Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE

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Abstract Based on satellite observations of Earth's time variable gravity field from the Gravity Recovery and Climate Experiment (GRACE), it is possible to derive variations in terrestrial water storage, which includes groundwater, soil moisture, and snow. Given auxiliary information on the latter two, one can estimate groundwater storage variations. GRACE may be the only hope for groundwater depletion assessments in data-poor regions of the world. In this study, soil moisture and snow were simulated by the Global Land Data Assimilation System (GLDAS) and used to isolate groundwater storage anomalies from GRACE water storage data for the Mississippi River basin and its four major sub-basins. Results were evaluated using water level records from 58 wells set in the unconfined aquifers of the basin. Uncertainty in the technique was also assessed. The GRACE-GLDAS estimates compared favorably with the well based time series for the Mississippi River basin and the two sub-basins that are larger than 900,000 km^2. The technique performed poorly for the two sub-basins that have areas of approximately 500,000 km^2. Continuing enhancement of the GRACE processing methods is likely to improve the skill of the technique in the future, while also increasing the temporal resolution.

Résumé A partir d'observations satellitaires du programme Gravity Recovery and Climate Experiment (GRACE), l'étude de la variation dans le temps du champ de gravité terrestre permet de déduire les variations du stock d'eau terrestre, ce qui comprend l'eau souterraine, l'humidité du sol et la neige. Les variations de stock d'eau souterraine peuvent être estimées à partir d'informations auxiliaires sur les deux autres composantes. GRACE pourrait être le seul espoir pour l'établissement des bilans d'eau souterraine dans les régions du monde où les données sont peu nombreuses. Dans cette étude concernant le bassin du fleuve Mississippi et ses quatre sous bassins principaux, l'humidité du sol et la neige ont été simulées par le modèle Global Land Data Assimilation System (GLDAS) et utilisées pour isoler les anomalies de stock d'eau souterraine à partir des données de stock d'eau du GRACE. Les résultats ont été évalués à partir d'enregistrements de niveaux piézomètriques réalisés dans 58 puits localisés dans les aquifères libres du bassin. L'incertitude liée à la technique a également été évaluée. Les estimations GRACE-GLDAS concordaient avec les chroniques de puits pour le bassin du Mississippi ainsi que pour les deux sous bassins présentant une superficie supérieure à 900,000 km^2. La technique s'est avérée peu performante pour les deux sous bassins d'environ 500,000 km^2. L'amélioration continue des méthodes de traitement des données du GRACE devrait à l'avenir augmenter la performance de la technique ainsi que la résolution temporelle.

Resumen Es posible derivar variaciones en el almacenamiento de agua terrestre en base a observaciones de satélite del campo gravitacional temporal variable de la Tierra a partir del Experimento Clima y Recuperación de Gravedad (GRACE), el cual incluye agua subterránea, humedad del suelo, y nieve. Dada la información auxiliar de los dos últimos, uno puede estimar variaciones en almacenamiento de agua subterránea. GRACE puede ser

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la única esperanza para las evaluaciones de agotamiento de agua subterránea en regiones del mundo con datos pobres. En este estudio se simularon la nieve y humedad del suelo mediante el Sistema de Asimilación de Datos Globales del Terreno (GLDAS) y se usaron para aislar anomalías de almacenamiento de agua subterránea de los datos de almacenamiento de agua GRACE para la cuenca del Río Mississippi y sus cuatros sub-cuencas principales. Los resultados se evaluaron utilizando registros de niveles de agua para 58 pozos emplazados en acuíferos no confinados de la cuenca. También se evaluó la incertidumbre de la técnica. Los estimados provenientes de GLDAS-GRACE se comparan favorablemente con las series de tiempo de los pozos para la cuenca del Río Mississippi y las dos sub-cuencas cuyas áreas son mayores de 900,000 km^2. La técnica se desempeñó pobremente para las dos sub-cuencas que tienen áreas de aproximadamente 500,000 km^2. El mejoramiento continuo de los métodos de procesamiento GRACE es posible que mejore la habilidad de la técnica en el futuro mejorando al mismo tiempo la resolución temporal.

