3725-00026

Final Report

Aug 4, 2005

Washoe County DWR/RWPC cooperative study with Dr. Gary Oppliger of the relation between satellite based radar differential interferometry (D-InSAR) ground deformations and groundwater production and level data in the Truckee Meadows

Jointly funded by DWR and RWPC

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Abstract

This study has developed new data and analysis for the Truckee Meadows region which strongly indicates Satellite radar D-InSAR technology will be a useful and cost effective compliment to existing aquifer monitoring methodologies over many heavily utilized aquifers in Washoe County (WaCo). The results provide convincing evidence D-InSAR is detecting previously unknown production related aquifer volume change which is relevant to aquifer mapping. Clear correlations of groundwater level (GWL) data with D-InSAR observations were apparent only in areas where the GWL changes were relatively large (10s of feet), spatially uniform and sustained over several years. D-InSAR appears to observe spatially and perhaps temporally smoothed summaries of the aquifer production stress changes (more exactly aquifer volume change). Since D-InSAR and GWL data observe aquifer production stresses from different perspectives they are complementary. Although we identified specific technical limitations to InSAR's application in southern WaCo, as noted in the final report, we also found it provides previously unavailable information on the area's most heavily utilized aquifers. Hence, we propose WaCo employ the collaborative framework established in this study to begin evaluation of the new D-InSAR radar data obtained during 2004-2005.

Executive Summary

Satellite Differential Interferometric Synthetic Aperture Radar (D-InSAR) is a radar imaging technology that is able to measure sub-centimeter surface elevation changes over intervals of months and years. The technology has been applied to groundwater use issues in several cities in the western USA. This study stands distinct from most other studies in that it is not motivated by groundwater use subsidence issues. In contrast, this study is concerned with proving the feasibility of observing and isolating the very small surface elevation changes in the Truckee Meadows, establishing how they related to known groundwater use patterns, defining the practical application limits of the technology in the Truckee Meadows, and then illustrating how this information can be useful to future groundwater management practices.

The author worked with three UNR graduate students who made important direct and indirect contributions to this study. UNR Ph.D. geology graduate student, Cheryl Goudy assisted with the initial radar data processing during 2004, and assessed the D-InSAR results for correlations with available groundwater records by examining changes in individual wells. Cheryl identified the cyclical inflation-deflation characteristics in the D-InSAR patterns, but because only a small number of wells had GWL records suitable for comparison with the D-InSAR results. A second phase of groundwater data analysis was initiated by the author and Michael Widmer. The author collaborated with and trained Washoe County (WaCo) Department of Water resources (DWR) Hydrogeologist, Michael Widmer in D-InSAR theory and application methodology using the Truckee Meadows radar datasets (largely within a UNR graduate course on InSAR). Michael Widmer provided expertise and assistance in accessing, assembling and applying available groundwater production and level monitoring datasets. In a separate radar course project, Hydrology graduate student, Justin Huntington, compiled GWL and production data for Carson City and examined Truckee Meadows soils type distributions for possible correlations with D-InSAR responses. His results provided additional insights into the processes acting in the Truckee Meadows.

Our study found that municipal groundwater utilization in the Truckee Meadows study is associated with very small (centimeter-level) surface elevation changes which are broadly distributed over areas one to six kilometers wide. In the Central Truckee Meadows (CTM) D-InSAR observations define two active areas which show cyclical surface deflation and inflation with elevation changes of 10 to 30 millimeters over one to nine years. Figures 1 to 4 show samples of these D-InSAR patterns. Some D-InSAR pattern perimeters appear to be localized by geologic structure while others are dynamic. In the CTM, surface deflation appears to be periodically restored by aquifer recharge processes (Figures 2 and 3). The CTM D-InSAR active areas correspond well with the most significantly utilized groundwater aquifers (Figure 5).

