Report as of 2006 for 2004FL76G: “Space-based monitoring of wetland surface flow”

Publications

- Conference Proceedings:
    - Bieler B., R. Garcia-Martine, S. Wdowinski and F. Miralles-Wilhelm, Modeling Water Flow inthe Water Conservation Area 1 Using Interferometric Synthetic Aperture Radar (InSAR) Observations, Greater Everglades Ecosystem Restoration (GEER) Conference, AbstractVolume, p. 15, 2006.
    - Kim S., S. Wdowinski, J. Wang, T. Dixon and F. Amelung, Comparison of Water LevelChanges in the Everglades as Calculated with the TIME Model and with Interferometric SARMeasurements, Greater Everglades Ecosystem Restoration (GEER) Conference, AbstractVolume, p. 118, 2006.
    - Kim S., S. Wdowinski, T. Dixon and F. Amelung, SAR Interferometric Coherence Analysis ofWetlands in South Florida, Greater Everglades Ecosystem Restoration (GEER) Conference,Abstract Volume, p. 119, 2006.
    - Wdowinski S., S. Kim, T. Dixon, F. Amelung, and R. Sonenshein, High Spatial-ResolutionSpace-Based Monitoring of Surface Water Level Changes in the Greater Everglades, GreaterEverglades Ecosystem Restoration (GEER) Conference, Abstract Volume, p. 242, 2006.
    - Wdowinski, S., F. Amelung, F. Miralles-Wilhelm, T. Dixon, and R. Carande, Space-based hydrology of the Everglades wetland, South Florida, First National Conference on Ecosystem restoration, Abstract Volume, p. 466, 2004. 44.
    - Wdowinski, S., F. Amelung, and T. Dixon, Towards operational monitoring of wetland water levels using InSAR: Applications for the Everglades Restoration Project, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract H23E-1169,2004.
    - Osmanoglu, M., D. Kartal, S. Wdowinski and T. Dixon, Altitude accuracy improvement by using a new radar altimeter simulator for ENVISAT data, 1st CRYOSAT meeting, 2005.
    - Kim, S., S. Wdowinski, F. Amelung, and T. Dixon, C-Band Interferometric SAR Measurements of Water Level Change in the Wetlands: Examples from Florida and Louisiana, IGARSS meeting proceedings, 2005.
    - Wdowinski, S., F. Amelung, and T. Dixon, Space-Based hydrology of the Everglades Wetlands, South Florida, Societyof Wetland Scientists, 26th Annual Meeting, Final program and abstracts, 125,

2005.

- Wdowinski, S., F. Amelung, T. Dixon, S. Kim, B. Osmanoglu, M. Kartal, and D. Harding, The Everglades wetlands as a laboratory for testing and calibrating space-geodetichydrological technologies, Eos Trans. AGU, 86(18), Fall Meet. Suppl., Abstract G23A-04, 2005.
- Kim, S., S. Wdowinski, F. Amelung and T. Dixon, Wetlands Application of Interferometric SAR Measurements: examples from Florida and Louisiana, Eos Trans. AGU, 86(18), Fall Meet. Suppl., Abstract G23A-03, 2005.
- Bieler, B.M, R. Garcia-Martinez, F. Miralles-Wilhelm, and S.Wdowinski, Modeling Water Flow in the Everglades Wetlands Using Interferometric Synthetic Aperture Radar (InSAR)Observations, Eos Trans. AGU, 86(18), Fall Meet. Suppl., Abstract G23A-05, 2005.
- Kim, S, A. Ferretti, F. Novali, S. Wdowinski, F. Amelung, T.H. Dixon, R.K. Dokka, and B. Rabus, Observation of Subsidence in New Orleans Using Permanent Scatterers, Eos Trans. AGU, 86(18), Fall Meet. Suppl., Abstract G43A-04, 2005.

- Other Publications:
  - Wdowinski, S., F. Amelung and T. Dixon, S. Kim, B. Osmanoglu, M. Kartal, D. Harding, The Everglades wetlands as a laboratory for testing and calibrating the CRYOSAT hydrological applications.
- Articles in Refereed Scientific Journals:
  - Wdowinski, S., F. Amelung, T. Dixon, F. Miralles-Wilhelm, andR. Sonenshein, Space-based detection of surface water level changes in South Florida, submitted to Remote Sensing for Environment, 2005.

Report Follows

Project Progress

Space-based monitoring of wetland surface flow

PI: Dr. Shimon Wdowinski

Division of Marine Geology and Geophysics, Rosenstiel School of Marine and Atmospheric Science, University of Miami

During the past six months, we have obtained progress in the following four categories:

1. Data acquisition

We continue acquiring C-band SAR data, mainly over the Everglades wetlands, but also over other wetlands. Our main source of data for Everglades is RADARSAT-1, which has a repeat orbit of 24 days. Using our Alaska SAR Facility (ASF) data project, we set 6 Data Acquisition Requests (DAR) that automatically acquire every repeat orbit. As a result, we get 6 new acquisitions within every 24 days, half using fine beam (7 m pixel resolution) and the other half with standard beam (15 m resolution). Due to a new agreement between ASF and CSTARS (University of Miami), since October we downlink the new acquisitions at CSTARS at no cost! So, we are getting high quality data at no cost and in real time.

We started new data acquisition projects in other wetlands, mostly in North and Central America, including Louisiana coast, Yucatan (Mexico), and the Bahamas. We also started a collaborative project with a French team to monitor wetlands in Mauritania (Africa). Our group acquires RADARSAT-1 data and the French team conducts ground measurements and develops hydrological model for the wetlands.

2. Data processing and results

We have continued processing both archive and current data. We recently received archived RADARSAT-1 data of both the Everglades and the Louisiana coast for the time period of 1996-2003. These data has been processed in order to constrain detailed flow model of both areas. We also continued processing current data that is downlinked at CSTARS. After a long effort we managed to automate the data processing procedures, resulting in an automated interferogram production every data acquired over the Everglades. Data acquired over other wetlands are partially processed automatically, but also requires human intervision.

3. Flow models

Water level is a key parameter in wetlands ecosystems, affecting flow and spatial extent of wetlands. As part of the Everglades restoration effort, the TIME model (Tides and Inflows in the Marshes of the Everglades) was developed by US Geological Survey and University of Miami, enabling us to investigate interacting effects of freshwater

inflows and coastal driving forces in and along the mangrove ecotone of the Everglades National Park. The TIME model solves for the spatial and temporal distribution of main hydrological parameters in both surface- and ground-water, including water levels, flows, and salinity, and is constrained by field measurements at its boundaries. The model has been calibrated for the 1996-2002 time period, because reliable field observations are available for that time period.

