# CANDIDATE SOLUTION REPORT

## Assimilation of GRACE data into the Chesapeake Bay Watershed Model for Improved Representation of Groundwater Storage

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### Abstract

The Gravity Recovery and Climate Experiment (GRACE) data set will be used to provide a solution for improvement of the Chesapeake Bay Watershed Model (CBWM). The current Decision Support Tool (DST) for the Chesapeake Bay watershed is the HPSF model developed by the U.S Environmental Protection Agency. In order to better represent groundwater storage in the watershed model, GRACE data will be used as a calibration target for groundwater storage in the CBWM. This solution is in alignment with the EPA Chesapeake Bay Program modeling efforts to provide an improved understanding of hydrologic and water quality processes within the Chesapeake Bay watershed. This candidate solution will benefit society by improving water quality models that will enhance decision-making strategies related to land management and setting TMDLs (Total Maximum Daily Loads) for Chesapeake Bay tributaries.

### 1. Problem description

The Chesapeake Bay watershed is 64,000 mi$^2$ (166,000 km$^2$) in area and includes parts of New York, Pennsylvania, West Virginia, Virginia, Delaware, Maryland and the District of Columbia (Figure 1). Nearly 16 million people live in the watershed (USEPA, 2008). Water quality is of a great concern in the region. Nutrients and sediment transported to the Bay are major pollutants. As the use of the land has changed and the watershed's population has grown, the amount of nutrients entering the Bay has increased tremendously. Efforts are underway to reduce that pollution. Since 1982, watershed models have been developed as management tools, in order to better understand the pollution processes and test the effects of prospective management actions (USEPA, 2008). These management actions are principally land management measures and setting Total Maximum Daily Loads for the watershed tributaries.
A study conducted by the U.S Geological Survey in 1999 suggests that groundwater contributes more than 50% to the total annual flow of streams in the Chesapeake Bay

with a range of 16 to 92% depending on the streams considered (Phillips et al., 1999). According to that study, 48% of the nitrogen load of streams entering the Bay is from groundwater. This shows the importance of groundwater in the water budget and the importance of having a consistent representation of the groundwater fluxes in water quality models.

## 2. EPA Chesapeake Bay Hydrological Simulation Program Fortran (HSPF) Watershed Model

The Chesapeake Bay Community Phase 5 watershed model (USEPA, 2008) is the most recent version used to simulate river flows and associated transport and fate of nutrients and sediments. This model is an application of the Hydrological Simulation Program Fortran (HSPF) (Bicknell et al., 2005). HSPF is a continuous-time, physically based, lumped-parameter model that simulates hydrology, sediment and chemical pollutants in the soil and streams. Figure 2 shows the representation of water balance in HSPF. The water balance is calculated in a submodule that converts rainfall and evaporation data into surface runoff, changes in soil moisture storage, infiltration, evapotranspiration, and discharge of subsurface flow to the stream channel (USEPA 1994).

Subsurface flows are represented in HSPF as follows: Water that infiltrates the soil to the upper soil zone may enter: (1) lower zone storage as determined by the parameter LZSN, (2) inactive groundwater storage, or (3) active groundwater storage. The fraction of groundwater that enters inactive groundwater is considered lost from the watershed as deep aquifer recharge as controlled by the parameter DEEPFR (because groundwater can be lost from the system, the model does not conserve mass). The remainder enters active groundwater storage and is available for discharge to surface channels (Bicknell et al. 2005). Groundwater outflow is estimated from active groundwater storage (AGWS), the active groundwater recession coefficient (AGWRC) and the active groundwater modifier (KVARY), which governs the extent at which aquifer recharge affects aquifer discharge to the stream. AGWS, AGWRC and KVARY are given nominal values, and corrected during the calibration exercise against stream flow measurements.

