Since "Groundwater and Surface Water–A Single Resource": some U.S. Geological Survey advances in modeling groundwater/surface-water interactions

Dalla pubblicazione di "Groundwater and Surface Water-A single resource": alcuni avanzamenti presso U.S. Geological Survey nella simulazione delle interazioni tra acque sotterranee e superficiali

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Riassunto: studi di campo e interpretativi condotti da T.C. Winter e dai colleghi del U.S. Geological Survey, ricapitolati nella pubblicazione "Groundwater and Surface Water – A Single Resource", del 1998, hanno generato un nuovo ambito di ricerca centrato sull'estensione del codice numerico di flusso sotterraneo MODFLOW verso sofisticate simulazioni di sistemi con interazione tra acque sotterranee ed acque superficiali. I cambiamenti apportati a MODFLOW, guidati dalle emergenti preoccupazioni relative alla disponibilità idrica, al prelievo sostenibile tramite pozzi, allo stato di salute degli habitat acquatici e alle variazioni climatiche, riguardano 1) l'abilità di rappresentare in modo più preciso ed accurato l'intefaccia tra i flussi superficiali e sotterranei e 2) la capacità di considerare una varietà di meccanismi che influenzano la loro interazione. Nel presente articolo, l'analisi dei più importanti cambiamenti apportati al codice è integrata, con casi di studio selezionati, nel tentativo di dimostrare le finalità degli avanzamenti modellistici. Gli aggiornamenti discussi comprendono i pacchetti Streamflow Routing (SFR), Lake (LAK), e Unsaturated-Zone Flow (UZF), presenti in MODFLOW-2005, oltre alle versioni di MODFLOW-2005 che includono Groundwater Management (GWM), Local Grid Refinement (LGR), and Newton (NWT). Nuovi futuri sviluppi riguardano l'integrazione di un modello precipitazioni-ruscellamento con MODFLOW in GSFLOW, l'accoppiamento di GFLOW e MODFLOW in un codice ibrido, e il raggiungimento di una versione di MODFLOW a griglia non strutturata. Questi sviluppi promettono avanzamenti continui nella possibilità di utilizzare la scienza nella protezione delle acque superficiali e sotterranee come unica risorsa idrica.

Parole chiave: interazione falda-fiume, modelli afflussi-deflussi, MODFLOW, gestione acquiferi

Keywords: *groundwater/surface-water interactions, rainfall/run off modelling, MODFLOW, aquifer management.*

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Abstract: *Field and interpretive studies conducted by T.C. Winter and U.S. Geological Survey colleagues, and summarized in the 1998 publication "Groundwater and Surface Water – A Single Resource", inspired a new generation of research centered on extensions of the groundwater-flow code MODFLOW to more sophisticated simulation of coupled groundwater and surface-water systems. Guided by emerging concerns with water availability, safe yields from wells, health of aquatic habitat, and climate change, the changes to MODFLOW involve: 1) the ability to more precisely and accurately represent the interface between surface and subsurface flows and 2) the consideration of a variety of mechanisms that influence their interaction. A review of the most important changes to the code is supplemented in this article by selected case studies in an effort to show the scope of the advances. The updates discussed include the Streamflow Routing (SFR), Lake (LAK), and Unsaturated-Zone Flow (UZF) Packages in MODFLOW-2005 and the Groundwater Management (GWM), Local Grid Refinement (LGR), and Newton (NWT) formulation versions of MODFLOW-2005. New developments feature the integration of rainfall-runoff modeling with MODFLOW in GSFLOW, coupling of GFLOW and MODFLOW in a hybrid code, and the forthcoming unstructured grid version of MODFLOW. They promise continued advances in the ability to use science to protect the single water resource.*