To meet the study's objective to develop and evaluate evidence for the direct relation between D-InSAR and groundwater production in the study area, comparisons between 1992-2002 groundwater levels, production rates and D-InSAR surface inflation-deflation features were needed. We first constructed traditional groundwater level change maps but found good correlations with D-InSAR observations were apparent only in areas where the GWL changes were relatively large (10s of feet), spatially uniform and sustained over several years. We identified several factors which likely contribute to the weak correlation of GWL's and D-InSAR responses. The most important of these factors relate to incomplete GWL coverages, GWL monitoring data representing different aquifer levels, proximity to production wells, delayed development of aquifer volume change when water levels are altered, and lateral change in

aquifer composition. Ultimately the search for convincing correlations with the D-InSAR observations led us to develop two new specialized types of water use maps – an extracted groundwater volume map and an average seasonal groundwater level change map.

The extracted groundwater volume map (Figure 5) was designed to model the volume of water taken from the aquifer at increasing radial distances from the well during the corresponding D-InSAR observation period. Extracted water volume maps based on this method showed exceptional correlations with the corresponding D-InSAR observations in the Central Truckee Meadows and form our strongest evidence for a direct association of groundwater use and D-InSAR responses.

The average seasonal groundwater level change map (Figure 6) was designed to compensate for the limited CTM GWL data coverage during the 1992-1999 D-InSAR observations by using the more complete GWL coverage from 2000-2004. It assumes the seasonal patterns defined during 2000-2004 will be grossly similar to the earlier period. This average seasonal change map showed only rough pattern correlation with the seasonally repeating D-InSAR patterns from the previous decade. Although this result is not robust in its details, it is the best GWL and D-InSAR correlation we have presently developed for the CTM. Analysis of D-InSAR observations from 2004 forward will benefit greatly from improved GWL and D-InSAR data overlap, so future use of this type of map may be unnecessary.

Combined, these results provide strong evidence D-InSAR is detecting previously unknown production related aquifer volume change which is relevant to aquifer mapping. D-InSAR appears to observe spatially and perhaps temporally smoothed summaries of the aquifer production stress changes (more exactly aquifer volume change). Since D-InSAR and GWL data observe aquifer production stresses from different perspectives they are complementary.

Although we identified specific technical limitations to D-InSAR's application in southern WaCo, as noted in the final report, we also found it provides significant previously unavailable information on the area's most heavily utilized aquifers. Hence, we propose WaCo employ the collaborative framework established in this study to begin evaluation of the new D-InSAR radar data obtained during 2004-2005. This collaboration makes it possible to conduct significant portions of future D-InSAR work within DWR, with the author's role reduced to providing technical management and assistance with the development of new methodologies and software tools to facilitate D-InSAR data use and interpretation.

Study focus and objectives

Study Area

The study area is confined to the Truckee Meadows (TM) Washoe County (WaCo), Nevada with emphasis on analysis of groundwater data in the Central Truckee Meadows (CTM).

Objectives

- Determine what types of groundwater related signals are present in D-InSAR
- Introduce WaCo hydrology staff to the application of D-InSAR technology
- Determine practical limits on its D-InSAR application in WaCo.
- Determine general applicability of D-InSAR for groundwater management in Southern WaCo.
- Acquire ENVISAT radar baseline data for summer 2004 – fall 2005

Background

This report is written for a reader with basic knowledge of how groundwater is utilized and managed in the Truckee Meadows. To understand the significance of the study's results the following groundwater concepts and issues need to be appreciated.

a.) There are conceptual differences between groundwater aquifers and surface reservoirs where it concerns estimating the stored water volume and net recharge rates. A reservoir's stored water volume is defined by its geometric shape and its current water level measured at a single location. The net effect of recharge and loss is always known from the reservoir's level. In groundwater aquifers complexity arises in the determination of the stored water volume from an incomplete knowledge of the aquifers geometry, variations in effective porosity, hydrologic communication with neighboring aquifers and time delayed propagation of cone-of-depression water level changes away from producing wells. The result is that no single measurement of an aquifer's groundwater level (GWL) is sufficient to define the current state of depletion or recharge in an aquifer.

b.) Just as in surface water reservoirs, the effects of multi-year droughts accumulate in aquifers creating long-term groundwater level cycles that can exceed annual variations by several times.