One of the weaknesses in the representation of the hydrologic cycle in the HSPF is the groundwater component, because through the lumped-parameter calibration process the model does not take into account groundwater dynamics and ignores any groundwater physical measurements. This represents a significant limitation of the model. However for other reasons, this model is presently used by the Chesapeake Bay program and the region as a decision support tool and will be continued to be used in a regulatory context in the foreseeable future. Thus, despite limited representation of groundwater, efforts continue to be made to improve and use the model. We believe that the GRACE data set has the potential of improving current estimates of groundwater storage in the HSPF-based Chesapeake Bay Watershed Model.

## 3. NASA Research Results: GRACE Mission

The Gravity Recovery and Climate Experiment (GRACE) is a mission jointly launched by NASA and the German Aerospace Research Establishment. GRACE level 3 products consist of data where non-hydrological contributions to gravitational variations have been removed, providing data of the Terrestrial Water Storage Changes (TWSC or $\Delta$TWS) that includes variations in groundwater, soil moisture, and snow pack.

Swenson et al. (2006) performed the first direct comparison between terrestrial water storage variations from GRACE and in-situ measurements (combined groundwater and soil moisture) and concluded that the GRACE-derived data agree well with in-situ measurements averaged over an area of approximately 280,000 km$^2$. By removing the specific contribution of soil moisture ($\Delta$SM) and snow ($\Delta$Snow), using in-situ measurements or models, one can determine the GRACE groundwater storage changes (GWSC or $\Delta$GW) estimates, i.e.,

$$\Delta GW = \Delta TWS - \Delta SM - \Delta Snow \quad (1)$$

The idea of using GRACE as a source of data in the Chesapeake Bay watershed comes from the combination of two identified problems: the weakness in the Chesapeake Bay watershed model regarding representation of groundwater storage, and the importance of the groundwater component of the hydrologic cycle in accounting for discharges to the Chesapeake Bay tributaries. In addition, recent applications of GRACE data to regional-scale problems e.g., the High Plains aquifer (Strassberg et al., 2007), the State of Illinois (Yeh et al., 2006; Swenson et al., 2006) and the Mississippi River Basin and its subbasins (Rodell et al., 2007) point to the feasibility of using GRACE data for regional applications. Recent conversations with Matt Rodell made us aware of the sub-continental-scale applications.

## 4. Previous GRACE Studies

Various studies have explored the potential of GRACE for providing groundwater data in different regions and at different scales (e.g. Rodell et al., 2007; Strassberg et al., 2007; Yamamoto et al., 2007; Yeh et al., 2006). Rodell et al. (2007) estimated groundwater storage changes in the Mississippi River basin using TWSC data from GRACE, and the Global Land Data Assimilation System (GLDAS) for determining soil moisture and snow. Groundwater estimates were calculated by removing the soil moisture and snow contribution from the TWSC (Equation 1). Comparisons between the groundwater changes estimates and well based time series showed a good match for sub-basins that were larger than 900,000 km$^2$.

Strassberg et al. (2007) compared seasonal groundwater-level measurements in the High Plains aquifer (450,000 km$^2$) with GRACE monthly water storage changes and found good agreement. GRACE data have also been used to compare to simulations of the groundwater component of hydrologic (Niu et al., 2007) and climate (Niu and Yang, 2006; Swenson and Milly, 2006) models. Niu et al. (2007) developed a groundwater model and coupled it with a Land Surface Model (LSM). The coupled model was then evaluated against the GRACE data and results showed that the total water storage change estimates from the coupled groundwater-LSM model agree well with the GRACE estimates.

Yeh et al. (2006) estimated the groundwater storage changes in Illinois using GRACE and in situ measurements of soil moisture. Comparisons with available in-situ measurements showed that estimating monthly to seasonal groundwater storage changes with GRACE performed well at the 200,000 km$^2$ scale. These studies show the potential of GRACE for providing groundwater storage changes data on a monthly to seasonal basis and at a regional scale.