Twelve InSAR-measured water level change maps are produced using ERS-1/2 and JERS-1 SAR images during 1996-1997. In addition 2-D water level maps at the satellite acquisition times are derived from the TIME model simulation and used to synthesize water level change maps similar to those obtained from satellite radar observations. We compare InSAR measurement with the synthetic water level change map from the TIME model and field data. Our initial findings show that InSAR measurement indicates similar patterns to those obtained using modeled water level, but there are also some differences. Investigation of coincidence and discrepancy between the two mapping methods will provide new scientific insight, especially regarding the role of spatial variation of water level. Eventually, the InSAR analysis can be used to calibrate, verify and refine the existing numerical model as well as a powerful tool to determine water level changes in wetlands with remote sensing.

We also continued our modeling efforts of Water Conservation Area 1 (WCA-1), as part of the MS thesis of B.M. Bieler, at the University of Miami. Using the space-based data we obtained time series of water level changes in the entire area 1. These maps of water level changes show very interesting patterns. Preliminary modeling results show very good fit to some of the observations, but not all. The model needs further improvements, which will be conducted in the next few months.

Additional project details and long-term objectives are discussed in the following section.

Space-based monitoring of wetland surface flow

Statement of critical regional or State water problem.

Coastal wetlands provide critical habitat for a wide variety of plant and animal species, including the larval stages of many ocean fish. Globally, most such regions are under severe environmental stress, mainly from urban development, pollution, and rising sea level. However, there is increasing recognition of the importance of these habitats, and mitigation and restoration activities have begun in a few regions. A key element of wetlands restoration involves monitoring and modeling its hydrologic system, in order to understand the underlying flow dynamics, assess potential restoration strategies, mitigate effects of past construction, and predict the effects of future changes to infrastructure such as new dams or levies, or their removal.

The Everglades region in south Florida is a unique ecological environment. This gently sloping terrain drains Lake Okeechobee in central Florida southward into the Gulf of Mexico. The combination of abundant water and sub-tropical climate promotes a wide diversity of flora and fauna. Anthropogenic changes in the past 50 years, mainly for water supply, agricultural development and flood control purposes, have disrupted natural water flow and severely impacted the regional ecosystem. Currently, Everglades flow is controlled by a series of hydraulic control structures to prevent flooding and regulate flow rates, but which also suppress natural water level fluctuations, essential for supporting the fragile wetland ecosystem. This controlled Everglades environment provides a large-scale laboratory for monitoring and modeling wetland surface flow. Enhanced modeling capabilities and understanding of the Everglades hydrological system are essential for the Everglades restoration project, which is the largest and most expensive (multi-billion dollar) wetland restoration project yet attempted.

The Everglades are currently monitored by a network of stage (water level), meteorological, hydrogeologic, and water quality control stations, providing daily average estimates of water level, rainfall and other key hydrologic parameters. Due to the limited number of stations (station spacing ~ 10 km) and their distribution, mainly along existing structures, the current data can constrain regional scale models, such as the 2 x 2 mile^2 SFWMM, but lack the spatial density for more detailed models.

Statement of results or benefits.

The proposed research will provide high resolution (~300 x 300 m^2) regional scale observations, more than an order of magnitude higher than the existing ground network, of wetland water levels and their changes. The new observations will be used as (1) a monitoring tool for water resources managements, and (2) constraints for high spatial resolution of wetland surface flow. The new measurement are important for managing and restoring wetlands damaged by human activity, because many species are threatened by wetlands degradation depend on restoration of hydroperiod (water level as a function of time). Flow management to achieve this depends on accurate flow models and accurate, spatially dense elevation measurements, currently lacking. Our test area, the Florida Everglades, is the focus of the largest wetlands restoration project yet attempted.

Nature, scope, and objectives of the project, including a timeline of activities.

Nature – The proposed research promote the usage of space-based regional-scale high spatial resolution observations for monitoring and understanding wetland surface flow.

Scope – The proposed work contains three components: InSAR analysis of wetlands, hydrological analysis, and numerical modeling. In the first component we will us SAR data of the Everglades (both C-band and L-band) and other wetlands (Louisiana, Chesapeake Bay) to detect water level changes between SAR data acquisitions. The second component – hydrologic analysis – will allow us to understand and utilize the high spatial resolution InSAR observation, by evaluating the observation with respect to terrestrial-based (e.g., stage data) and field observations. In the third component we will use the high spatial resolution observations to constrain surface flow models. This part of the project will be conducted by the USGS, which already developed a flow model for the southern Everglades.

Objectives – Our proposed research will provide new space-based observations, which will be used to understand in details the complexity of wetland surface flow. Furthermore using the new observations as constraints in 3-D flow models, we will be able to evaluate the tempo-spatial distribution of key hydrologic parameters that govern shallow surface flow in the Everglades and other wetlands.

Timeline - During the first phase of the project, until the new Japanese L-band SAR satellite (ALOS PALSAR) will be launched in December 2004, we will use mostly archived SAR data (L-band JERS-1, and C-band ERS-1/2), but also current C-band data (ENVISAT and RADARSAT-1), for further developing the technique and for generating high resolution historic observations (1992-1998) for constraining flow models. After the ALOS satellite will launched and calibrated, we will focus the research on current L-band InSAR observations for monitoring purposes, as well as for providing better model constraints.

Methods, procedures, and facilities.

The proposed work contains three components: InSAR analysis of wetlands, hydrological analysis, and numerical modeling. The first two components will be conducted at the University of Miami and the third one by the USGS.

InSAR analysis of wetlands

This component of the proposed project includes additional InSAR data processing of the Everglades and other wetlands. We plan to process additional L-band JERS data of southern Florida, which were acquired during the JERS mission during 1992-1998. The data are available at the Japanese Space Agency (NASDA, which recently changed its name to JAXA). We also plan to process C-band ERS and EVISAT data collected by the European Space Agency (ESA). In order to obtain the C-band data, we submitted a data proposal to ESA, which was approved last August. Although so far only L-band data were successfully used to detect wetland water level changes, we plan

to test the C-band data and compare between the two data types. We also plan to purchase and process L-band data from other wetlands, such as the Louisiana Coast and the Chesapeake Bay.

