. Kitanidis. A field proof-of-concept of aquifer imaging using 3-D transient hydraulic tomography with modular, temporarily-emplaced equipment, Water Resources Research, (05 2012): 0. doi: 10.1029/2011WR011704
12/18/2013	51	Brady Johnson, Bwalya Malama, Warren Barrash, Alejandro N. Flores. Recognizing and modeling variable drawdown due to evapotranspiration in a semiarid riparian zone considering local differences in vegetation and distance from a river source, Water Resources Research, (02 2013): 0. doi: 10.1002/wrcr.20122
12/19/2013	52	Warren Barrash, Peter K. Kitanidis, Michael Cardiff. Hydraulic conductivity imaging from 3-D transient hydraulic tomography at several pumping/observation densities, Water Resources Research, (11 2013): 0. doi: 10.1002/wrcr.20519

TOTAL: 4

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
TOTAL:	**5**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Barrash, W., Cardiff, M., and Kitanidis, P., 2012, 3D Transient hydraulic tomography (3DTHT): An efficient field and modeling method for high-resolution estimation of aquifer heterogeneity (abs.): AGU Fall Annual Meeting, Dec 2012, San Francisco, CA, Abstract H33G-1422.

Leven, C., Barrash, W., and Cardiff, M., 2012, Using optic pressure measurements in hydrogeology - New experimental possibilities (abs.): AGU Fall Annual Meeting, Dec 2012, San Francisco, CA, Abstract H33G-1421.

Loughridge, R., Benner, S., McNamara, J., and Flores, A., 2012, Remote sensing data to classify functional groups of vegetation and their distribution and abundance in a semiarid mountain watershed, Idaho, USA (abs.): AGU Fall Annual Meeting, Dec 2012, San Francisco, CA, Abstract H21B-1173.

McCutcheon, R., Benner, S., Kohn, M., Flores, A., McNamara, J., 2012, Stable isotopes of water used to trace relationships between vegetation and streamflow in a semi-arid catchment (abs.): AGU Fall Annual Meeting, Dec 2012, San Francisco, CA, Abstract H31B-1121.

Thoma, M., Barrash, W., and Bradford, J., 2012, Quantifying magnitude, timing, and distribution of mass flux at a river-aquifer boundary using head and temperature response to step and seasonal changes in river stage and a variable river edge boundary (abs.): AGU Fall Annual Meeting, Dec 2012, San Francisco, CA, Abstract H14B-05.

Walters, R., Watson, K., and Flores, A., 2012, A physiographic approach to downscaling remotely sensed fractional snow cover data, (abs.): AGU Fall Annual Meeting, Dec 2012, San Francisco, CA, Abstract C21C-0633.

Barrash, W., Cardiff, M., and Kitanidis, P., 2011, Quantitative imaging of 3D aquifer heterogeneity with hydraulic tomography: Approaching a tractable field and modeling system, Poster 222 presented at the SERDP-ESTCP 2011 Symposium, Nov-Dec 2011, Washington DC.

Bradford, J., 2011, Frequency Dependent Attenuation Analysis of GPR Data for Material Property Characterization: A Review and New Developments: Keynote talk given at International Workshop on Advanced Ground-Penetrating Radar, Aachen, Germany

Cardiff, M., 2011, Data weighting & estimate updating: Novel and time-tested strategies for getting the best predictions out of multiple data sources (Invited), H42F-01 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Cardiff, M., Barrash, W., and Kitanidis, P, 2011, Advances toward field application of 3D hydraulic tomography, H53N-07 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Cardiff, M. and Barrash, W., 2011, 3D hydraulic tomography at the BHRS: Results and lessons from the field (abs.): NovCare Conference Novel methods for Subsurface Characterization and Monitoring, May 2011, Cape Cod, MA.

Cardiff, M., Barrash, W., and Kitanidis, P., 2011, Bringing 3D hydraulic tomography into field practice: Opportunities, complications, and new developments (abs.): NGWA Ground Water Summit and Spring Meeting, May 2011, Baltimore, MD.

