Monitoring Effects of Climate Change on Groundwater Recharge through Remote Sensing of Seasonally Frozen Ground

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Problem.— Seasonally frozen ground occurs over approximately one-third of the contiguous United States (Zhang and others, 2003), and increased winter runoff as a result of frozen ground has been well documented (Shanley and Chalmers, 1999; Zuzel and Pikul, 1987). A corresponding decrease in groundwater recharge can be expected in these areas because frozen ground generally rejects potential recharge. In semi-arid regions such as the Columbia Plateau and the Snake River Plain in the Pacific Northwest, nearly all recharge from precipitation occurs between October and March when precipitation is most abundant and transient or seasonal frozen ground is commonplace.

The temporal and spatial distribution of frozen ground has been changing as a result of global warming. The estimated maximum extent of frozen ground in the Northern Hemisphere has decreased by 7 percent from 1901 through 2002, and the timing of surface thaw and subsequent initiation of the growing season over North America has advanced by about 8 days from 1988 to 2001 (Zhang and Armstrong, 2008).

Satellite remote sensing combined with ground truth measurements have been used to investigate seasonally frozen ground at local to regional scales with some success. Data from passive microwave sensors, such as Scanning Multi-channel Microwave Radiometer (SMMR; 1978–1987) and the Special Sensor Microwave Imager (SSM/I; 1987 to present) can be used to detect surface soil freeze or thaw. These sensors have the advantages of continuity and coverage, all-weather capability, and frequent repeat time (every other day or twice daily) that ensure detection of temporal and spatial variations of surface soil freeze and thaw. A disadvantage is that SMMR and SSM/I data have a relatively low resolution of about 25 to 30 km, although this scale is not inappropriate for evaluating groundwater recharge from ambient precipitation. The more recent Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E), launched in 2002 has lower-frequency channels and higher resolution, which may be superior for detecting soil freeze/thaw cycles. Multiple algorithms using passive microwave data are available and they generally perform well for identifying frozen ground that is snow free and was relatively wet when it froze. These features are not likely problematic for recharge studies because near-surface soils over the contiguous United States generally freeze before they are snow covered or not at all (Zhang and Armstrong, 2001), and because soils that freeze when relatively wet potentially reject recharge on a more consistent basis than soils that freeze when dry. Overall, the identification of frozen ground using passive microwave data shows great potential for providing insight into climate change effects on the extent, frequency, and duration of frozen ground, and the subsequent influence of frozen ground on groundwater recharge. Combined with existing precipitation-runoff algorithms to estimate recharge during frozen or thawed-ground episodes, a monitoring strategy to track changes in groundwater recharge attributable to climate change effects on seasonally frozen ground may be feasible.

Objectives — The objectives of this proposed investigation are to explore the linkages between seasonally frozen ground, climate change, and groundwater recharge in the Pacific Northwest; to analyze recent historical trends groundwater recharge as influenced by frozen ground; and to develop a first tier monitoring strategy for trends in frozen ground and recharge over time. The study area includes the U.S. portion of the Columbia River Basin with a primary focus on the Columbia Plateau and Snake River Plain Regional Aquifer Systems.

Approach — The major steps in this approach involve 1) processing historical remote sensing imagery using available algorithms to create a time series of frozen-soil conditions beginning in about 1980, 2) assessing the accuracy of the method using available soil temperature, frost tube, and similar data, 3) validating a frozen-soil algorithm (Emerson, 1994) that has been coded into a local in-house version of the USGS Modular Modeling System (MMS) by the WAWSC, 4) estimating historical groundwater recharge with the MMS at selected locations that have refined climate available (and directly measured recharge if available), and 5) evaluating the linkages between climate change, frozen ground, and recharge to develop a feasible stretegy for monitoring trends in groundwater recharge as influenced by frozen ground. The study area will primarily be focused on the Columbia Plateau and Snake River Plain Regional Aquifer Systems, although the methods and results are expected to transferrable to other western principal aquifers such as the basin and fill and high plains systems.