## 5. GRACE USE in Chesapeake Bay Water Management Model as Candidate Solution

Within the HSPF model, groundwater outflow is estimated from active groundwater storage (AGWS), the active groundwater recession coefficient (AGWRC), and the active groundwater modifier (KVARY). AGWS is the parameter that would be estimated using GRACE data.

GWSC can be obtained by vertically disaggregating GRACE TWS by subtracting soil moisture and snow pack contributions as discussed above (Equation 1). Previous studies have used successfully the Land Data Assimilation System (LDAS) soil moisture product to estimate the soil moisture component. This dataset provides daily and monthly soil moisture fields in a vertical profile at 1/8 to 1 degree resolution. Averaged vertically, it can give soil moisture storage change ($\Delta$SM in Equation 1) as done in previous studies (Strassberg et al., 2007; Rodell et al., 2007).

Changes in snow ($\Delta$Snow in equation 1) can be either retrieved from the MODIS snow cover product (http://modis-snow-ice.gsfc.nasa.gov/intro.html) or the GLDAS snow water equivalent product(http://disc.gsfc.nasa.gov/services/grads-gds/gldas.shtml) as done in previous studies. The value of MODIS snow covered area (SCA) retrievals depends upon cloud-free coverage within an area in which it is to be used.

To corroborate the GRACE data, field groundwater measurements from the USGS National Water Information System (NWIS) will be used. GRACE data can be compared to water level elevation changes scaled by the specific yield of the aquifer. Figure 1 shows wells distribution throughout the physiographic provinces of the Chesapeake Bay watershed. Confined, mixed confined/unconfined and unconfined aquifers are present. The rock types range from unconsolidated clastic sediments to igneous and metamorphic rocks to clastic and carbonate sedimentary rocks. The spatial density and the frequency of water level measurements in NWIS wells are highly variable.

Anticipated issues are the temporal and spatial scales of GRACE compared to CBWM data. The time step of the CBWM is hourly as opposed to the monthly time step of the GRACE data. Although hourly values of AGWS are not necessary, a finer time step will improve the calibration process. Temporal downscaling of the GRACE data could be carried out to temporally disaggregate the data. Zaitchick et al. (in review, 2008) present a downscaling method for assimilation of GRACE data in a land surface model. Using an ensemble Kalman smoother (enKS), the monthly data was disaggregated into smaller time periods of data (5th, 15th and 25th days of the month). This technique could be use to provide finer time step of GWSC that will enhance calibration of AGWS. There are approximately 5 years of monthly GRACE data available that could be utilized in the model.

The smallest spatial resolution of GRACE data available to date is 1-degree pixel size, whereas the discretization of the Chesapeake Bay watershed model is currently 1063 “land-river segments”, of an average of 170 km$^2$ in size. Each GRACE cell therefore spans about 60 watershed model segments, which would necessitate assigning a homogeneous groundwater storage value to groups of model segments (Figure 3) without further downscaling of the GRACE data. An example GRACE data set (1 degree grid) from 2003 is shown in Figure 4.

## 6. Conclusions and Benefits

This solution provides the opportunity to quantify groundwater storage characteristics throughout the Chesapeake Bay Watershed and implement its variations in the model. Improvement of groundwater representation is one of the recurrent comments that has been made by the Chesapeake Bay Watershed Phase 5 Model review committee (Band et al., 2008); utilization of GRACE data is one step toward addressing this comment. This solution presents the advantage of being usable in the current version of the model, with minor manipulations. The information it can provide about groundwater contribution to the water budget could be a valuable step towards the improvement of this community model. This candidate solution could benefit society by providing the Chesapeake Bay program with more consistent water budget and thus more accurate pollution simulations for use in decision making.