Eriksson, D., McNamara, J., Marshall, HP, and Bradford, J., 2011, Assessment of the hydrologic significance of lateral water flow in snow, C33E-0688 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Flores, A., LaPorte, P., Smith, K., 2011, Developing a regional retrospective ensemble precipitation dataset for watershed hydrology modeling, Idaho, USA, H41C-1049 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Hopkins, A., Heilig, A., Marshall, HP, and Flores, A., 2011, Potential application of NASA SMAP radar data to detect the aerial extent of snowpack melt, H23G-1360 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Kunkel, M., Raff, D., Brekke, L., and Flores, A., 2011, Non-Stationarity in Atmospheric and Oceanic Teleconnections: Historical Effects on Streamflow and Statistical Models for Forecasting Streamflows, H42H-02 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Loughridge, R., LaPorte, P., Benner, S., McNamara, J., and Flores, A., 2011, Quantifying topographic controls on the distribution and abundance of terrestrial vegetation in a semiarid mountain watershed, Idaho, USA, H13E-1249 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Poulos, M., Pierce, J., Flores, A., Benner, S., and McNamara, J., 2011, Valley Asymmetry and Topoclimate-Driven Feedbacks among Hillslope Hydrology, Soil Development, Vegetation, and Erosion, EP31A-0793, presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Tappa, D., Aishlin, P., Kohn, M., Benner, S., McNamara, J., Flores, A., 2011, Stable Isotope Compositions of Precipitation in a Semi-Arid Climate: Variations from the Global Meteoric Water Line, PP21A-1764 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Thoma, M., Barrash, W., and Bradford, J., 2011, Infiltration Experiment to Determine Vadose Zone Hydrologic Properties of a Stony Sediment Sequence Incorporating Geophysical Methods, H43E-1272 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Walters, R., McNamara, J., Marshall., HP., and Flores, A., 2011, A physically-based approach to downscale coarse snow model output for hydrologic modeling at hillslope scales, C33D-0668 presented at AGU Annual Mtg, Dec. 2011, San Francisco, CA.

Barrash, W., Flores, A., Bradford, J., and McNamara, J., 2010, Measuring and modeling hydrologic fluxes and states from aquifer to atmosphere at multiple scales: presentation to 3rd Interagency Land Surface Dynamics Coordination Meeting, February 11-12, 2010, CRREL, Hanover, NH.

Barrash, W., Bradford, J., Cardiff, M., Dafflon, B., Johnson, B., Malama, B., Thoma, M., 2010, Integrated site investigation methods and modeling: Recent developments at the BHRS (abs.): AGU Fall Annual Meeting, Dec 2010, San Francisco, CA, Abstract H24E-04 (Invited).

Boe, E., McNamara, J., and Marshall, HP, 2010, Quantifying snow variability using an inexpensive network of ultrasonic depth sensors (abs.): AGU Fall Annual Meeting, Dec 2010, San Francisco, CA, Abstract H11A-0796.

Burnop, A., Sridhar, V., McNamara, J., Flores, A., 2010, The impact of accurate parameterization of snow storage in operational hydrology models (abs.): AGU Fall Annual Meeting, Dec 2010, San Francisco, CA, Abstract H11G-0893.

Johnson, B., Malama, B., Barrash, W., and Flores, A., 2010, Characterization of evapotranspiration in the riparian zone of the Lower Boise River, with implications for groundwater flow (abs.): AGU Fall Annual Meeting, Dec 2010, San Francisco, CA, Abstract H31B-0983.

McNamara, J., Link, T., Marks, D., Seyfried, M., Kumar, M., and Kormos, P., 2010, On the value local knowledge in conceptualizing physically-based models (abs.): AGU Fall Annual Meeting, Dec 2010, San Francisco, CA, Abstract H31L-05 (Invited).

Shallcross, A., McNamara, J., Flores, A., Marshall, HP, Marks, D., and Glenn, N., 2010, Estimating basin snow volume using aerial LiDAR and binary regression trees (abs.): AGU Fall Annual Meeting, Dec 2010, San Francisco, CA, Abstract C33C-0537 (Invited).

Thoma, M., Bradford, J., and Barrash, W., 2010, Ground penetrating radar response to water table drawdown and vadose zone dewatering (abs.): AGU Fall Annual Meeting, Dec 2010, San Francisco, CA, Abstract H11K-03.