Hydrological analysis of interferograms – interpretation of the observations

The new spaced-based observations (interferograms) describe with high spatial resolution (~30 x 30 m^2) lateral phase changes between two acquisitions. Because each phase cycle (2 pi) corresponds to 12 cm of displacement in the radar line-of-sight, which translates into 15.1 cm of vertical displacement, we were able to translate the observed phase changes into maps of water level changes occurring between two acquisitions. Producing such water level change maps is only one step in understanding the corresponding hydrological system, because the observations are relative both in time and in space. The relative aspect in the time domain is derived from the fact that the measurements describe water level changes from one unknown situation to another unknown situation. In the preliminary study described below, we spent almost a year to understand the hydrological significance of the InSAR measurements. Fortunately, we found that during one of the SAR data acquisitions (1994/12/19) water level conditions in the three water conservation areas (1, 2A, and 2B) were almost flat. As a result, we were able to calculate the dynamic water level topography occurring during the two other acquisitions (1994/6/26 and 1994/8/9). The relative aspect in the space domain arises from the nature of the InSAR observations, which measures relative changes continuously and not across levies or other structures. We resolved this issue by using stage data for validation and calibration of the InSAR technique. In summary, the translation of the interferograms into hydrological meaning observations requires a good knowledge of the wetland environment, which we acquired by field trips, and good integration between the high spatial resolution space-based observations with high temporal resolution stage data.

As part of the proposed research, we plan to continue our hydrological analysis of already processed observations (interferograms) to other regions in the Everglades, beyond the three water conservation areas, analyzed in the preliminary study presented below. The hydrological analysis will involve field trips to the study areas, including airboat trips to less accessible locations. The field trip will enable us to relate space-based phenomena to local structure, as we did in our preliminary study. The hydrological analysis component will also include integration of stage, gate and meteorological data with our observations. The stage and gate data collection will be conducted as a summer job of an undergraduate student. Field work and the integration of the space- and terrestrial-based observations will be conducted by a post-doc under the PI's supervision.

Numerical Modeling

After obtaining Hydrological understanding of surface flow in the Everglades and other wetlands, we will use the high spatial resolution observations to constrain surface flow models. This part of the project will be conducted by the USGS, which developed a 500 x 500 m^2 resolution grid for studying surface flow in the southern section of the Everglades. The space-based observations will allow us to (i) evaluate spatial and

temporal variation of the flow transmissivity, (ii) relate transmissivity variations to vegetation, and (iii) estimate spatial and temporal evapo-transpiration rates.

Facilities at the University of Miami

The Geodesy Lab at the University of Miami (UMGL), located at the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS) on Virginia Key, maintains a network of 7 Unix workstations: one SGI Octane, one Sun Ultra 60, 3 Sun Ultrasparc 10's and 2 rack-mounted Sun "pizza boxes"(Sunfire V-100). The system includes a CD ROM reader, a CD writer for data archiving, an 8 mm tape drive, 100 Gbytes of hard disc storage, and color and black&white laser printers. All computer equipment except the printer is powered by a UPS (Uninterruptible Power Supply) to allow us to span power interruptions and protect data on hard disc against voltage spikes associated with electrical storms, a frequent problem in south Florida. The Sun workstations are equipped with the GIPSY software (release version 2.5) for high precision GPS data analysis, provided by the Jet Propulsion Lab. Two Linux boxes are equipped with the "roi-pac" software from JPL for processing raw SAR data and generating interferometric and other advanced image products. The SGI is equipped with EarthView SAR processing software from Atlantic Scientific and VEXCEL software with similar features. The computer facilities are adequate for all the data analysis and modeling described in this proposal.

The Geodesy Lab performs daily analysis of more than 900 globally distributed GPS stations, for studies of crustal deformation, volcano monitoring, coastal stability, plate motion and plate rigidity, as well as analysis of SAR images for crustal deformation. Selected results are available our web site: http://www.geodesy.miami.edu

CSTARS - http://cstars.rsmas.miami.edu/

UMGL is connected by 2Gb/s fiber optic to CSTARS (Center for Southeastern Advanced Remote Sensing) located at UM's Richmond campus, the center for much of the university's space-related activities. CSTARS includes 2 11.3 m diameter X-band antennas for downlinking data from a variety of earth-orbiting satellites. This facility includes a 64Tbyte tape cartridge archive for raw satellite data, and numerous computers for data analysis, with more than 2 Tbyte of hard disc storage.

Related research.

A recent study by *Wdowinski et al.* [2004] describes new space-based hydrologic observations of South Florida, revealing spatially detailed, quantitative images of water levels in the Everglades. Their observations capture dynamic water level topography, providing the first three-dimensional regional-scale picture of wetland sheet flow, showing localized radial sheet flow in addition to a well defined southward unidirectional sheet flow. In this preliminary work, they used a 1-D linear diffusive flow formulation to simulate the unidirectional flow and to determine its corresponding hydrological parameters (vegetative friction coefficient). This proposal expands upon the initial study of *Wdowisnki et al.* [2004]. The main points of this work and its relationship to this work are described below.