c.) Groundwater recharge rates are highly variable across the Truckee Meadows. Time-scales required to replenish extracted groundwater range from a few months, for wells fields adjacent to the Truckee River, to many years or more, for well fields in the Southwest Truckee Meadows foothills.

d.) Water use planning proceeds on the basis of water right allocations that are based on estimates of surface and subsurface flows into the Truckee Meadows. These water allocations are anticipated to be realistic when averaged over many years and applied to the Truckee Meadows as a whole. However, they do not predict or account for local aquifer characteristics which vary radically across the TM. These characteristics include: realizable production volumes, acceptable water chemistry, and seasonal and long-term aquifer recharge characteristics. The first two characteristics preclude the development of many production wells in what would otherwise be logically located areas. With regard to the third item, the effectiveness of seasonal and long term recharge may not be apparent in a newly developed well field, until multiple wells are in operation. As a result, the success of planned new groundwater development cannot be guaranteed.

The difficulty associated with the full utilization of these incompletely defined underground resources makes it important that we assess the possible contributions of D-InSAR.

D-InSAR

Repeat-orbit satellite Differential Interferometric Synthetic Aperture Radar (D-InSAR) became an operational technology in1992 with the comissioning of the European Space Agency's (ESA) Earth Remote Sensing 1 (ERS -1) satellite followed by ERS 2 in 1995, and ENVISAT in 2003. These satellites operate in the C-band at a frequency of 5.3 GHz that corresponds to a wavelength of 5.66 centimeters. See Table 1 for ERS radar specifications. D-InSAR has been utilized for its ability to image earth surface deformation related to earthquakes, volcanic intrusions, and the production of groundwater, geothermal energy and petroleum (Massonnet, 1998). D-InSAR is a surface displacement change detection method with millimeter level sensitivity. Surface displacements that occur in the time interval between the acquisitions of two radar scenes are inferred by comparing the differences in travel times of radar waves at discrete points within the surface radar image. This is accomplished by combining the two radar scenes to form an interferogram or phase interference image. D-InSAR offers two distinct advantages over traditional optical leveling and GPS for vertical surface change detection. First it can provide map-like images at resolutions of 20-40 meters covering 100 km by 100 km regions. Second, it can be applied in retrospective change studies by using the 12 year archive of ERS 1/2 scenes.

Historic Radar Data (1992-2002)

Eighteen Synthetic aperture radar (SAR) scenes from the ERS 1 & 2 satellites from orbital Track 256, Frame 2817 were available to this study. The scenes were acquired through the Western North America D-InSAR Consortium (WinSAR) archive (13 scenes) and purchased through a Nevada NASA EPSCoR grant (5 scenes). They were processed at UNR under the author's direction into 24 differential interferograms using JPL's ROI_PAC V2.2.2 Linux software in the Arthur Brant Laboratory for Exploration Geophysics. Figure 7 shows the full scene coverage. See Table 2 for the complete scene list.

Radar data for continuing and future work (2004-2005)

The last of the ESA ERS 1 & 2 satellites ceased practical operation in late 2002, and was replaced by the new ESA ENVISAT ASAR satellite in 2003. (launched March 2002) . Although this system was operational, only two scenes had been acquired of the study area from Jan 2003 to June 2004 because no one was ordering scenes. To facilitate continued radar observations in this area, 21 new ENVISAT ASAR radar scenes were scheduled and prepaid for acquisition to the storage archive were they can be assessed for usability before purchase. This acquisition program began August 2004 and will continue through at least Oct 2005.

Acquisition of Southern Washoe County ENVISAT Radar data to facilitate continuity in radar groundwater studies in 2004 and 2005

ENVISAT ASAR radar data over southern Washoe County area (Reno-Tahoe) is being purchased through UNR from RadarSat International (Richmond, B.C. Canada under a prepaid data acquisition purchase order. Washoe County DWR provided $5,960 (paid to UNR on August 12, 2004) and Dr. Oppliger provided an addition $3640 (from his UNR research funds) for a total of $9600. On August 13, 2005 a UNR purchase order with check for $9,600 was sent

to RadarSat International for the purchase of 30 scene acquisitions ($120 each pair) , 12 scene purchases ($480 per scene) and $240 shipping.
To allow selection and purchase of only the highest radar quality scenes, a two step data acquisition process is employed.