Number of Presentations: 29.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
02/03/2012	24.00	Brady Johnson , Warren Barrash, Bwalya Malama , Alejandro Flores. Recognizing and modeling variable drawdown due to ET in a semi-arid riparian zone considering local di♂erences in vegetation and distance from a river source, Water Resources Research (01 2012)
02/03/2012	26.00	Michael Poulos, Alejandro Flores, Shawn Benner, Jennifer Pierce. Hillslope Asymmetry Maps Reveal Widespread, Multi-Scale Organization, Geophysical Research Letters (01 2012)
02/03/2012	25.00	Alejandro Flores, Rafael Bras, Dara Entekhabi. Hydrologic data assimilation with a hillslope-scale 1 resolving model and L-band radar observations: Synthetic experiments with ensemble Kalman filter , Water Resources Research (01 2012)
02/15/2011	9.00	I.J. Geroy, M.M. Gribb, H.P. Marshall, D.G. Chandler, S.G. Benner, J.P. McNamara. Aspect influences on soil water retention and storage, Hydrological Processes (02 2011)
02/16/2011	10.00	T. Smith, J. McNamara, A. Flores, M. Gribb, P. Aishlin, S. Benner. Limited storage capacity constrains upland benefits of winter snowpack, Hydrological Processes (02 2011)
05/06/2011	11.00	Dafflon, B., Barrash, W., Cardiff, M.. Hydrological parameter estimations from a conservative tracer test with variable-density effects at the Boise Hydrogeophysical Research Site, Water Resources Research (05 2011)
05/06/2011	12.00	Michael J. Thoma, James P. McNamara, Molly M. Gribbb, Shawn G. Benner. Seasonal Recharge Components in an Urban/Agricultural Mountain Front Aquifer System Using Noble Gas Thermometry, Journal of Hydrology (05 2011)
06/21/2011	13.00	Cardiff, M. and Barrash, W.. 3D transient hydraulic tomography in unconfi♀ned aquifers with fast drainage response, Water Resources Research (06 2011)
06/21/2011	14.00	Dafflon, B. and Barrash, W.. Benefits of using GPR velocity tomograms in conjunction with porosity log data for 3-D stochastic estimation of porosity distribution at the Boise Hydrogeophysical Research Site, Water Resources Research (05 2011)
06/28/2011	16.00	I.J. Geroy, M.M. Gribb, H.P. Marshall1, D.G. Chandler, S.G. Benner, and J.P. McNamara. Aspect influences on soil water retention and storage, Hydrological Processes (06 2011)
09/03/2010	1.00	B. Dafflon, J. Irving, W. Barrash. Inversion of multiple intersecting high-resolution crosshole GPR profiles for 3-D hydrological characterization, Wear (08 2010)

TOTAL: **11**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Modular hydraulic packer-and-port system (13/232,846 PCT/US11/61032)

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Brady Johnson	0.84	
Michael Thoma	0.96	
Reggie Walters	0.26	
FTE Equivalent:	**2.06**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Michael Cardiff	0.16
FTE Equivalent:	**0.16**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Warren Barrash	0.45	
Alejandro Flores	0.11	
John Bradford	0.11	
FTE Equivalent:	**0.67**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Jared Law	0.88	Computer and Computational Sciences
FTE Equivalent:	**0.88**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 1.00

Names of Personnel receiving masters degrees

NAME	
Brady Johnson	
Reggie Walters	
Ricci Loughridge	
Total Number:	**3**

Names of personnel receiving PHDs

NAME	
Michael Thoma	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

1 a. Colorado School of Mines

1 b. 1500 Illinois Street, Guggenheim Ha

Golden CO 804011887

Sub Contractor Numbers (c): 693G 1 06257 -A

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): The $20,000 sub-contract funds to Colorado School of Mines were primarily used for par

Sub Contract Award Date (f-1): 10/1/09 12:00AM

Sub Contract Est Completion Date(f-2): 9/30/13 12:00AM

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1 a. Colorado School of Mines

1 b. 1500 Illinois Street

Golden CO 804011911

Sub Contractor Numbers (c): 693G 1 06257 -A

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): The $20,000 sub-contract funds to Colorado School of Mines were primarily used for par

Sub Contract Award Date (f-1): 10/1/09 12:00AM

Sub Contract Est Completion Date(f-2): 9/30/13 12:00AM

Inventions (DD882)

Scientific Progress

* We have continued to focus on the use of remote sensing data to improve knowledge of hydrologic conditions at spatial scales of hillslopes. Specifically, we have developed a landscape physiography-based downscaling algorithm to downscale MODerate-resolution Imaging Spectroradiometer (MODIS) fractional snow covered area (fSCA) estimates at spatial scales of 500 m to produce a binary snow covered area (SCA) map at a spatial resolution of 30 m. The advantage of the MODIS fSCA product (MOD10A1) is that it provides daily estimates of fSCA in snow-covered regions. The principal disadvantage is the spatial resolution, which is too coarse for many Army applications. The developed algorithm uses remote sensing information in the form of 30 m digital elevation models (DEMs) to compute a terrain score within each MOD10A1 pixel. The terrain score is a simple linear combination of the normalized elevation and normalized slope factor. The slope factor combines slope and aspect angles and is meant to capture the fraction of direct beam solar radiation a pixel receives relative to a flat pixel for a particular day. The terrain score-based downscaling algorithm, which is parameterized only by the weights of the normalized elevation and slope factor and must sum to unity, is calibrated to reproduce a time series of historical Landsat retrievals of SCA at 30 m resolution. We then validate the algorithm against a Landsat SCA retrieval withheld from the calibration process (blind validation). While the Landsat SCA retrievals are a much higher spatial resolution, they are very sporadic in time because they represent remote sensing imagery from a single satellite overpass and are very sensitive to cloud contamination.