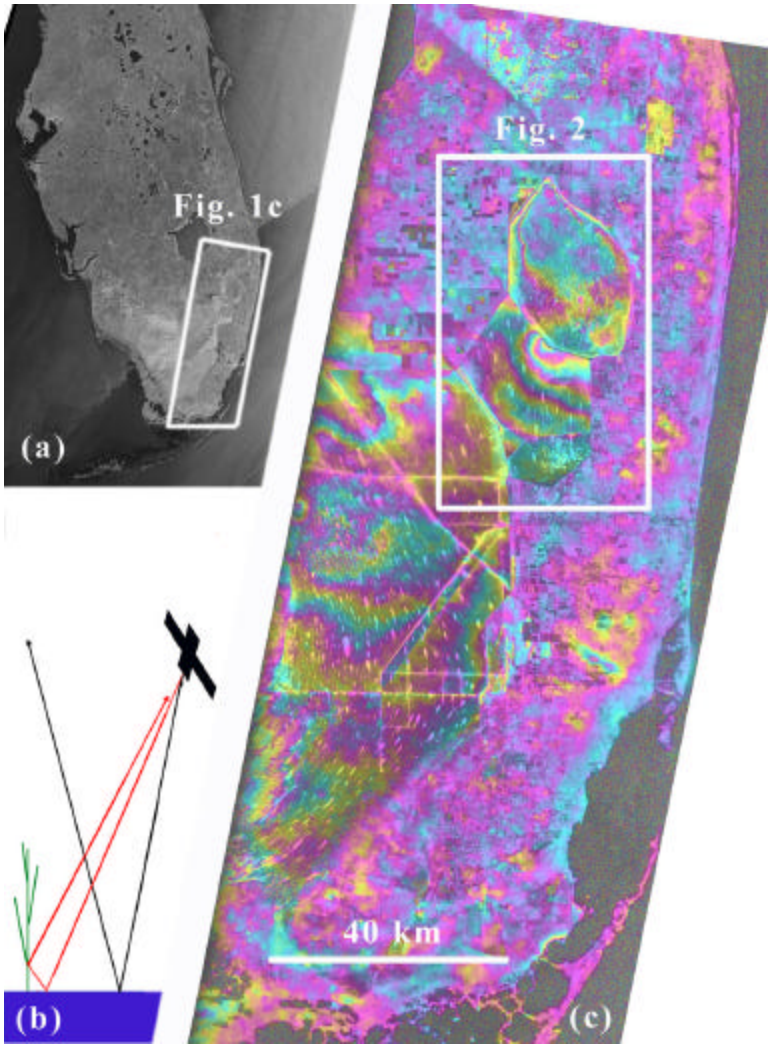

Figure 1: (a) RADARSAT-1 ScanSAR image of Florida showing location of study area (RADARSAT data © Canadian Space Agency / Agence spatiale canadienne 2002. Processed by CSTARS and distributed by RADARSAT International). (b) Cartoon illustrating the double-bounce radar signal return in vegetated aquatic environments. The red ray bounces twice and returns to the satellite, whereas the black ray bounces once and scattered away. (c) JERS L-band interferogram of the eastern south Florida area showing phase differences occurring during 44 days (1994/6/26-1994/8/9). Each color cycle represents 15.1 cm of elevation change (See color scale in Figure 2).

InSAR Data

InSAR combines SAR images of the same area acquired at different times from roughly the same location in space. By comparing the phase of individual pixels, cm-level changes of the Earth's surface can be detected. Most InSAR studies use C-band data (5.6 cm wavelength) to detect crustal deformation induced by earthquakes, magmatic activity, or water-table fluctuations [e.g., Massonnet et al., 1994]. L-band SAR data (24 cm wavelength), which penetrates through vegetation, were also used to study

crustal deformation in vegetated terrain [e.g., Murakami et al., 1996]. A different use of L-band data was developed by *Alsdorf et al.* [2000; 2001a; 2001b] to detect water-level variation in the Amazon wetland environment. They showed that interferometric processing of L-band SAR data (wavelength 24 cm) acquired at different times is suitable to detect water level variations in wetlands with emergent vegetation (measurement accuracy 3-6 cm). The radar pulse is backscattered twice ("double-bounce" [*Richards et al.,* 1987] – Figure 1b), from the water surface and vegetation (Figure 1b). A change in water level between the two acquisitions results in a change in travel distance for the radar signal (range change), which is recorded as a phase change in the interferogram.

The data consists of three SAR passes over South Florida acquired by the JERS satellite in 1994 (1994/6/24, 1994/8/9, and 1994/12/19), at the beginning, middle, and end of the local wet season (June-November). We calculated 3 interferograms, spanning 44 days (June-August), 132 days (August-December), and 176 days (June-December) covering the rural Everglades and urban Miami-Fort Lauderdale (Figure 1a).

The June-August interferogram shows very high interferometric coherence, in both rural and urban areas, and allows the following observations: (i) Significant elevation changes occur in the controlled-flow regions (within the white box in the upper half of Figure 1b). (ii) Discontinuities occur across man-made structures (canals, levees, and roads), and (iii) Elevation changes in Miami-Ft. Lauderdale metropolitan area are small. The two other interferograms, spanning longer periods, have lower coherence. *Wdowinski et al.* [2004] applied a spatial filter, improving the interferogram quality with some degradation in horizontal resolution (100x100 to 300x300 m^2), still significantly better than any available terrestrial monitoring technique.

InSAR detected water level changes

The most significant elevation changes occur in the northern section of the interferogram, across man-made structures, known as Water Conservation Areas (WCA) 1, 2A, and 2B. Figure 2 shows both the L-band backscatter amplitude and interferograms for the three time spans. The amplitude (brightness) variations (Figure 2a) represent the radar scatter, which depends on the surface dielectric properties and surface orientation with respect to the satellite. The small, elongated white areas are vegetated tree islands aligned along the long-term regional flow direction. The large white areas in areas 2A and 2B are dense vegetated areas. The pattern of water level change is unidirectional in the eastern section of area 2A and radial in the western part. In the northern section of area 2B the water level change is characterized by 3 radial ("bulls eye") patterns (b and c). The interferometric phase (Figure 2b, 2c and 2d) show water level changes in area 2A; the change direction and amount vary. The change in Figure 2b indicates water level decrease towards the NE by about 60 cm (4 cycles), in Figure 2c a NE decrease of about 105 cm (7 cycles), and in Figure 2d an increase by 45 cm (3 cycles with opposite color scheme), which agrees with the difference between (2b) and (2c).