1) First scenes are ordered for acquisition to the ENVISAT radar data archive at a cost of $120 per spatially continuous frame pairs. (see the scene list below)
2) Second, after the archive is filled with 8 -12 months of data, matching scene pairs will be selected for radar interferometry and purchased at a cost of $480 per scene for the first scene and $336 per scene for each following scene per order.

By summer 2005 sufficient archive data should be present to make practical the selection and ordering of the actual ASAR data scenes. .See Figure 8 for the scene index map and Table 3 for the scenes programmed.

ENVISAT current price list
http://www.rsi.ca/products/sensor/envisat/envisat_pricelist.asp

Groundwater production induced aquifer stress and strain
With regard to groundwater use, D-InSAR observes surface inflation and deflation patterns produced by volume change in aquifers. According to aquifer deformation theory (Poland, 1984) an aquifer compresses when groundwater levels (i.e. aquifer potentiometric pressures) are reduced; and part of or all of that compression will be relieved when groundwater levels are restored. An aquifer's sensitivity to volume change (strain) per unit change in ground water level, or potentiometric pressure (stress), depends strongly on the aquifer's compositional characteristics and its degree of hydrologic confinement. Incompletely consolidated sedimentary aquifers with clay layers and lenses tend to be the most susceptible to this type of volume change, but theoretically all aquifers produce some response to pressure changes. Pressure change drives aquifer volume change through elastic compression of the granular sediment matrix, dewatering of clay lenses, granular rearrangement (compaction) or closure of bedrock fractures.

Aquifer thermal changes may also produce volume change, but the required temperature changes and affected rock volumes must be large to produce observable effects. Consequently, they are not expected to contribute to municipal water production anomalies. In contrast, the Steamboat geothermal system in the South Truckee Meadows (STM) appears to be exhibiting a thermal contraction response.

A second factor to consider is that a fixed distribution of groundwater pumpage will produce different GWL - pressure change distributions in different aquifers. The pressure change distribution will be influenced by the aquifer's effective permeability thickness product, the effective total aquifer volume, and the rate that external flow enters the aquifer to replace the pumped water. During the high water use season an aquifer will be subject to its highest internal pressure reductions (aquifer production stress) because production may far outpace available recharge. This is generally a temporary condition as recharge gradually restores the balance over the low water use season. Where high aquifer transmissivity allows rapid groundwater recharge, production volumes can be relatively large without inducing significant local aquifer pressure stress and related volume strain. Hence, the center of groundwater production is not always coincident with the loci of extreme aquifer pressure stresses (GWL changes) nor will the loci of aquifer strain (volume change) correspond to the pressure distribution.

We use the term aquifer-strain-state to describe the total elastic and plastic volume change (compression or expansion) currently developed in an aquifer as compared to its "original" or preproduction volume. Aquifer-stress-state then describes the distribution of pressure change developed over the same period. Hence an aquifer that is described as stressed by groundwater production is one in which hydrostatic pressures have been reduced. An aquifer described as strained by groundwater production is one exhibiting volume change.

Prior to the introduction of the D-InSAR method, aquifer deformation was only known and studied when it became extreme and produced surface subsidence manifestations. The theory, however, predicts that all aquifers change volume in response to potentiometric pressure change and that we should expect a continuum of responses. Because the study area's observed aquifer responses do not correspond to the classic definition of monotonic subsidence we refer to these D-InSAR features as aquifer inflation-deflation.

We note that D-InSAR observes only the difference in aquifer strain states on the two radar scene dates used in the interferogram. As examples, an aquifer identically strained on both radar scene dates will theoretically not have a D-InSAR response. An aquifer that is strained on date 1, and recovered by recharge to a normal on date 2 will appear inflated.

Methods

This section describes the primary methods we used to develop and evaluate evidence of correlations of the D-InSAR responses with groundwater use. We begin with a review of D-InSAR interferogram formation.