* To address the major challenge of the coarse resolution of the forcings, Dr. Flores' research group has begun the effort to produce a very high-resolution decadal forcing dataset for southwestern Idaho by running the Weather Research and Forecasting (WRF) model at sub-kilometer resolutions over the entire Boise River Basin, and at 2 km resolution over the entire Snake River Basin. Recent studies in the Colorado headwaters region found that in complex terrain, WRF simulations were able to reproduce observed, point-scale precipitation to within 10-15% accuracy when the resolution of the model was 6 km or finer. We are using WRF to generate hourly hydrometeorological forcings in southwest Idaho for the period from approximately 1984-present. In particular we are performing "production runs" now on the Yellowstone facility at the NCAR Wyoming Supercomputing Center. We are starting with Water Year 2009 because we have some novel Lidar data to validate simulated snow depths in Reynolds Creek. But we will be confirming against available point data (AgriMET, SNOTEL, SCAN, etc) and spatially distributed data (SNODAS, NEXRAD, etc). Once complete, the dataset will be uploaded, along with appropriate metadata, to a public data archive. This work is supported by a NASA EPSCoR grant (Remote Sensing of the Cryosphere: Calibration and Validation) and fills a critical gap in our current research interests.

* In late summer 2012, an undergraduate student installed sap flow sensors at a coniferous forest site in the Dry Creek Experimental Watershed. Sap flow sensors were initially installed in mature Ponderosa pine and Douglas fir trees. We have been interpreting preliminary sap flow data and transpiration estimates and will make adjustments to sensor placement prior to the beginning of the Spring 2013 green-up season (see below). On-going results will be used to check and/or calibrate assumptions and dynamics for ET components in local-scale and hillslope scale hydrologic modeling.

We have installed, in 2013, one set of sap flow sensors in Dry Creek Experimental Watershed and are monitoring several Ponderosa Pine and Douglas Fir individuals at this site. These data will be invaluable in confirming some preliminary results from the thesis of Ricci Loughridge that near infrared (NIR) reflectance in August, along with aspect, provides good discriminatory power for predicting the presence of ponderosa pine in semiarid landscapes. We hypothesize that this observation arises because Ponderosa Pine are adapted to put down tap roots that are able to extract water from the saturated zone (causing greater August NIR reflectance) while more shallow-rooted Douglas Fir rely on water from the unsaturated zone. Since August is the approximate time of highest water tension (lowest moisture content), the contrast between the NIR reflectance from Ponderosa and Douglas Fir becomes sufficiently large that it allows for discrimination between the species based, in part, on NIR reflectance. The sap flow sensors will allow us to test this hypothesis. Based on our hypothesis, we would predict that Ponderosa Pine are able to continue transpiring at a greater rate into the summer than Douglas Fir. To our knowledge NIR has not previously been identified as being able to discriminate between these coniferous species during periods of water stress.

* As follow-up to the in-situ infiltration test at the BHRS conducted in 2011, we have analyzed and modeled results to estimate unsaturated hydraulic conductivity in a vertical series of natural (coarse cobble conglomerate and sand) sediment units as functions of moisture content and tension, and including geophysical measurements for independent verification of wetting front movement through the different units. Also the time-lapse GPR and 3D ERT monitoring data from the experiment are available for joint inversion for lateral variation and calibration to variable moisture content for the local layers and lenses or different units. Important findings include (a) demonstration that moisture pass-through at high steady (e.g., most-intense storm equivalent) infiltration rate occurs over extended time periods at significantly less than saturated K, (b) interpretation of response and Brooks-Corey parameters indicate unsaturated K behavior is dominantly controlled by interconnected matrix with little influence by the cobbles (i.e., inclusion of cobbles in representative grain size calculations causes overestimation of unsaturated K), (c) van Genucthen-Mualem parameterization explains the unsaturated behavior of moisture content-tension-hydraulic conductivity without need for adjustments due to cobble presence or size etc, and (d) results at the infiltration test site are improved by treating the system as 2D (lateral variation in one of the layers) rather than 1D - which is consistent with the scale of heterogeneity observed in roadcuts and quarries for this scale of investigation.

Results are applicable to unsaturated fluid (moisture and gas) and heat fluxes in this widely occurring class of deposits (coarse conglomeratic sediments with minimal silt or clay) such as high-energy fluvial deposits and periglacial deposits. As such these results can help parameterize models in high-latitude cold regions with sensitive responses to environmental conditions and climate change - i.e., where high infiltration rates without ponding can be expected even for high-intensity storms. Also saturated hydraulic parameterization for such high-energy and periglacial deposits can be assisted by findings in the aquifer at the BHRS (see publications at http://cgiss.boisestate.edu/bhrs/#Publications).