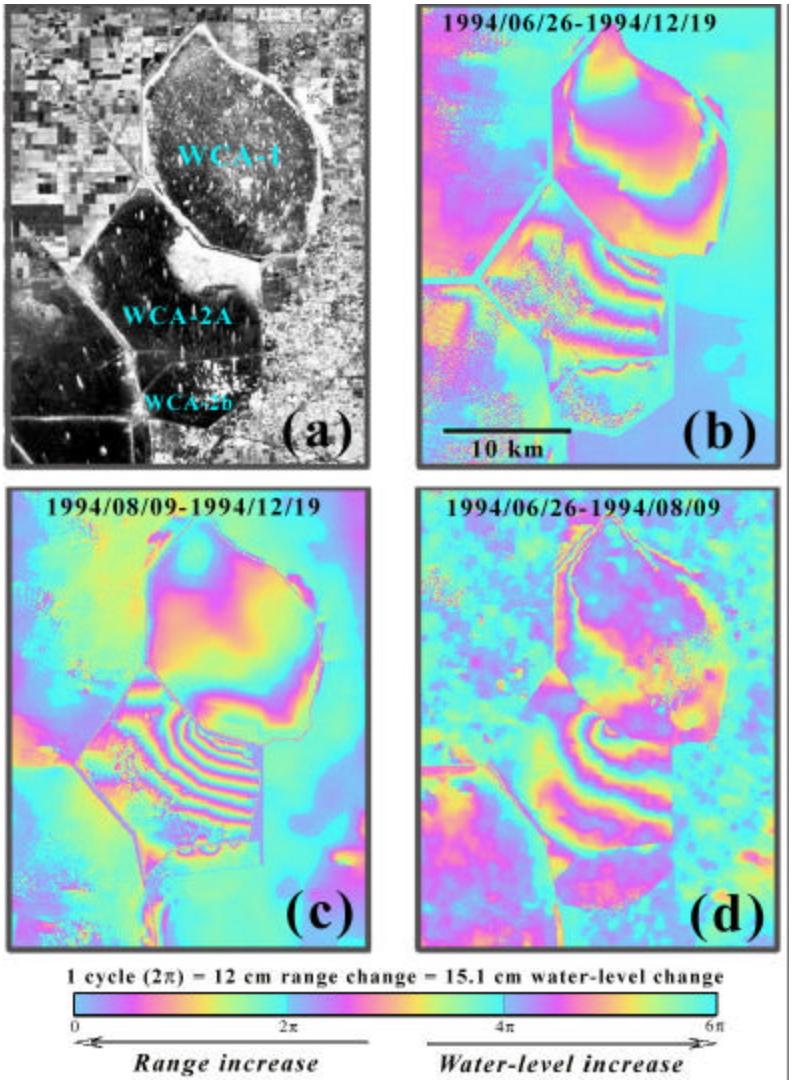

Figure 2: L-band backscatter amplitude and interferograms of the Water Conservation Areas (WCA) 1, 2A, and 2B (location in Figure 1c). (a) Amplitude (brightness) variations represent radar backscatter, which depends on the surface dielectric properties and surface orientation with respect to the satellite. The small elongated white areas in the WCAs are vegetated tree islands (*10*), aligned along regional flow direction. Large white areas in 2A and 2B are dense vegetated areas. (b) 176-day (June-December) interferogram, (c) 132-day (August-December) interferogam, and (d) 44-day (June-August) interferogram. The interferograms show the largest water level changes occurred in area 2A (up to 1 m – 7 cycles in (c)) and smaller scale ones in areas 1 and 2B. (ii) The pattern of water level change is unidirectional in the eastern section of area 2A and radial in the western part. In the northern section of area 2B the water level change is characterized by 3 bulls-eye radial patterns (b and c).

Figure 3 shows the June-December water level changes in areas 1, 2A, 2B and their surroundings. Because InSAR measures relative changes within each area, but not between the areas, we assigned in each area the lowest change level to zero. The most significant water level changes occur in the eastern section of area 2A, where the level changes can be described by a series of NWN-ESE almost parallel contours.

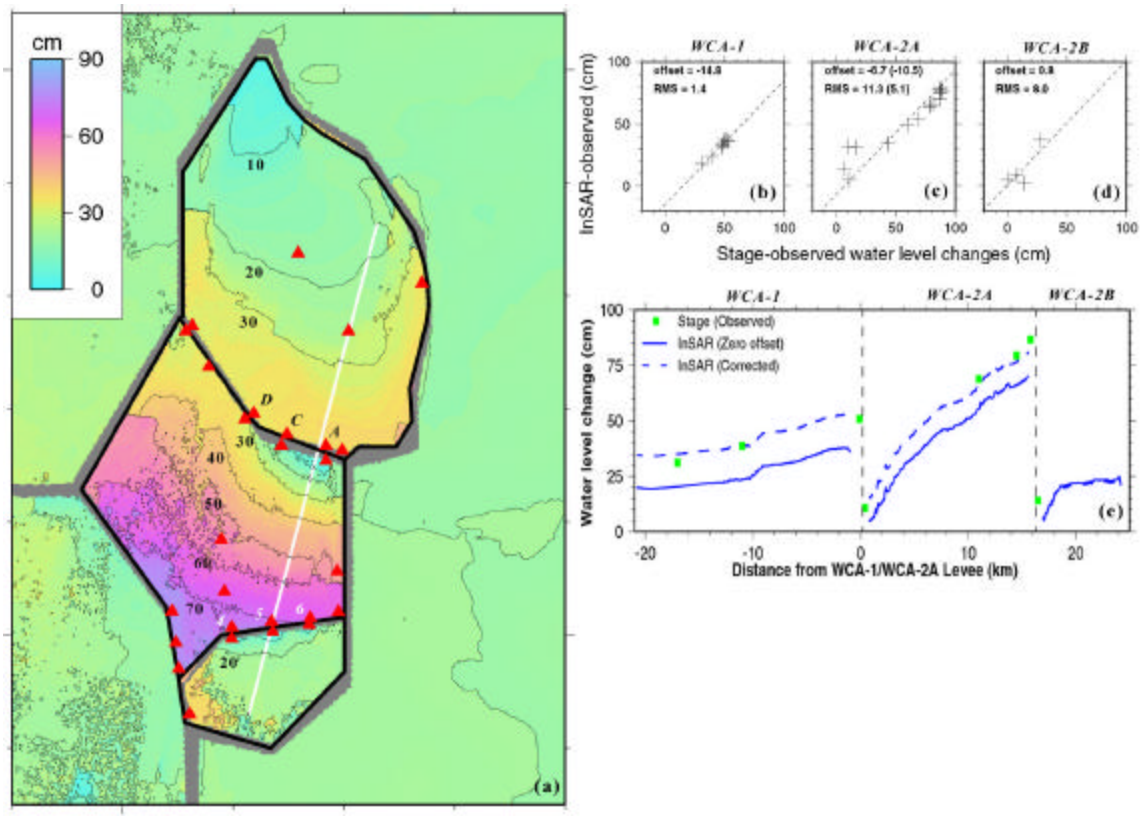

Figure 3: (a) InSAR-based water level change map for the June-December time interval of areas 1, 2A and 2B. Red triangles mark the location of stage stations and the white line marks the water level profile location. The characters (A, C and D) and (digits 4, 5 and 6) mark gate locations, presented in Table 1. (b, c, and d) Comparison between the zero-offset InSAR and the stage data calculated separately for each area. (e) Comparison between InSAR and stage water level changes along the profile. Stage data observed in the center of areas 1 and 2A are projected onto the profile. The vertical dashed lines mark the location of levees separating between the conservation areas. The corrected InSAR curve (dashed line) is calculated from a least-squares adjustment.

Table 1: Flow observation (CFS – cubic feet per second) collected by the SFWMD during the JERS data acquisition at the gates feeding and draining area 1A. (Data source: DBHYDRO - http://www.sfwmd.gov/org/ema/dbhydro/index.html). The symbol indicates the gate location in Figure 3a.