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Introduction

"Understanding the interaction of ground water and surface water is essential to water managers and water scientists. Management of one component of the hydrologic system, such as a stream or an aquifer, commonly is only partly effective because each hydrologic component is in continuing interaction with other components." So begins the influential publication "Ground Water and Surface Water – A Single Resource", released by the U.S. Geological Survey at the end of the last century (Winter et al., 1998). Groundwater/surface-water interactions had long been a focus of hydrogeologic studies dedicated to topics such as bank storage, transient mounding near streams, stream depletion from pumping, conjunctive use, estimation of base flow or recharge from stream hydrographs, and estimation of hydraulic diffusivity from river-level fluctuations. However, the 1998 publication, a clearly written and beautifully illustrated compilation of theory and practice, marked a turning point in two ways: it summarized the state of knowledge at that time regarding natural processes and the effects of human activities on the interaction of groundwater and surface water (using examples from the U.S.), but it also inspired new lines of research centered on the difficult task of quantifying water fluxes across stream, lake, wetland, and water-table interfaces. This article offers a highly selective account of some of these advances. It only considers developments in the simulation of flow (as opposed to advances in the fields of water quality and contaminant transport). It is limited to a discussion of the development of new modeling techniques and applications centered on the U.S. Geological Survey groundwater flow program MODFLOW. This three-dimensional groundwater flow finite-difference code has been widely used in both the public and private sectors since its release in 1984 as a research vehicle for addressing difficult problems of simulation and interpretation. In recent years the pace of research on the issues identified in the 1998 publication has accelerated and some problems have been partly resolved, making this a good time to offer a brief assessment of today's state of the art.

The importance of groundwater/surface-water interactions

It is well known that the interaction of groundwater and surface water is one component of the water cycle. But its central importance as a topic of scientific research is linked in large measure to the theme of "safe yield" and sustainability of water supply. A number of prominent hydrogeologists (Bredehoeft, 1987; Sophocleous, 1997 and 2000; Alley et al., 1999; Alley and Leake, 2004) have underlined the idea that the availability of groundwater for drinking water, irrigation, and other uses should not be calculated only in terms of the rate of recharge to aquifers, but also by the effects of withdrawals on surface-water bodies such as streams, lakes, and wetlands (fig. 1). This shift in emphasis is crucial, especially for temperate areas of the world where the amount of water that percolates to aquifers is very large relative to the quantity pumped by wells, but where the diversion to wells of