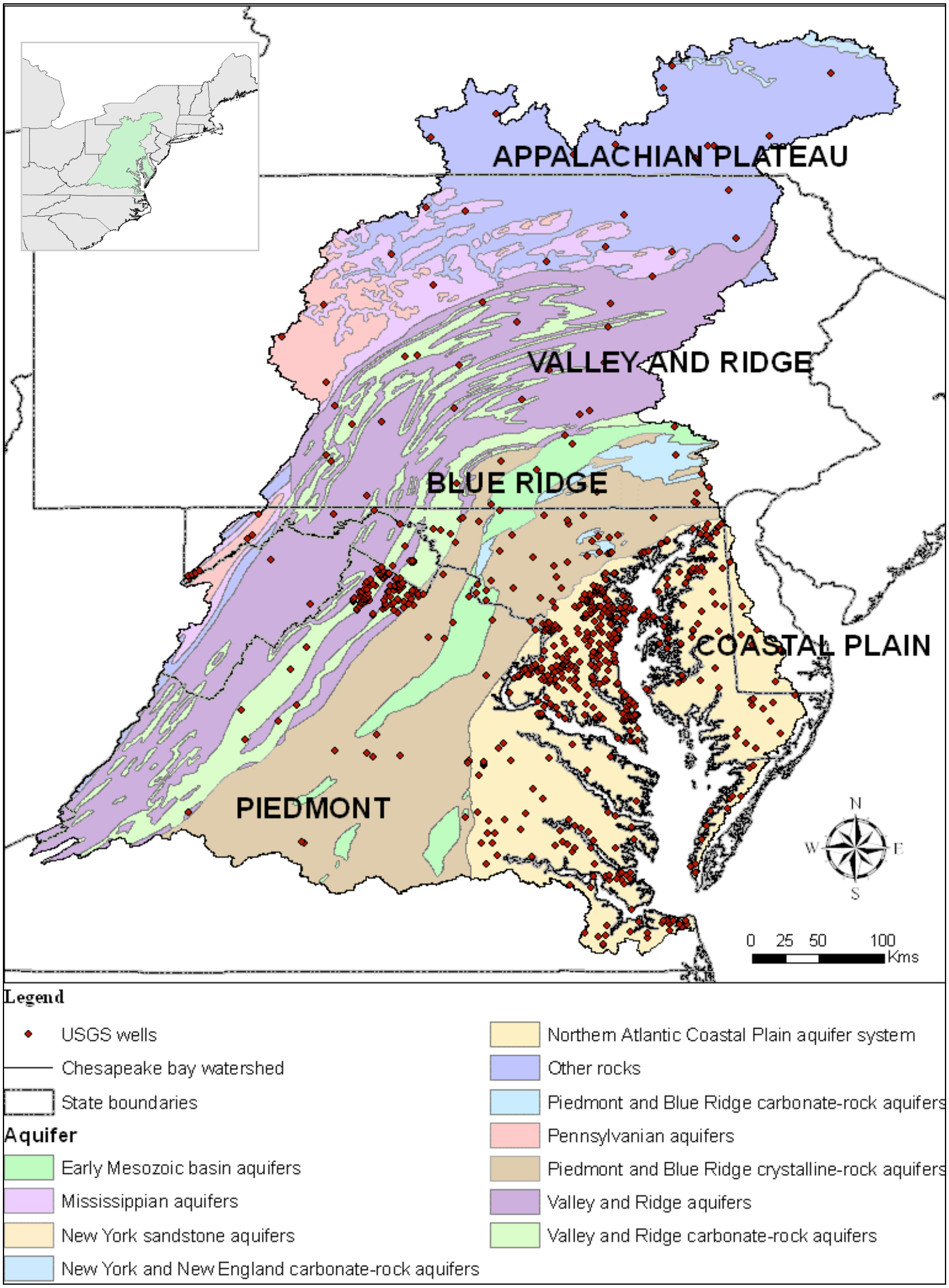

Figure 1. Chesapeake Bay watershed physiographic provinces and USGS wells monitored during 2002 - 2006.