Station	Levee	Symbol	1994/06/26	1994/08/09	1994/12/19
S10D	1-2A	D	0	1170	0
S10C	1-2A	C	489	1447	88
S10A	1-2A	A	510	1485	0
S144	2A-2B	4	90	83	0
S145	2A-2B	5	117	95	0
S146	2A-2B	6	82	53	0

In order to validate and calibrate our InSAR technique, we compared the InSAR observations with stage data (red triangles in Figure 3a) collected by the South Florida Water Management District (SFWMD). The stage data consist of daily average level above the NGVD29 datum. We use these data to calculate water level differences

between the two acquisition dates. Comparison between the InSAR and stage data shows excellent agreement for each of the three water conservation areas (Figure 3b, 3c and 3d). It also allows us to compute and correct the datum offset between stage and InSAR data, which were set arbitrarily to zero value at the lowest level in each area (Figure 3e).

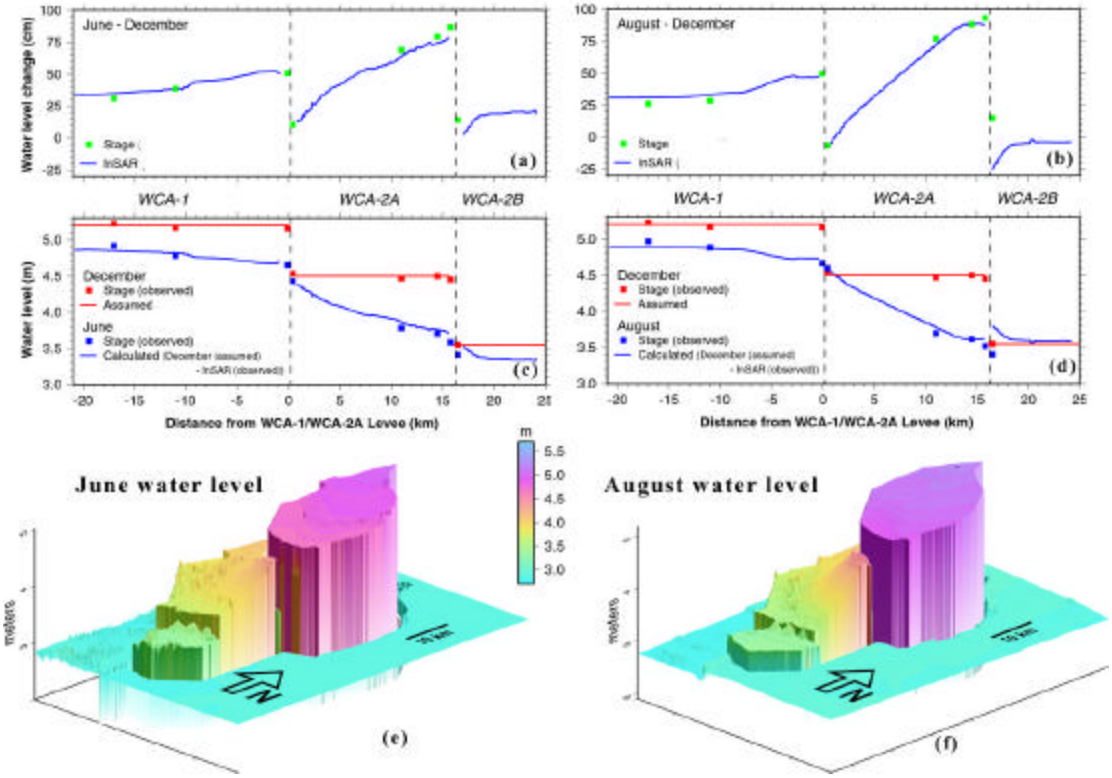

Figure 4: (a) Water level changes along the profile in Figure 3c, showing corrected InSAR curve and stage data for June-December time interval. Vertical dashed lines mark location of levees separating the WCAs. (b) Water level changes for the August-December time interval. (c) June and December water levels along the profile. Based on the December stage data (red squares) and gate information (Table 1), we assume flat water level in each area (red lines). The June water level (blue line) is obtained by subtracting the corrected InSAR curve from the assumed flat December level.(d) August and December water levels following the same procedure as in (c). (e) Three-dimensional illustration of the June water levels, calculated by subtracting the corrected InSAR data from the assumed flat December levels, for the entire studied area. (f) Three-dimensional illustration of the August water levels.

From water level change to absolute water level

The new space-based observations provide, with very high spatial resolution, water level changes in the Everglades occurring over 44, 136 and 176 day time intervals (Figures 3, 4a and 4b). Because these time intervals are long compared to the duration of natural and anthropogenic water level changes in the Everglades (days to several weeks), the observed water level changes represents the differences between two states and not a continuous process. Figures 4c and 4d present stage elevations during the three observation periods. The December InSAR observation occurred during a period of

negligible water flow across the conservation areas (Table 1), resulting in almost flat water levels in the three areas (red lines in Figures 4c and 4d).

Hydrologic Model

Wdowinski et al. [2004] used a diffusion flow model to explain the observed dynamically supported water topography and derive quantitative estimates of transmissivity and Manning's friction parameter. Their model follows the *Akan and Yen's* [1981] diffusion flow formulations, which are derived from conservation of mass and momentum principles, neglecting inertial terms. The model is appropriate to low-Reynolds hydrologic flows, where the flow is predominantly laminar. It follows the same formulation as the SFWMM [*Lal*, 1998, 2000] which has been used extensively to model surface flow in South Florida. For overland flow, the water level (H) can be describe in terms of its derivatives in time (dH/dt) and space (dH/dx), water transmissivity (or diffusivity) (D), and sink terms representing rainfall, evapotranspiration, and infiltration [Lal, 1998, 2000]. The transmissivity (diffusivity) represents a Fickian form for the relation between volumetric flow rate and surface water elevation gradient and is a function of flow frictional characteristics. For instance, if Manning's friction relationship is applied, then $D = h^{5/3} / (\boldsymbol{n}\ |dH/dx|^{1/2})$, where $\boldsymbol{n}$ is Manning's dimensionless friction coefficient, a measure of the resistance to flow [*Lal*, 1998, 2000].