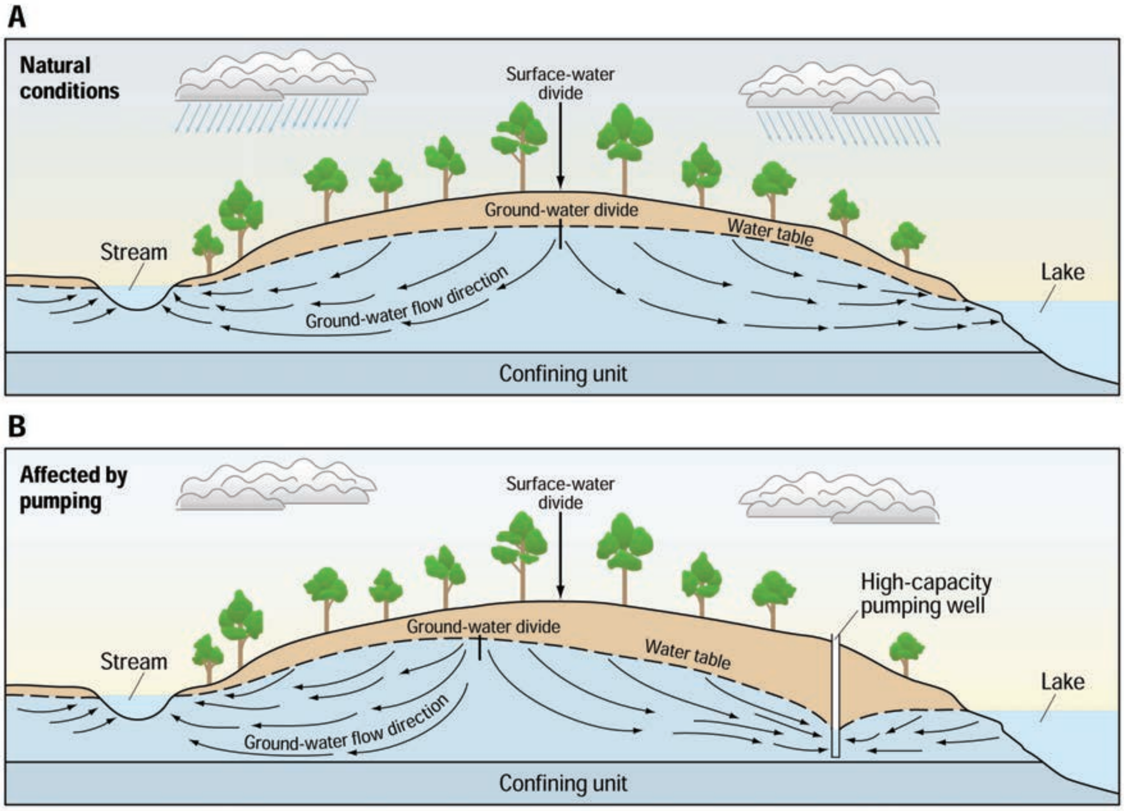

Fig. 1 - Effect of pumping on surface water (from Grannemann et al., 2000).

Fig. 1 - Effetto dei prelievi da pozzo sulle acque superficiali (da Grannemann et al., 2000)

groundwater that would naturally discharge to surface-water bodies can have dramatic consequences for low-flow conditions in streams (Kraft et al., 2012) and on the health of lakes and wetlands (Skalbeck et al., 2009). A key concept is that small changes in the elevation of the water table resulting from pumping (or climate change), while having little effect on the overall storage of subsurface water, can have dramatic effects on the interface between groundwater and surface water (Alley, 2007), leading to surface-water depletion especially in the dry seasons of the year.

Understanding "safe yield" in sustainability terms is connected to several areas of research that bear on groundwater/surface-water interactions. Of obvious concern is the ability to provide water managers with the tools to quantify the effect of groundwater pumping on surface-water depletion, in the form of groundwater-flow models of different levels of complexity (for example, Leake et al., 2008; Leake et al., 2010) or by use of indicators that synthesize model results to provide summary measures of depletion (Weiskel et. al, 2007; Cherkauer, 2010; Pruneda et al., 2010). The effect of surface-water depletion on the health of aquatic ecosystems is commonly studied in terms of the effect on fish reproduction in streams (for example, Armstrong et al., 2004). A growing area of research targets the effect of anticipated climate change on groundwater and ecologic conditions (Alley, 2001; Gurdak et al., 2009; Holman and others, 2011); this research highlights the likely sensitivity of fluxes between the groundwater and surface-water systems to changes in temperature and precipitation, especially when combined with stresses from pumping (for example, Hanson and Dettinger, 2005; Hanson and others, 2012).

Increased ability to directly quantify groundwater/surface-water interactions has also influenced the state of the art, yielding a better understanding of how rates vary over space and time, and also furnishing data against which to test models. The USGS has recently published a volume dedicated to specific field techniques (Rosenberry and LaBaugh, 2008). A very promising estimation technique involves employing heat as a tracer applied directly to the streambed interface (Anderson, 2005; Constantz, 2008). Distributed temperature sensors (DTS) in the form of kilometers of fiber optic cable are particular useful because they identify zones of concentrated exchange (Lowery et al., 2007). Increased data are not only available at the field scale, but also at the regional scale through GIS compilations (for example, in the United States, the National Hydrography Dataset Plus, 2012). They combine many sources of information, including remote sensing, into tools that allow the attributes of the stream network (for example routing and slope) to be mapped in detail sufficient for sophisticated quantitative applications. Finally, the availability of data supports more ambitious model calibration schemes applying parameter estimation codes using inverse methods such as UCODE (Poeter et al, 2005) and PEST (Doherty and Hunt, 2010). The reliability of groundwater-flow models is greatly enhanced when the calibration process takes advantage of multiple target types (Hunt et al., 2006, Hill and Tiedeman, 2007). Flux targets, commonly in the form of base-flow estimates at gaging stations, are particular important because they help to independently estimate hydraulic conductivity and recharge values, two crucial parameters in almost any model calibration (see, for example, Feinstein et al., 2010). The growing emphasis on measuring, estimating, and simulating groundwater exchange with surface water leads naturally to an emphasis on testing the reliability of flow models in terms of their interaction.

Advances

The evolution of motives and means for studying coupled groundwater/surface-water systems has led not only to advances in model construction but also an enlarged scope of applications related to water availability, ecology, and climate change.