* Variable head and mass flux river-aquifer boundary conditions are important for quantitative understanding of hydrologic processes in riparian systems, especially in semi-arid regions which are sensitive to water table fluctuations on daily, seasonal, and flood-event scales for both the saturated and vadose zone "compartments." For this project we have been monitoring temperature and hydraulic head profiles in, adjacent to, and at progressive distances from the river-aquifer boundary in both the saturated and unsaturated zones and with hydrologic and geophysical methods, Now we are modeling river-aquifer interaction to quantify mass flux, trace the spatial-temporal distribution of mass flux in the aquifer including vadose zone filling and draining, include local heterogeneity estimated with geophysical survey assistance, quantify pressure redistribution and mass displacement for the water table aquifer in detail in the hyporheic-river-edge zone and behavior 10s of meters away from the river edge including explicit representation of inundation associated with high river stages. Preliminary findings are encouraging for capturing long-term head and temperature behavior and for responses to more "instantaneous" step rises and drops in river stage. Heterogeneity based on GPR geophysical profiles is needed to match high-resolution monitoring data near the river-aquifer boundary. Accurate boundary representation of the river (including inundation) and sub-river is important for detailed near-boundary response matching. Modeling is nearly complete as of the end of 2013 and will be submitted for publication in a peer-reviewed journal in 2014.

* A database and database management system have been developed for the monitoring of aquifer-to-atmosphere and river-aquifer states and fluxes for this project - these are freely available to the public at the BHRS data repository page: http://cgiss.boisestate.edu/bhrs/bhrs-data/

The manual for use of the database is also available at this site. Data include: aquifer water levels at wells and piezometers; aquifer temperatures including temperatures at several depths in some wells; vadose zone moisture content, tension, and temperature profiles; river and sub-river heads and temperatures; and atmospheric temperature and pressure. Most of these measurements were taken at 15 min intervals during most of the project period from 2010 continuing into 2013.

* We are one of the leading groups in the development of hydraulic tomography. In particular we have developed and are improving an efficient field, data acquisition, and modeling system for 3D transient hydraulic tomography (3DTHT)that gives direct estimation of distributed 3D hydraulic conductivity, with uncertainty calculations, at high resolution (approximately 1m^3) in shallow aquifers including water table aquifers. Equipment from this DEPSCoR and associated DURIP grants have greatly assisted this development. Results are providing the capability to trace high and low conductivity bodies and interruptions in their continuity, and to trace variations in hydraulic conductivity within such bodies. This information is important for quantifying heterogeneity, providing heterogeneity models that can pass upward to the vadose zone, modeling aquifer responses to system forcing at boundaries and to detailed modeling of fluxes and states, and supporting groundwater contamination remediation decisions and designs, especially for source zones of difficult contamination sites.

Recent publications document improving capabilities with this method and support new findings on the spatial structure of saturated hydraulic conductivity - which is different than that for porosity and lithology and electrical conductivity in these coarse conglomeratic (high-energy fluvial and periglacial) sedimentary deposits. Follow-up demonstration of the 3DTHT method at a contaminated industrial site with greater hydraulic conductivity range and greater heterogeneity that at the BHRS is in progress; preliminary results strongly suggest that the method has general applicability in shallow aquifers.

* We have completed development and testing of four algorithms that represent substantial advances in both imaging of the vadose zone imaging and characterization of hydrologically relevant material properties. Each is described below.

- Joint petrophysical inversion of ground-penetrating radar (GPR), electrical resistivity (ER), and hydrologic data: We developed this algorithm to estimate porosity, saturation, and Archie's law parameters in the vadose zone from coincident, time lapse, multi-offset GPR and ER profiles. With GPR and ER, we can formulate a joint optimization for porosity and saturation based on GPR velocity and electric conductivity. However, we must solve for a third parameter – the saturation exponent in Archie's Law. We can solve this problem by adding the dimension of time to our formulation, assuming that there is significant change in water saturation over time. In our algorithm, we first estimate GPR velocity using reflection tomography with the multi-offset GPR data. An integral product of this process is production of an accurate map of reflecting boundaries. Because these reflecting boundaries necessarily occur at electrical property discontinuities, we incorporate this information into the inversion of ER data by relaxing the smoothness constraint at the position of the boundaries in the ER inversion. This has two benefits – first it improves the resolution of the ER inversion, and second since the same reflecting boundaries are explicitly incorporated into the GPR reflection tomography and ER inversion, it ensures that the two models are structurally consistent. The final step in the procedure is a joint petrophysical inversion. We form an integrated objective function using Archie's Law for the ER model, and the CRIM equation for the GRP velocity model. Porosity and water saturation are common parameters in the two petrophysical relationships and we invert directly for these distributions. Water saturation varies as a function of time whereas porosity is time independent. The solution becomes better constrained as the range of water saturations is increased and therefore long term monitoring over seasonal variations can improve the solution. The inversion is also designed to include other hydrologic information. For data collected at the BHRS, we integrated the site wide porosity distribution as a constraint in the inversion. This enables simultaneous estimation of the Archie's law exponent and improved estimation of the porosity and time dependent saturation distributions.