Keywords Groundwater monitoring · Water budget · Mississippi River basin · Geophysical methods · Remote sensing

Introduction

Aquifer water storage variability is routinely monitored by piezometers at point to local scales, but regional to continental scale monitoring using conventional methods is problematic. In developed nations, monitoring well networks are often dense, and studies which utilized these networks have shown that groundwater exhibits significant variability on seasonal and longer timescales relative to other water-cycle variables (e.g., Eltahir and Yeh 1999; Rodell and Famiglietti 2001; Seneviratne et al. 2004). Still, estimating regional groundwater storage variations in this way is complicated by data formatting and inconsistency, spatial and temporal data gaps, human and mechanical errors, and sparsely available metadata for converting piezometric head to volumetric water storage. Installing and maintaining a new well network or even supplementing an existing network is labor intensive and expensive. In other parts of the world, access to records may be limited by political boundaries, and what records are accessible may not be reliable, well documented, and available from a central location in digital format.

These sorts of issues are not uncommon in hydrology. Monitoring snow depth, soil moisture, runoff, and other water-cycle components over large scales can be equally or more challenging. In the 1970s, scientists began to hypothesize and test the potential of aircraft and satellite-based remote-sensing systems for measuring hydrologically and meteorologically significant phenomena. Groundwater is one of the last areas of hydrological science to benefit from remote sensing (Becker 2006).

The Gravity Recovery and Climate Experiment (GRACE; Tapley et al. 2004) is the first satellite remote-sensing mission which is directly applicable to the assessment of groundwater storage under all types of terrestrial conditions. Traditional remote sensors measure electromagnetic emissions in order to infer Earth surface and atmospheric conditions. GRACE is unique in that it relies on observations of satellite orbit perturbations, which are caused by gravitational anomalies near the land surface. So precise is the technique that it resolves changes in the gravity field due to redistribution of mass near the surface, including oceanic and atmospheric circulations and terrestrial water cycling. By separating the contributions to temporal mass variability using auxiliary observations and numerical models, it is possible to estimate changes in groundwater storage over sufficiently large regions (Rodell and Famiglietti 2002). Rodell and Famiglietti (1999) estimated that the minimum region size in which GRACE could resolve water mass variability would be about 200,000 km^2. Error sources not foreseen before launch have impacted the effective resolution, so that based on the analysis of Swenson and Wahr (2006b), the figure may be closer to 500,000 km^2, if an optimized data filtering and smoothing technique is used. Many studies are now demonstrating the value of GRACE to hydrological research and applications (e.g., Rodell et al. 2004b; Chen et al. 2005b; Syed et al. 2005; Velicogna et al. 2005; Swenson and Wahr 2006a). This paper presents a case study of the application of GRACE to the estimation of groundwater storage variability in the Mississippi River basin, USA.

Summary and discussion

This paper presents a simple approach for estimating groundwater storage variability based on remotely sensed terrestrial water storage observations from GRACE. In order to isolate groundwater variations from the total water storage signal, auxiliary information on the other component variations is required. Based on prior studies the assumption was made here that regionally averaged surface water and biomass variability are negligible in the Mississippi River basin. Groundwater, soil moisture, and snow then remain as the only significant contributors to the regional water storage observations. Because reliable and spatially continuous measurements of soil moisture and snow water equivalent are not currently available, output from three sophisticated land surface models driven by the Global Land Data Assimilation System was used to disaggregate variations in groundwater from those of soil moisture and snow water.

The approach appears to be appropriate for regions larger than about 900,000 km^2, based on the results for the Mississippi River basin and its four major sub-basins. At finer scales, the uncertainty in the GRACE observations and model products prohibit disaggregation of the water storage signal. However, ever more advanced techniques for deriving hydrological information from GRACE are continuing to be developed, and these could lead to error reductions and better spatial and temporal resolutions. In particular, improved noise filtering algorithms are being tested (e.g., Swenson and Wahr 2006b) and methods based on the level 1B intersatellite range data rather than the level 2 global gravity solutions are enabling sub-monthly retrievals with arguably better error characteristics (Rowlands et al. 2005; Han et al. 2005). Furthermore, advanced land surface modeling techniques such as data assimilation are being implemented in GLDAS (e.g., Rodell and Houser 2004), and these may ultimately improve the disaggregation of GRACE terrestrial water storage anomalies.