Updates to MODFLOW code

One of the original intents of MODFLOW was to provide a programming structure that could be easily enhanced as new capabilities were needed. Since 1998 important capabilities have been added, some of which overcome limitations arising from the original finite-difference formulation. The MODFLOW-2005 code (Harbaugh, 2005; Barlow and Harbaugh, 2006) includes packages specifically designed for simulating groundwater/surface-water exchange. The Streamflow Routing (SFR) Package (Prudic et al., 2004, Niswonger and Prudic, 2004, Niswonger and Prudic, 2006) represents streams as flow reaches associated with MODFLOW cells. Simulated reaches are either directly connected to the groundwater system across a streambed or separated from the groundwater system by an unsaturated zone. SFR (which builds on the original STR Streamflow-Routing Package and replaces the simpler River (RIV) Package in MODFLOW) accounts for the routing of base flow (that is, groundwater inflow), as well as any overland flow added at arbitrary locations. The resulting streamflow is routed downstream through the network of user-defined channels; the SFR package includes the option to also route transient flood waves. Headwater conditions are simulated, allowing ephemeral portions of the stream network to be identified. In addition, the reduction of streamflow or spring flow due to capture by pumping wells is calculated, allowing vulnerable surface-water reaches to be delineated under both steady-state and transient conditions. The SFR Package has multiple options for characterizing the streambed geometry and hydraulic properties, which influence the calculation of stream stage in addition to adjacent groundwater levels. A crucial option is the ability to link the flow through the stream network not only to the groundwater system but also to lakes and wetlands (fig. 2). The Lake (LAK) Package (Merritt and Konikow, 2000) simulates lake levels as a function of their entire water balance, including fluxes through all the connecting surfaces with adjoining simulated

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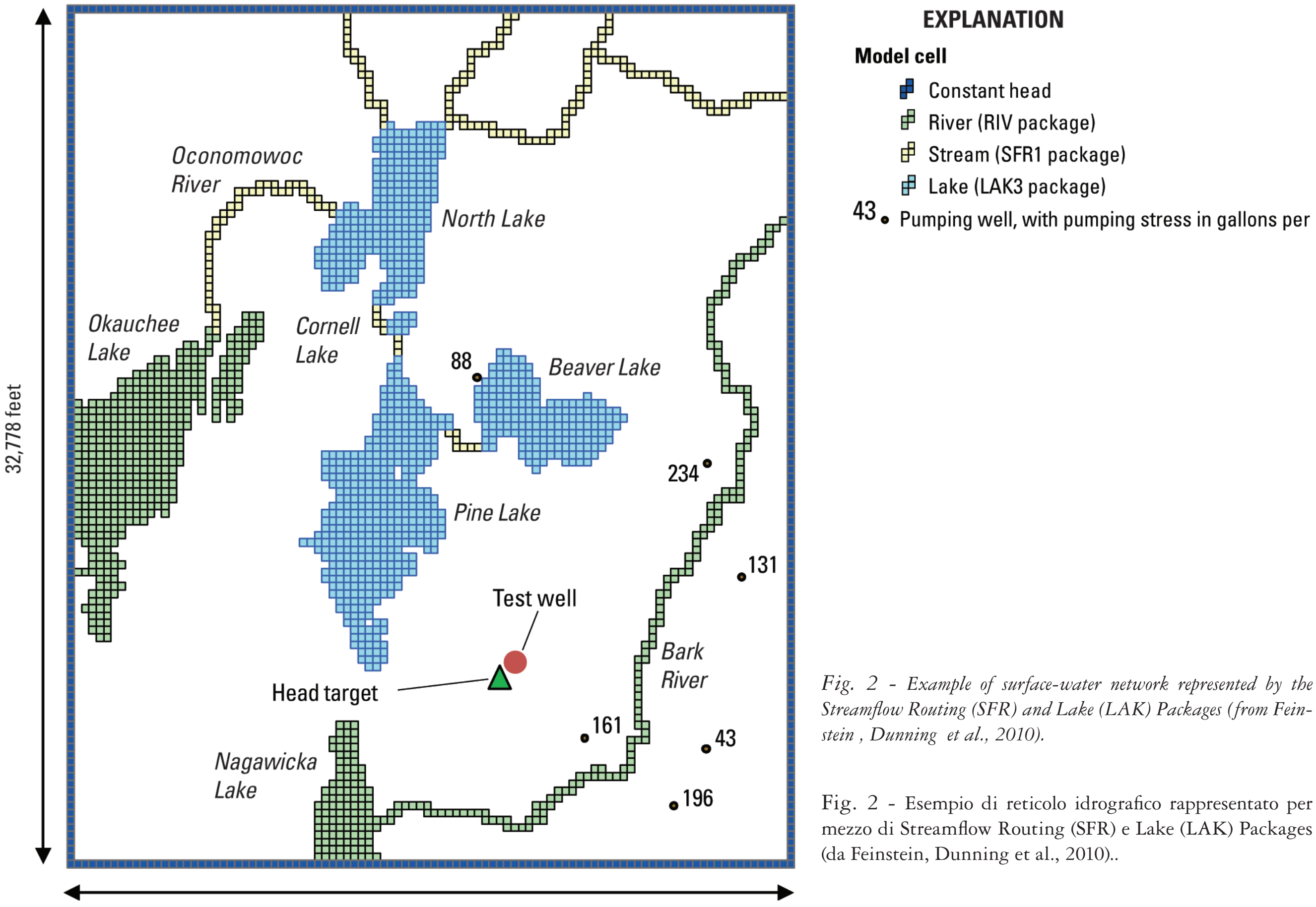