- Full-waveform inversion of GPR data for estimation of van Genuchten parameters using a coupled hydrologic and GPR forward model: The dynamic response of the capillary fringe during a pump test causes the water saturation curve to either stretch during drawdown or compress during recovery. When the dominant wavelength of a GPR signal is on the same order as the spatial extent of this dynamic portion of the saturation curve a strong reflection is generated near the point of full saturation. However, the reflected wavelet is highly sensitive to the shape of the saturation curve and stretching or compression of the curve causes substantial variations in the amplitude, phase, and spectrum of the wavelet. This sensitivity then provides the opportunity to invert for the hydrologic parameters that control the dynamic saturation response during a pump test. In our algorithm, we use a coupled hydrologic and GPR forward model to invert GPR data for saturated hydraulic conductivity , α and n van Genuchten parameters. Note that the method does not require the van Genuchten model and other models such as Brooks-Corey can easily be incorporated into the same framework. In the forward step, we use Hydrus 1D to simulate the dynamic saturation response to drawdown and then model the time-lapse GPR response using a 1D reflectivity algorithm. The reflectivity algorithm is the exact analytical solution to a finely layered medium, and we simulate a smooth saturation curve as a stack of discrete layers with variable saturation and each layer is much thinner than the GPR wavelength. The algorithm uses full frequency dependent electrical properties to simulate the GPR signal. In each iteration of the inversion, we first simulate the water saturation, then convert the water saturation to a dielectric permittivity and electrical conductivity model using the CRIM equation and Archie's Law respectively. With the electrical property model we then simulate the GPR response and compare to the measured GPR data. The van Genuchten parameters are then updated and the process is completed until the difference between the recorded and modeled GPR data are minimized. The GPR inversion is carried out in the time domain using a simplex grid search method, and we simultaneously invert for the effective GPR source wavelet.

- GPR prestack amplitude recovery for radiation patterns using a full wave-equation, reverse-time migration algorithm: While reverse-time, prestack migration (RT-PSDM) has become a common imaging method in seismic exploration, its use has remained relatively limited in GPR applications. Antenna radiation patterns have a significant impact on ground-penetrating radar (GPR) data amplitudes. Radiation patterns must be properly accounted for in quantitative amplitude analysis. We use a full wave-equation RT-PSDM algorithm to correct multi-offset, ground-penetrating radar (GPR) amplitudes for antenna radiation pattern effects. By including the earth-air interface in the source wavefield estimation, the radiation pattern effect is removed at the reflecting interface. Further, geometric spreading and attenuation due to conductivity are naturally corrected in the RT-PSDM framework. This approach can substantially improve the both the accuracy of GPR images and the amplitude information which is useful for subsequent estimation of material properties.

- Estimating Debye parameters from GPR reflection data using spectral ratios: In the GPR frequency range, electromagnetic wave attenuation is largely controlled by dielectric relaxation processes. A primary relaxation commonly occurs in the 10 – 100 MHz range for many earth materials in which the GPR signal propagates effectively. This relaxation leads to strong nonlinearity in the frequency dependent attenuation and occurs in a frequency range that is often used for groundwater investigations. This non-linearity complicates data analysis but also may provide additional material property information. We implemented a non-linear inversion for Debye relaxation parameters directly from GPR reflection data. Our approach includes increasing the bandwidth of the signal by summing the response from 25 MHz, 50 MHz, 100 MHz, and 200 MHz radar antennas. We first compute the time-frequency distribution of the GPR data using spectral decomposition, then use the method of spectral ratios to measure the attenuation vs frequency curve for significant reflection events. We then fit the curve with the multi-parameter Debye model. Using synthetic and field data we have shown that this approach provides reliable estimates of the primary relaxation time for a variety of realistic subsurface models. This approach has the potential to improve our understanding of aquifer material properties. We currently have manuscripts in preparation for each of the above projects and anticipate submission within the next 6 months.