D-InSAR interferogram formation

With reference to the European Space Agency ERS 1/2 radar satellites and JPL's ROI PAC processing software, we outline the essential processing steps and data considerations.

Radar scene acquisition and focusing

The ERS 1/2 satellite illuminates the earth to the side of the satellite track with frequency modulated 5.3 GHz radar chirps repeated at 1.7 kHz. The ~4 km wide radar beam propagates across the terrain in the range direction returning a continuous "echo" stream to the satellite receiver. On the ground, chirp compression and Doppler filtering focus the raw radar return to an image with 20 m by 20 m ground resolution. Each ground resolution cell contains a single complex value representing the sum of the real (R) and imaginary (I) (i.e., in-phase and quadrature) returns from all reflectors in that cell. This focused radar image is referred to as Single Look Complex (SLC) image represented here as

$$SLC1(x, y) = (R1 + iI1), \text{ where } i \text{ is } SQRT(-1).$$

Interferogram formation

SLC image pairs are spatially registered to better than 0.1 pixel using correlation algorithms; then the images are multiplied point-wise to produce the complex valued interferogram, INT:

$$INT(x, y) = (R12 + iI12) = (R1 + iI1)\,(R2 + iI2)^*,$$

where * denotes the complex conjugate operator.

$$PHS(x, y) = atan2(I12, R12),$$

then defines the interferometric or phase difference between two images.

In the special case of a zero baseline (or alternatively zero topography) and no ground deformation, the interferogram phase is theoretically constant across the scene. Local ground deformation in the interferogram period alters the radar travel distance and is expressed as a relative phase anomaly over the deformed area. In the general case of a non-zero baseline with topography, a terrain related phase pattern occurs that is easily predicted and removed using a digital elevation model. Where ground deformation exceeds half the radar wavelength, (2.83 cm) the phase vector wraps around, constraining phase between 0 to 2pi. These 2pi intervals are referred to as phase fringes and are typically colored with one full cycle of the color pallet. (for an example see Figure 7) The average 23° radar incidence angle of the ERS 1/2 satellite renders it 2.4 times as sensitive to vertical displacement as to displacement in the best coupled horizontal component. One fringe is produced by either 3.07 cm of vertical or 7.24 cm of orbit-track-perpendicular horizontal ground displacement.

Interferogram Signal and Noise

Selecting SLC image pairs

Baseline and time separation are primary interferogram parameters. Preferred scene pairs have no more than 300 meters offset (or perpendicular baseline) in their orbital paths perpendicular to the radar line-of-sight (LOS) vector. The time separation between scenes must be long enough to allow the surface deformation patterns to be well expressed in the interferogram, but not so long that heavy vegetation growth or other surface processes cause a loss of phase correlation between the images.

Decorrelation signal dropouts

In many regions vegetation growth drives decorrelation and sets the maximum effective interferogram time interval. In our study area in the Great Basin, sage and scrub growth over five years has little effect. However, we find that areas with wind blown sand or playas are subject to relatively rapid decorrelation.

Dynamic range

InSAR's deformation observation dynamic range is subject to time and spatial constraints. On the minimum signal side, our experience has shown under good atmospheric and ground conditions, surface deformation features with 100 m to 5 km widths and 5 mm displacement over five years can be reliably imaged in a single interferogram. Under these favorable conditions, the non-deformation in-band noise is about 1 - 2 mm. Use of multiple interferograms can further reduce this noise level. On the maximum signal side, there is no practical limit on the total observable deformation, as long as the horizontal gradient in surface displacement projected on the radar LOS vector does not exceed one-half wavelength per ground resolution cell (20 meters) during the interferogram interval.

Noise

Tropospheric water vapor variation is the dominate source of in-band noise and occasionally mimics a few centimeters of surface deformation. It is identified and avoided by the use of multiple interferogram periods. Short wavelength out-of-band decorrelation noise can be reduced by spatial filtering at the expense of detail.