Details of this approach are as follows:

1) Existing passive microwave imagery will be analyzed using available frozen-soil algorithms for the study area to create a time series of frozen-soil conditions back to about 1980. Frozen ground metrics for the two RASs (such as maximum extent, duration, date of onset) will be compiled for each year and trends will be evaluated.
2) The accuracy of the method will be assessed using available soil temperature, frost tube, and similar data from various sources including
    a) the regional SCAN (Soil Climate Analysis Network) and Agrimet networks sponsored by the USDA NRCS National Water and Climate Center and the US Bureau of Reclamation, respectively,
    b) the DOE Hanford Site,
    c) the USDA-ARS Reynolds Creek Experiment Station,
    d) other USDA-ARS efforts run through the University of Idaho and Washington State University, and
    e) compiled literature information concerning the reported accuracy of the methods across the US.
3) We will work with NRP personnel to validate the frozen-soil algorithm of Emerson (1994) that has been incorporated into a local (WAWSC) version of MMS, and to fully incorporate the algorithm into the USGS MMS and GSFLOW models. Alternative more recent algorithms will be considered, particularly if they directly incorporate remotely sensed data in lieu of weather station data.

4) The model resulting from 3) will be used to estimate historical groundwater recharge at least two locations that have refined climate available (and directly measured recharge if available). The likely candidate sites would be at the DOE Hanford Site and one of the USDA-ARS research sites such as the Reynolds Creek Experimental Watershed where at least some historical recharge measurements are available post-1980.
5) Linkages between climate change, frozen ground, and recharge will be evaluated to propose a feasible strategy for monitoring trends in groundwater recharge as influenced by frozen ground. The monitoring program would likely require at least the three elements of tracking frozen ground using remote sensing, collecting or assembling ground-truth data on the frozen ground, and direct monitoring of recharge at selected highly instrumented sites at Hanford, Reynolds Creek, or similar. We will also explore developing a simplified remote-sensing based strategy that employs MODIS or similar surface-temperature products because of the frequent and relatively fine-scale (1-km) resolution offered by those sensors. And finally, the potential for integrating the results and products from planned activities by others, such as NASAs Soil Moisture Active and Passive (SMAP) mission, into a USGS coordinated monitoring program will be evaluated.

Timelines and Products – The project will require two years and $174,900 to complete. In FY2010, tasks will focus on the remote sensing analyses and comparison to field data, and the rainfall-runoff code selection and validation. A Fact Sheet will be prepared first quarter FY2011. In FY2011, tasks will focus on application of the rainfall0runoff on frozen ground model, formulating a monitoring strategy, and publishing results. The tasks could also be spread over three years with funding at about $58,000 per year. Specific products will include:

- USGS Fact Sheet describing the conceptual link between climate change, frozen ground, and recharge. Remote sensing methods will be highlighted.
- USGS SIR/Journal article describing the remote-sensing analyses and results, historical recharge analysis, and proposed monitoring strategies.
- A frozen-ground algorithm incorporated into the USGS MMS and GSFLOW software.

Budget.—

Budget Category	**FY2010**	**FY2011**
PSC Services	$0	$15,000
Labor and Leave	$50,000	$40,600
Indirect Costs	$34,700	$34,600
Total	$84,700	$90,200

Personnel.—

Ed Josberger (Research Oceanographer) has extensive experience working with remotely-sensed passive microwave datasets for snow and ice research, and has already processed some of the needed datasets in support of other work for the Center. Rick Dinicola (Groundwater Specialist) and Marijke van Heeswijk (Supervisory Hydrologist) are experienced in both watershed and groundwater modeling, and have both led frozen-ground related projects in the Pacific Northwest. Steve Markstrom (Research Hydrologist) is a member of the Precipitation-Runoff Modeling Group of the USGS National Research Program.

Position	**FY2010 hours**	**FY2011 hours**
Josberger	400	160
Dinicola	80	160
Van Heeswijk	80	160
Markstrom	80	0
Hydrologist GS-11	80	80

Literature Cited.--

Emerson, D.G., 1994, A heat and water transfer model for seasonally frozen soils with application to a precipitation-0runoff model: USGS Water-Supply Paper 2389, 72 p.

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Zhang, T., and R. L. Armstrong, 2001, Soil freeze/thaw cycles over snow-free land detected by passive microwave remote sensing: Geophys. Res. Lett., 28, 763–766.

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