Technology Transfer

Scientific Progress and Accomplishments

* We have continued to focus on the use of remote sensing data to improve knowledge of hydrologic conditions at spatial scales of hillslopes. Specifically, we have developed a landscape physiography-based downscaling algorithm to downscale MODerate-resolution Imaging Spectroradiometer (MODIS) fractional snow covered area (fSCA) estimates at spatial scales of 500 m to produce a binary snow covered area (SCA) map at a spatial resolution of 30 m. The advantage of the MODIS fSCA product (MOD10A1) is that it provides daily estimates of fSCA in snow-covered regions. The principal disadvantage is the spatial resolution, which is too coarse for many Army applications. The developed algorithm uses remote sensing information in the form of 30 m digital elevation models (DEMs) to compute a terrain score within each MOD10A1 pixel. The terrain score is a simple linear combination of the normalized elevation and normalized slope factor. The slope factor combines slope and aspect angles and is meant to capture the fraction of direct beam solar radiation a pixel receives relative to a flat pixel for a particular day. The terrain score-based downscaling algorithm, which is parameterized only by the weights of the normalized elevation and slope factor and must sum to unity, is calibrated to reproduce a time series of historical Landsat retrievals of SCA at 30 m resolution. We then validate the algorithm against a Landsat SCA retrieval withheld from the calibration process (blind validation). While the Landsat SCA retrievals are a much higher spatial resolution, they are very sporadic in time because they represent remote sensing imagery from a single satellite overpass and are very sensitive to cloud contamination.

* To address the major challenge of the coarse resolution of the forcings, Dr. Flores' research group has begun the effort to produce a very high-resolution decadal forcing dataset for southwestern Idaho by running the Weather Research and Forecasting (WRF) model at sub-kilometer resolutions over the entire Boise River Basin, and at 2 km resolution over the entire Snake River Basin. Recent studies in the Colorado headwaters region found that in complex terrain, WRF simulations were able to reproduce observed, point-scale precipitation to within 10-15% accuracy when the resolution of the model was 6 km or finer. We are using WRF to generate hourly hydrometeorological forcings in southwest Idaho for the period from approximately 1984-present. In particular we are performing "production runs" now on the Yellowstone facility at the NCAR Wyoming Supercomputing Center. We are starting with Water Year 2009 because we have some novel Lidar data to validate simulated snow depths in Reynolds Creek. But we will be confirming against available point data (AgriMET, SNOTEL, SCAN, etc) and spatially distributed data (SNODAS, NEXRAD, etc). Once complete, the dataset will be uploaded, along with appropriate metadata, to a public data archive. This work is supported by a NASA EPSCoR grant (Remote Sensing of the Cryosphere: Calibration and Validation) and fills a critical gap in our current research interests.

* In late summer 2012, an undergraduate student installed sap flow sensors at a coniferous forest site in the Dry Creek Experimental Watershed. Sap flow sensors were initially installed in mature Ponderosa pine and Douglas fir trees. We have been interpreting preliminary sap flow data and transpiration estimates and will make adjustments to sensor placement prior to the beginning of the Spring 2013 green-up season (see below). On-going results will be used to check and/or calibrate assumptions and dynamics for ET components in local-scale and hillslope scale hydrologic modeling.

We have installed, in 2013, one set of sap flow sensors in Dry Creek Experimental Watershed and are monitoring several Ponderosa Pine and Douglas Fir individuals at this site. These data will be invaluable in confirming some preliminary results from the thesis of Ricci Loughridge that near infrared (NIR) reflectance in August, along with aspect, provides good discriminatory power for predicting the presence of ponderosa pine in semiarid landscapes. We hypothesize that this observation arises because

Ponderosa Pine are adapted to put down tap roots that are able to extract water from the saturated zone (causing greater August NIR reflectance) while more shallow-rooted Douglas Fir rely on water from the unsaturated zone. Since August is the approximate time of highest water tension (lowest moisture content), the contrast between the NIR reflectance from Ponderosa and Douglas Fir becomes sufficiently large that it allows for discrimination between the species based, in part, on NIR reflectance. The sap flow sensors will allow us to test this hypothesis. Based on our hypothesis, we would predict that Ponderosa Pine are able to continue transpiring at a greater rate into the summer than Douglas Fir. To our knowledge NIR has not previously been identified as being able to discriminate between these coniferous species during periods of water stress.