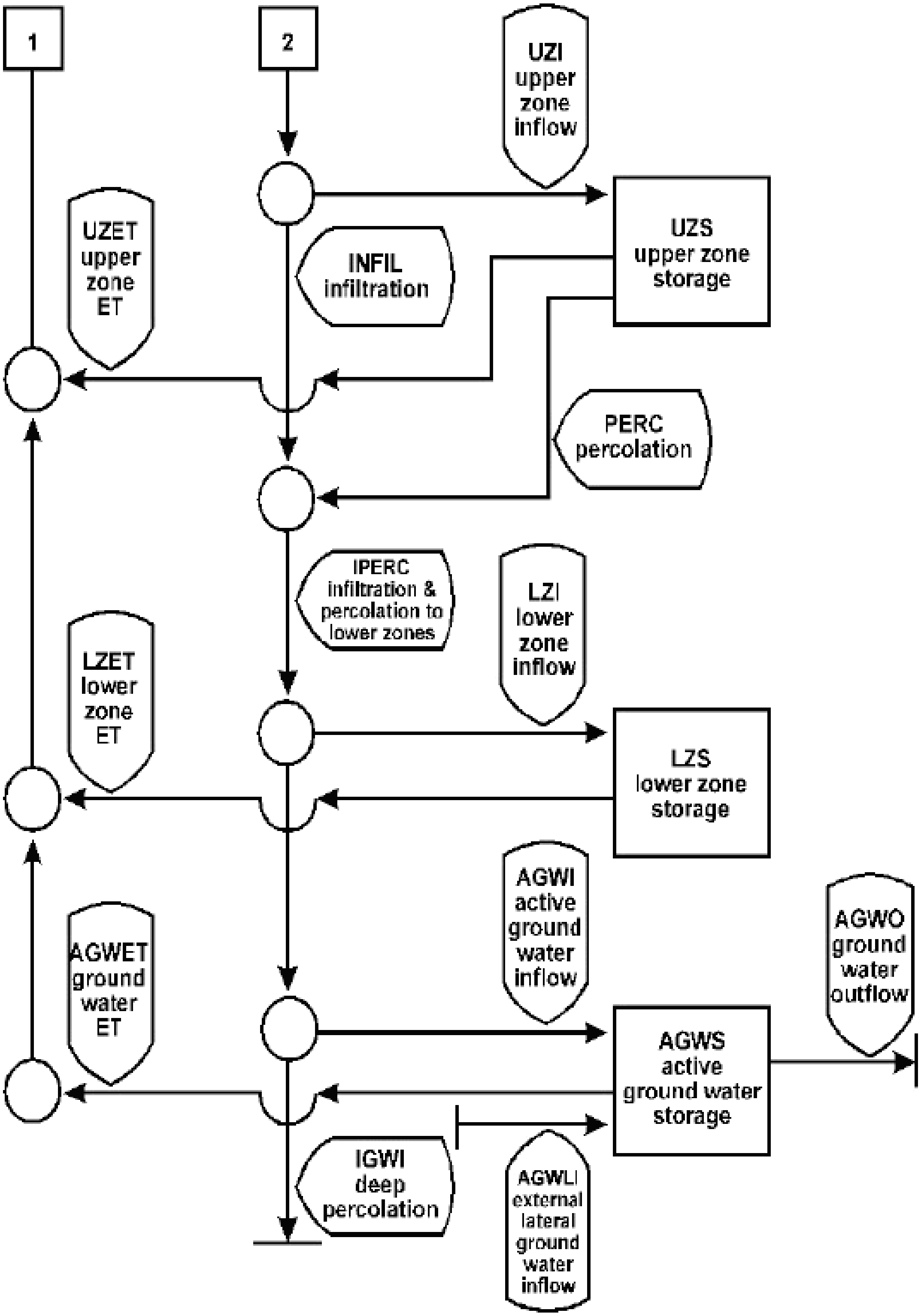

Figure 2. Flow diagram of water movement and storages modeled in HSPF.