In order to calculate dynamically supported water levels, we need to specify initial and boundary conditions, which are poorly constrained. Rather then modelling water levels in all three water conservation areas and accounting for complex gate operation history, we focus on the process that governs dynamically supported water level topography and model the region where this phenomenon is most pronounced - the eastern section of area 2A (Figure 3a). In this region the hydrologic flow lines are orthogonal to InSAR water level contours, indicating a southward flow during June and August 1994. The unidirectional flow in this region allows a simple one-dimensional analytical solution. As a first approximation, we: (1) assume a spatially uniform transmissivity (D); and (2) neglect sink terms, deriving the familiar one-dimensional diffusion equation:

$$\frac{dH}{dt} \ ?\ D\frac{d^2H}{dx^2} \qquad (1)$$

The boundary conditions are derived from the stage and gate operation time series. We apply an instantaneous gate opening model, which assumes (1) a flat water level in area 2A prior to the opening of the gates (supported by the stage data), (2) area 2A is infinitely long, and (3) water level in area 1 remains constant (supported by stage data). The above assumptions allow us to determine initial and boundary conditions and to solve equation (1) analytically [*Carslaw and Jaeger*, 1959] using a three term series expansion. We use a best-fit adjustment to estimate the polynomial coefficients and calculate two flow parameters: the initial water elevation difference across the gate (H_0) and the flow characteristic length $(Dt)^{1/2}$.

Figure 5 and Table 2 show that the InSAR data constrain the model parameters to ~5% uncertainty. However, the full coupling of time and transmissivity as a single parameter - the diffusion characteristic length $(Dt)^{1/2}$ - does not allow us to uniquely determine the transmissivity coefficient (D). Nevertheless, we use the gate operation

history to estimate the time since opening, as 16±2 days for June and 8±2 days for August, in order to estimate transmissivity.

Wdowinski et al. [2004] also calculated the corresponding Manning friction factor *n* for diffusive flow. Reported values of *n* for sheet flow through vegetation are in the range $0.10 < n < 1.0$ [*Overton and Meadows*, 1976; *Akan and Yen*, 1993; *Nepf*, 1999; *Lal*, 2000; *Lee et al.*, 1999; *Wu et al.*, 1999; *Kouwen and Irrig*, 1992]. We find our InSAR based determined *n* to be in the same range. For the June period, *n* is somewhat higher (0.7-1.0) compared to the August period (0.3-0.7). The difference represents the influence of vegetation on flow, with higher friction at lower water levels (June) compared to higher water levels (August). This decrease of resistance to flow with increasing water depths has been reported in the literature [*Lee et al.*, 1999; *Wu et al.*, 1999; *Kouwen and Irrig*, 1992]. The obtained range of friction values of the flow transmissivity for vegetated flow is, as expected, higher than that of unvegetated earthen beds, in the range of 0.01-0.04 [*Akan and Yen*, 1993]. A higher Manning friction coefficient implies a lower flow transmissivity and vice versa. This finding is also consistent with estimated decreases of 1-2 orders of magnitude in scalar transport dispersion between unvegetated and vegetated surface flows [*Nepf*, 1999].

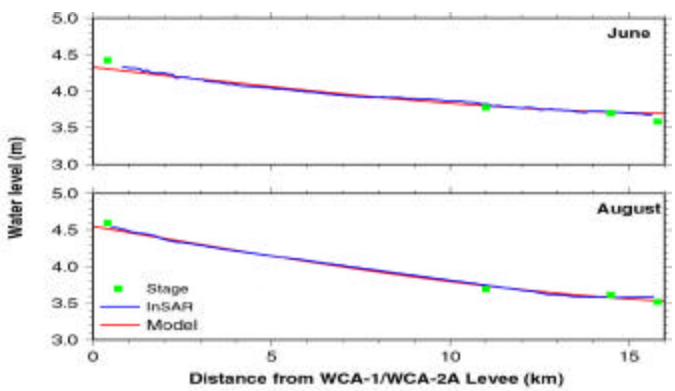

Figure 5: Comparison between observed stage, InSAR, and best-fit modeled water levels in June and August 1994 across area 2A (along the N-S profile shown in Figure 3). Model parameters are described in Table 2.

Table 2: Summary of Hydrologic Modeling (see in Figure 5).

Parameter	Description	June 1994	August 1994
H_0 (m)	Elevation difference	0.85±0.04	1.41±0.05
Dt (m^2)	Characteristic length	$73.2 \pm 3.3 \times 10^6$	$91.9 \pm 3.8 \times 10^6$
D (m^2/s)	Transmissivity	52±11	133±46
$\boldsymbol{n}$ [i]	Manning's coefficient	0.7 – 1.0	0.3-0.7

[i]: $\boldsymbol{n}$ is estimated using reference values of $h=1$ m and $-dH/dx=7\ 10^{-2}$ m/km.

Training potential.

The proposed research will support the training of one graduate student and one undergraduate student. The graduate student is Dawn James, who is a USGS employee and is in the process of applying to UM for her Ph.D. program. She is hydrologist by

training and is interested to learn and apply InSAR technique and observations to hydrological problems. Her research focus will be on the usage of InSAR-measured surface elevation changes and aquifer-system deformation in southern Florida. Although her thesis research has a different focus than our proposed research to NIWR, she will greatly benefit from the data, resources and personnel working on a related problem.

An undergraduate student will work for the project during two summers. He will be trained in remote sensing, InSAR data processing and hydrology, as well as enriching his computer skills. The planned undergraduate training will prepare him/her to any good graduate programs in Earth Science and/or to a real job.

Statement of Government Involvement.

The co-PI Roy Sonenshein (USGS) will be responsible to transfer and use the space-based water-level observations for constraining the USGS's TIME (Tides and Inflows in the Mangroves of the Everglade - http://time.er.usgs.gov/) flow model of the Everglades. The high-spatial resolution InSAR measurements (300 x 300 m2) are excellent observations for constraining the 500 x 500 m2 spatial resolution of the TIME model.

Information Transfer Plan.

The project's disseminating information plan includes the following three components:

1. Local (southern Florida) – We plan to present the project results at local academic, research, environmental, and water managements organizations. So far, we presented our preliminary study results and received very positive feedback at following local institutes: University of Miami, Florida International University, Everglades National Park and the Loxahatchee Wildlife refuge. We plan to further inform these institutes about our results, as well as contacting other local organizations, such as the South Florida Water Management District, the local office of the Army Core of Engineers, the Miami and other regional offices of the USGS. We also plan to present the project results at the up coming GEER (Greater Everglades Ecosystem Restoration) Conferences. By presenting our results locally we hope to promote the usage of the space-based measurements as a monitoring tool, as well as important constraints for detailed surface flow models of the Everglades.