* As follow-up to the in-situ infiltration test at the BHRS conducted in 2011, we have analyzed and modeled results to estimate unsaturated hydraulic conductivity in a vertical series of natural (coarse cobble conglomerate and sand) sediment units as functions of moisture content and tension, and including geophysical measurements for independent verification of wetting front movement through the different units. Also the time-lapse GPR and 3D ERT monitoring data from the experiment are available for joint inversion for lateral variation and calibration to variable moisture content for the local layers and lenses or different units. Important findings include (a) demonstration that moisture pass-through at high steady (e.g., most-intense storm equivalent) infiltration rate occurs over extended time periods at significantly less than saturated K, (b) interpretation of response and Brooks-Corey parameters indicate unsaturated K behavior is dominantly controlled by interconnected matrix with little influence by the cobbles (i.e., inclusion of cobbles in representative grain size calculations causes overestimation of unsaturated K), (c) van Genucthen-Mualem parameterization explains the unsaturated behavior of moisture content-tension-hydraulic conductivity without need for adjustments due to cobble presence or size etc, and (d) results at the infiltration test site are improved by treating the system as 2D (lateral variation in one of the layers) rather than 1D - which is consistent with the scale of heterogeneity observed in roadcuts and quarries for this scale of investigation.

Results are applicable to unsaturated fluid (moisture and gas) and heat fluxes in this widely occurring class of deposits (coarse conglomeratic sediments with minimal silt or clay) such as high-energy fluvial deposits and periglacial deposits. As such these results can help parameterize models in high-latitude cold regions with sensitive responses to environmental conditions and climate change - i.e., where high infiltration rates without ponding can be expected even for high-intensity storms. Also saturated hydraulic parameterization for such high-energy and periglacial deposits can be assisted by findings in the aquifer at the BHRS (see publications at http://cgiss.boisestate.edu/bhrs/#Publications).

* Variable head and mass flux river-aquifer boundary conditions are important for quantitative understanding of hydrologic processes in riparian systems, especially in semi-arid regions which are sensitive to water table fluctuations on daily, seasonal, and flood-event scales for both the saturated and vadose zone “compartments.” For this project we have been monitoring temperature and hydraulic head profiles in, adjacent to, and at progressive distances from the river-aquifer boundary in both the saturated and unsaturated zones and with hydrologic and geophysical methods, Now we are modeling river-aquifer interaction to quantify mass flux, trace the spatial-temporal distribution of mass flux in the aquifer including vadose zone filling and draining, include local heterogeneity estimated with geophysical survey assistance, quantify pressure redistribution and mass displacement for the water table aquifer in detail in the hyporheic-river-edge zone and behavior 10s of meters away from the river edge including explicit representation of inundation associated with high river stages. Preliminary findings are encouraging for capturing long-term head and temperature behavior and for responses to more “instantaneous” step rises and drops in river stage. Heterogeneity based on GPR geophysical

profiles is needed to match high-resolution monitoring data near the river-aquifer boundary. Accurate boundary representation of the river (including inundation) and sub-river is important for detailed near-boundary response matching. Modeling is nearly complete as of the end of 2013 and will be submitted for publication in a peer-reviewed journal in 2014.

* A database and database management system have been developed for the monitoring of aquifer-to-atmosphere and river-aquifer states and fluxes for this project - these are freely available to the public at the BHRS data repository page:
http://cgiss.boisestate.edu/bhrs/bhrs-data/

The manual for use of the database is also available at this site. Data include: aquifer water levels at wells and piezometers; aquifer temperatures including temperatures at several depths in some wells; vadose zone moisture content, tension, and temperature profiles; river and sub-river heads and temperatures; and atmospheric temperature and pressure. Most of these measurements were taken at 15 min intervals during most of the project period from 2010 continuing into 2013.

* We are one of the leading groups in the development of hydraulic tomography. In particular we have developed and are improving an efficient field, data acquisition, and modeling system for 3D transient hydraulic tomography (3DTHT)that gives direct estimation of distributed 3D hydraulic conductivity, with uncertainty calculations, at high resolution (approximately $1m^3$) in shallow aquifers including water table aquifers. Equipment from this DEPSCoR and associated DURIP grants have greatly assisted this development. Results are providing the capability to trace high and low conductivity bodies and interruptions in their continuity, and to trace variations in hydraulic conductivity within such bodies. This information is important for quantifying heterogeneity, providing heterogeneity models that can pass upward to the vadose zone, modeling aquifer responses to system forcing at boundaries and to detailed modeling of fluxes and states, and supporting groundwater contamination remediation decisions and designs, especially for source zones of difficult contamination sites.

Recent publications document improving capabilities with this method and support new findings on the spatial structure of saturated hydraulic conductivity - which is different than that for porosity and lithology and electrical conductivity in these coarse conglomeratic (high-energy fluvial and periglacial) sedimentary deposits. Follow-up demonstration of the 3DTHT method at a contaminated industrial site with greater hydraulic conductivity range and greater heterogeneity that at the BHRS is in progress; preliminary results strongly suggest that the method has general applicability in shallow aquifers.

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