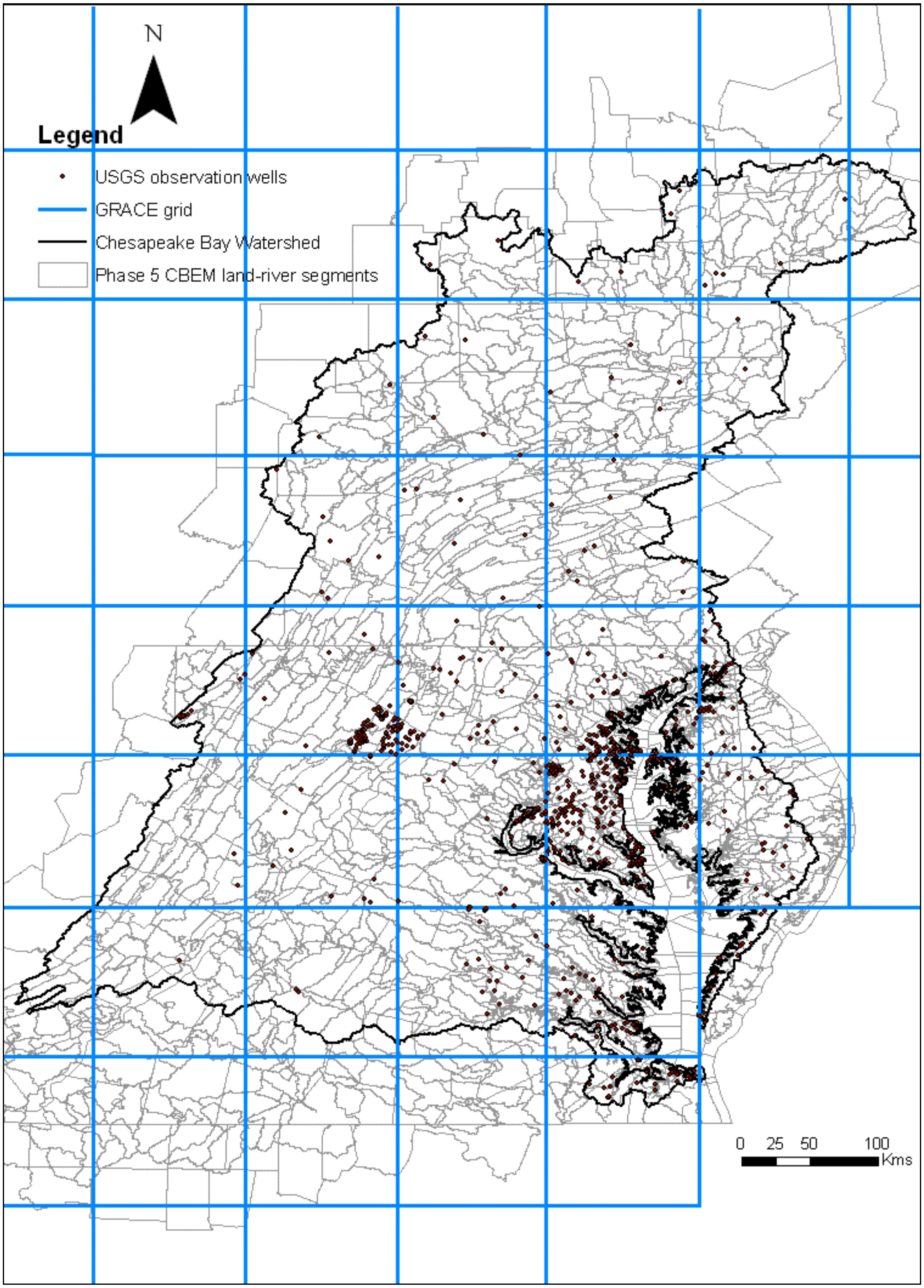

Figure 3. CBWM segmentation and GRACE 1 degree grid.