Interferogram selection and post processing to vertical surface deformation
To develop the data used in this study we formed 24 interferograms from 18 ERS 1 & 2 raw SAR radar scenes with 1 to 9 year intervals over the 1992 to 2002 period using JPL's ROI_PAC software. From these interferograms we selected a subset of 5 high-quality, low atmospheric noise interferograms for conversion from observed phase patterns to millimeters of local ground displacement and further processing. Even these interferograms contained some areas of localized phase decorrelation and data dropouts. This problem occurs when the centimeter-scale textural patterns of surface reflectors are altered significantly in a group of adjacent image pixels. ROI_PAC's phase unwrapping algorithm automatically masks those areas as being too ambiguous for algorithm treatment. We have found we can reliably interpolate across no data holes up to 100 meter wide in the unwrapped phase grid by employing minimum curvature interpolation to generate the missing surface.

To remove the D-InSAR anomaly's directional asymmetry resulting from combined sampling of vertical and horizontal surface displacement fields along the satellite's 24 degree off-vertical line-of-sight (LOS) viewing angle, we apply elastic deformation theory to transform the LOS anomalies to apparent vertical deformation. (Oppliger, publication in preparation). We find it advantageous to be able to work with deformation maps and profiles in which the anomaly asymmetry originates only from source-body asymmetry and not viewing angle.

Construction of groundwater level (GWL) change maps
Groundwater level (GWL) histories were extracted from TMWA and DWR provided databases. Water levels at times most closely approximating the interferogram start and stop dates were differenced to form a groundwater level change field in the database which was girded and contoured.

Construction of average GWL seasonal change maps
<u>Devising a time independent statistical GWL fluctuation approach</u>
We encountered some practical difficulties using groundwater level change maps to make comparisons with our set of available interferograms. The most significant issue in the Central Truckee Meadows data sets was there are too few wells with GWL observation records between 1992 and 1999 to allow the creation of a useful interpolated groundwater surface in that interval. It should be noted that the number of wells with level records increases significantly beginning in 2000, and continues through 2004, but only half of one of our available D-InSAR scene dates (Sept 2002) extends into that period. In the South Truckee Meadows the availability of GWL data back through 1992 is much better.

We had available D-InSAR observations from intervals with dates between 1992 and 1999, but the corresponding GWL well data coverage on these dates was too sparse to allow useful ground water level change maps to be constructed for comparison in the CTM. On the other hand, we had excellent ground water coverage available after 2000. To try to bridge this temporal data mismatch we developed a time independent statistical GWL fluctuation approach. The idea of using statistical GWL fluctuations rather than actual groundwater change was suggested by the cyclical repeating patterns apparent in the D-InSAR observations of 1992 to 1999. Hence, our objective was to look for similar repeating patterns in the cyclical seasonal GWL amplitudes of the groundwater records in 2000 to 2004.

From the CTM well data we extracted and tabulated the average seasonal GWL change amplitudes, grided these and prepared contour maps for comparison with the D-InSAR data. Statistical GWL fluctuations for monitoring wells deeper than 100 feet and shallower than 100 feet were tabulated and mapped separately.

Basin averaged GWL vs. time charts

As a compliment to the average seasonal GWL change maps in which time has been removed from each well's data, we created an experimental CTM basin-averaged GWL vs. time chart in which all wells have been averaged into one hypothetical well. Here we attempt to enhance GWL temporal detail by sacrificing spatial information – i.e. the well coordinates.

To form the GWL spatial averages for the 1992-2004 period, mean recorded water levels were subtracted from each well's records, then the records were interpolated and resampled to monthly intervals. With the water level observations from all wells on a common monthly sample interval, the records were added to estimate the average GWL in the basin. The result is shown in Figure 11.

One weakness in the data set for the average is that only five wells have reasonability complete GWL records prior to 1998 and most of these wells are adjacent to the Truckee River. Since water levels in most of these wells rose abruptly by ~8 feet immediately after the January 1997 flood, the averaged GWL vs. time chart may not be representative of the basin as a whole.

Construction of extracted water volume maps

To create extracted groundwater maps we had to develop a way to represent the volume of water removed from the aquifer.