2. National – We plan to present the project results at least two national meetings, e.g., AGU, the NASA Surface Water Working Group (SWWG), etc. When we'll achieve significant results for the Louisiana Coast and Chesapeake Bay wetlands, we'll contact local organization in these areas, in order to expose them to the project and its results.

3. International – As part of project's information transfer plan, we also plan to attend the upcoming JAXA's (Japan Aerospace Exploration Agency) ALOS meeting (9 month after the launch of the ALOS satellite, which is scheduled for 12/04) to report on our progress and further promote the usage of SAR data for hydrological applications. If possible, we will also attend other international meetings with SAR/InSAR focus.

Literature Citations/References

Akan, A.O. and B.C. Yen, J. Hyd. Div. ASCE, **107**, 719, 1981.

Alsdorf DE, Melack JM, Dunne T, Mertes LAK, Hess LL, Smith LC, Interferometric radar measurements of water level changes on the Amazon flood plain, Nature, 404 (6774): 174-177 MAR 9 2000.

Alsdorf D, Birkett C, Dunne T, Melack J, Hess L, Water level changes in a large Amazon lake measured with spaceborne radar interferometry and altimetry, GEOPHYSICAL RESEARCH LETTERS, 28 (14): 2671-2674 JUL 15 2001a

Alsdorf DE, Smith LC, Melack JM, Amazon floodplain water level changes measured with interferometric SIR-C radar, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, 39 (2): 423-431 FEB 2001b.

Amelung, F., D. L. Galloway, J. W. Bell, H. A. Zebker, and R. J. Laczniak, Geol., **27**, 483, 1999.

Amelung, F., S. Jónsson, et al. (2000). "Widespread uplift and 'trapdoor' faulting on Galápagos volcanoes observed with radar interferometry." Nature 407(26 October): 993 - 996.

Bawden G. W., W. Thatcher, R. S. Stein, K. W. Hudnut, and G. Peltzer, Nature, **412**, 812, 2001

Bhallamudi, S.M., S. Panday and P.S. Huyakorn, Sub-timing in fluid flow and transport simulations, *Adv. Wat. Resour*. 26, 477-489, 2003.

Burgmann, R., P. A. Rosen, and E. J. Fielding, Ann. Rev. Earth Planet. Sci., **28**, 169, 2000.

Carslaw H. S., and J. C. Jaeger, *Conduction of heat in solids* (second edition), Oxford University Press, New York, 1959.

Kouwen N., and J. Irrig. Drain. E.-ASCE **118**, 733, 1992.

Lal, W.A.M, J. Hydraul. Eng., **124**, 342 1998; Water Resources Res., **36**, 1237, 2000.

Lee, J.K, V. Carter, and N.B. Rybicki, Proceedings of the Third International Symposium on Ecohydraulics, July 1999.

Massonnet, D., M. Rossi, C. Carmona, F. Adragna, G. Peltzer, K. Feigl, and T. Rabaute, The displacement field of the Landers earthquake mapped by radar interferometry, *Nature*, *364*, 138-142, 1993.

Massonnet, D., K. Feigl, M. Rossi, F. Adragna, Radar interferometric mapping of deformation in the year after the Landers earthquake. *Nature, 369,* 227-230, 1994.

Massonnet, D., and K. L. Feigl, Discriminating geophysical phenomena in satellite radar interferograms, *Geophys. Res. Lett., in press*, 1995a.

Massonnet, D., P. Briole, et al. (1995). "Deflation of Mount Etna monitored by spaceborne radar interferometry." Nature 375: 567-570.

Massonnet, D. and K. L. Feigl, Rev. Geophys., **36**, 441, 1998.

Mumby, P.J., Edwards, A.J., 2002, Mapping marine environments with IKONOS imagery: enhanced spatial resolution can deliver greater thematic accuracy, Remote Sensing of Environment, 82, 248-257.

Murakami, M., M. Tobita, et al. (1996). "Coseismic crustal deformations of the 1994 Northridge, California earthquake detected by interferometric analysis of SAR images acquired by the JERS-1 satellite." J. Geophys. Res. 101: 8605-8614.

Overton, D.E., and M.E. Meadows, *Stormwater Modeling* (Academic Press, New York, 1976).

Maidment D.R., *Handbook of Hydrology*, McGraw-Hill, New York, 1993.

McLaughlin, D.B. and L.R. Townley, A reassessment of the groundwater inverse problem, *Water Resour. Res*., 32(5), 1131-1161, 1996.

Nepf H. M., Water Resour. Res. **35**, 479, 1999.

Richards, L. A., P. W. Woodgate, and A. K. Skidmore., Inter. J. Remote Sensing, **8**, 1093, 1987.

Storm, B. and A. Rafsgaard, Distributed physically-based modeling of the entire land phase of the hydrologic cycle, Kluwer Academic Publishers, 1996.

Wdowinski, S., F. Amelung, F. Miralles-Wilhelm, T. Dixon, and R. Carande, Space-based measurements of sheet-flow characteristics in the Everglades wetland, Florida, Submitted to Geophys. Res. Lett., 2004.

Wu F.-C., H. W. Shen, and Y.-J. Chou, J. Hydraul. Eng.-ASCE, **125**, 934, 1999.

Yeh, G. T., 1999. Computational Subsurface Hydrology Fluid Flows. Kluwer Academic Publishers

Zebker, H. and J. Villasenor, Decorrelation in interferometric radar echoes, *IEEE Trans. Geosci. Rem. Sensing, 30*, 950-959, 1992.

Zebker, H., P. Rosen, R. Goldstein, A. Gabriel, and C. Werner, On the derivation of coseismic displacement fields using differential radar interferometry: the Landers earthquake, *J. Geophys. Res.*, 99, 19617-19634, 1994a.

Zebker, H.A., T.G. Farr, R.P. Salazar, and T. Dixon, Mapping the world's topography using radar interferometry: the TOPSAT mission, *Proc. Inst. Electrical Electonic Eng., 82.*, 1774-1786**,** 1994b.

Zebker, H.A., C. Werner, P.A. Rosen, S. Hensley, Accuracy of topographic maps derived from ERS-1 interferometric radar, *IEEE Trans. Geosci. Rem. Sens., 32*, 823-836, 1994c.

Zebker H. A., P. A. Rosen, and S. Hensley, J. Geophy. Res., **102**, 7547, 1997.