Fig. 2 - Example of surface-water network represented by the Streamflow Routing (SFR) and Lake (LAK) Packages (from Feinstein , Dunning et al., 2010).

Fig. 2 - Esempio di reticolo idrografico rappresentato per mezzo di Streamflow Routing (SFR) e Lake (LAK) Packages (da Feinstein, Dunning et al., 2010)..

aquifers, any stream inflow or outflow accounted for by the SFR Package, water added by precipitation and removed by evaporation, and any water-use diversions. The surface area of a lake may expand or contract, depending on changes in stage and the specified lake geometry (including the shape of the lake bottom).

The surface-water flow algorithms added to MODFLOW-2005 gives great flexibility to the user in representing the hydrologic system. The degree of detail and sophistication adopted depends on available data, the fineness of the model grid, and the objectives of the study.

In addition to the packages devoted primarily to groundwater/surface-water interactions, several other updates to the MODFLOW code enhance its ability to simulate the combined resource. Mention was made of the capability of the SFR Package to represent a stream disconnected from the groundwater by an unsaturated zone. Unsaturated flow is simulated using a one-dimensional kinematic-wave approximation that neglects capillary forces but assumes that downward flow beneath streams is a result of gravity. When the simulated water table falls below the bottom of the streambed, the intervening material is characterized by an unsaturated hydraulic conductivity and water content defined on the basis of the Brooks-Corey function whose variables can vary by stream reach. The same kinematic approximation and Brooks-Corey function is used in the Unsaturated-Zone Flow (UZF) Package (Niswonger et al., 2006) to simulate infiltration from the land surface - or the bottom of the root zone - to the water table (fig. 3). This package replaces the recharge package: it effectively solves for recharge as a function of the infiltration rate, depth to water, and sediment properties. It also simulates evaporation from the unsaturated zone and the water table, and the infiltration that is rejected from the subsurface during periods when the infiltration rate exceeds the vertical hydraulic conductivity of the shallow sediment or when the water table rises to the land surface. The UZF Package can simulate rejected infiltration under short-term conditions associated with storms, or under average conditions in lowland areas that host wetlands, often adjacent to streams. The rejected infiltration can be routed to reaches in the SFR Package or to lakes in the LAK Package as a function of topography.