Defining a mathematical function to spatially represent extracted water volume around each well. (i.e., production influence function, PIF.) We prepared initial maps by over plotting each production well with a circle proportionally sized to represent the water volume produced during the D-InSAR observation interval. This showed a strong general correlation with the D-InSAR patterns; but it was apparent that a more quantitative comparison with the D-InSAR patterns would require that the produced GW volumes be represented as continuous surfaces reflecting the actual quantity of water extracted over the observation interval.

Generating this surface can not be accomplished by interpolating (griding) the individual well production volume numbers between adjacent wells. Hence, we defined a mathematical distribution function to simulate the basic physics of radial water flow toward a well in a layered aquifer system. The resulting function is similar in shape to a 2-D Gaussian distribution function (bell curve) with a total under-curve volume equal to the produced water volume. In other words, the function represents the thickness of an equivalent layer of free-standing water removed from the aquifer. The along-surface width or spread of the production distribution function depends on the depth and effective thickness of the aquifer system and physically represents the amount of water per unit area (acre) taken from the aquifer at a given radial distance from the well.

Summing monthly production at each well

A procedure is needed to sum a well's monthly production volumes over the observation period before assigning it to the production influence function. We employed a simple time-independent tabulation approach which ignores the recharge received by the aquifer during the observation period. Since aquifer recharge eventually erases all effects of production, D-InSAR observes only the difference in aquifer stress (depletion) states on the two radar scene dates defining the interferogram. Therefore, the actual instantaneous water deficit in the aquifer is always less than the total extracted volume we estimate. Hence a future refinement to the method should include an adjustment for aquifer recharge process. Even thus limited, our time-independent tabulation produced an effective extracted groundwater map for the period evaluated.

Defining production influence function widths

The width for each well's production influence function is an unknown, but it may be inferred from matching it to the widths of the corresponding D-InSAR anomalies. Matching the widths of the well production distribution functions to the D-InSAR anomalies is physically justified. Similarities in the physics of radial fluid flow and the associated pressure field reductions link water extraction and D-InSAR ground deformations calculations. Our independently formulated production influence function differs only by a constant from the Mogi pressure deformation source (Mogi, 1958) which is commonly used to model D-InSAR anomalies. This correspondence is notable given that our purpose was to represent extracted groundwater volumes.

The PIF width is defined by an apparent source depth parameter, which is not related to the well's actual production depth. For the CTM groundwater production test interval, a fair match to the D-InSAR data was obtained by setting PIF widths corresponding to apparent source depths of 1000 meters.

Summing production influence functions from all of the wells

A completed grid and map of the extracted water volume is obtained through summation of the overlapping distribution functions associated with each well.

Discussion

Overview

To meet the study's objective to develop and evaluate evidence for the direct relation between D-InSAR and groundwater production in the study area, comparisons between 1992-2002 groundwater levels, production rates and D-InSAR surface inflation-deflation features were needed. We first constructed traditional groundwater level change maps but found good correlations with D-InSAR observations were apparent only in areas where the GWL changes were relatively large (10s of feet), spatially uniform and sustained over several years. We identified several factors which likely contribute to the weak correlation of GWL's and D-InSAR responses. The most important of these factors relate to incomplete GWL coverages, GWL monitoring data representing different aquifer levels, proximity to production wells, delayed development of aquifer volume change when water levels are altered, and lateral change in aquifer composition. Ultimately the search for convincing correlations with the D-InSAR observations led us to develop two new specialized types of water use maps – an extracted groundwater volume map and an average seasonal groundwater level change map.

The extracted groundwater volume map (Figure 5) was designed to model the volume of water taken from the aquifer at increasing radial distances from the well during the corresponding D-InSAR observation period. Extracted water volume maps based on this method show good correlations with the corresponding D-InSAR observations in the Central Truckee Meadows and form our strongest evidence for a direct association of groundwater use and D-InSAR responses.

The average seasonal groundwater level change map (Figure 6) was designed to compensate for the limited CTM GWL data coverage during the 1992-1999 D-InSAR observations by using