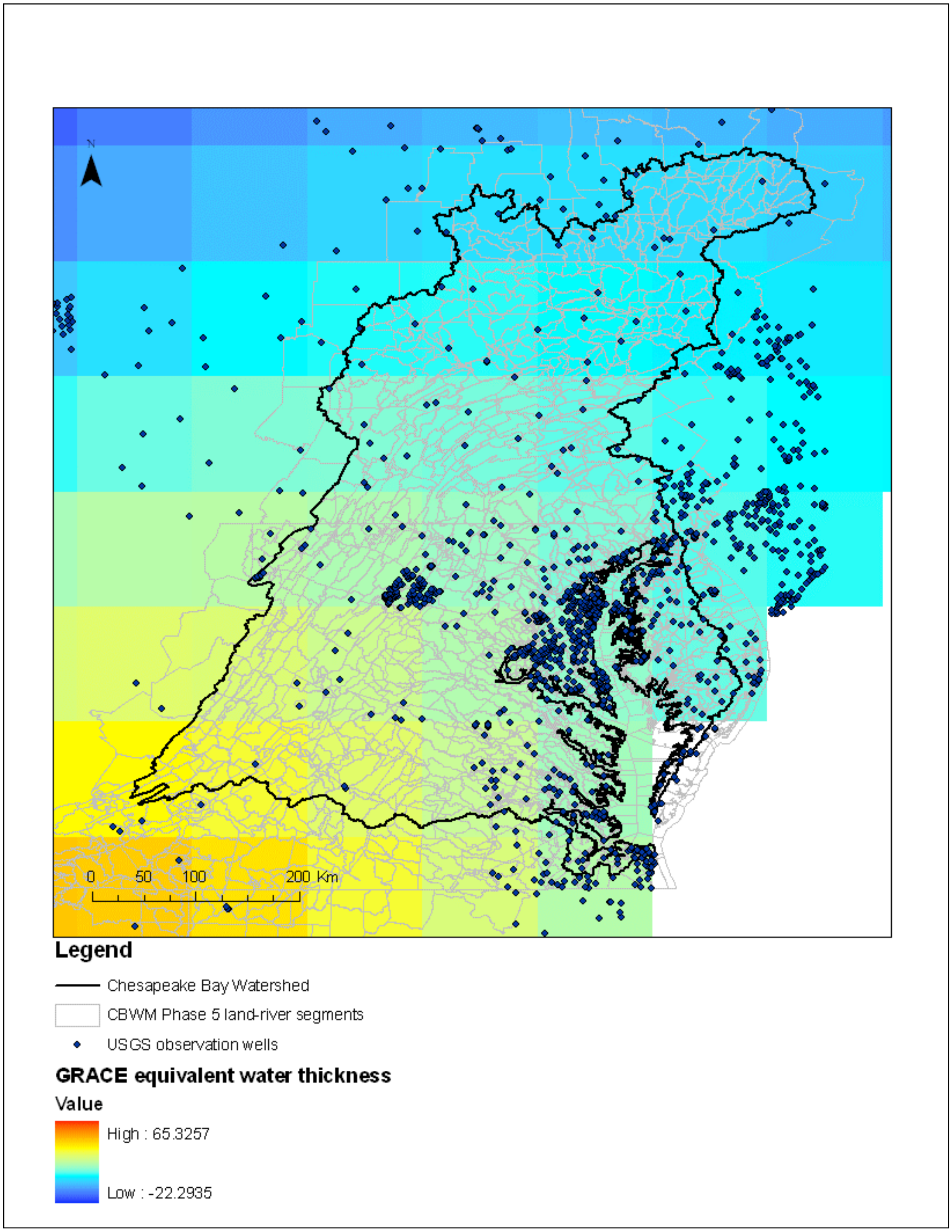

Figure 4. GRACE Terrestrial Water Storage Change in July 2003 (1 degree grid) superimposed on the Chesapeake Bay Watershed region.

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