There are several updated versions of MODFLOW-2005 that are useful for simulating the interaction of groundwater and surface water

- MODFLOW-LGR (Local Grid Refinement; Mehl and Hill, 2005), which facilitates the construction of local models from regional models by embedding one or more child grids with local refinement (either horizontally, ver-

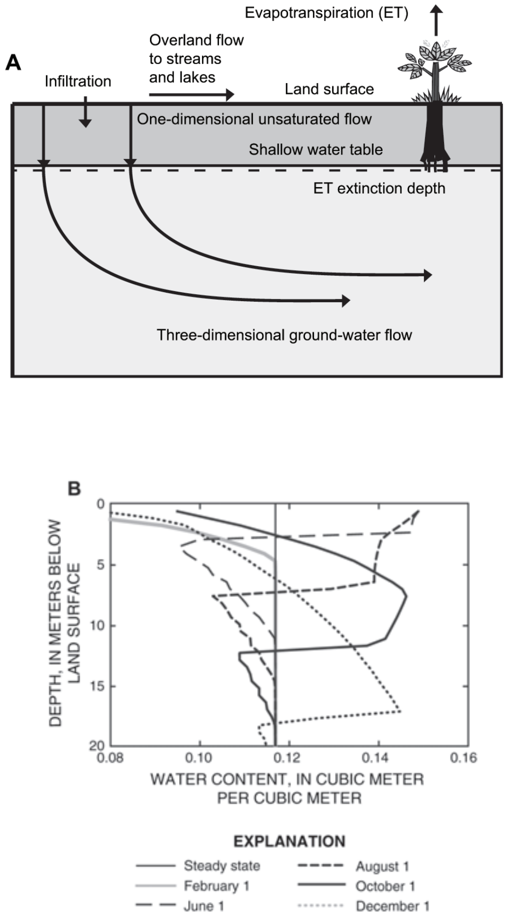

Fig. 3 - (A) One-dimensional unsaturated flow simulated with the Unsaturated-Zone Flow (UZF) Package and (B) representative water-content profiles calculated by UZF for a model cell in a test simulation with time-varying infiltration rates (from Barlow and Harbaugh, 2006, modified from Niswonger et al., 2006).

Fig. 3 - (A) Flusso nel mezzo insaturo in una dimensione simulato con Unsaturated-Zone Flow (UZF) Package e (B) profilo rappresentativo del contenuto d'acqua calcolato con UZF per una cella di un modello in una simulazione test con tassi di infiltrazione variabili nel tempo (da Barlow e Harbaugh, 2006, modificato da Niswonger et al., 2006).

tically, or both) within a parent grid in a way that allows more precise representation of surface-water features in the child grids, and automatically updates the boundary conditions between the child and parent in response to local or regional stresses;

- MODFLOW-GWM (Groundwater Management; Ahlfeld et al., 2005 and 2009), a management code that combines the solution for subsurface and surface flows with linear, nonlinear, and mixed-binary programming capabilities to allow for optimized resource management - for example, by determining the maximum yield from wells that satisfies constraints associated with drawdown and stream depletion;
- MODFLOW-NWT (Newton formulation; Niswonger et al., 2011), which reformulates the groundwater-flow equation to avoid the instabilities that arise from "dry" cells, thereby allowing design of unconfined models with upper layers thin enough to accurately represent shallow horizontal and vertical gradients around surface-water bodies.

Examples of recent applications of these functionalities to groundwater/surface-water problems are provided in the next section.

Advanced Applications

Four applications are discussed:

Coupling processes with the SFR/LAK/UZF Packages

There is a rich literature on using models to simulate the exchange of groundwater with water bodies such as lakes, springs, and wetlands (a sampling: Winter, 1976; Lee, 2000; Townley and Trefey, 2000; Hunt et al., 2003, Haitjema, et al., 2001; Haitjema, 2005). One challenge to modeling their interaction is that part of the exchange occurs in zones around the water body where groundwater discharges to the land surface and then moves down slope as overland flow. These zones (or "wetland source areas") enlarge in seasons when the water table is high and shrink in dry periods. By combining the capabilities of the SFR, LAK, and UZF Packages in MODFLOW-2005, it is possible to simulate the behavior of these variable-source areas. A study conducted in the Trout Lake watershed in northern Wisconsin (Hunt et al., 2008) coupled the subsurface and surface processes in MODFLOW to: 1) track the lag between infiltration through the root zone and percolation to the water table as recharge, and 2) identify lowland areas where the water table approaches the land surface such that recharge is rejected and routed as overland flow to streams and lakes (fig. 4). The model accounted for the seasonal nature of the transition of groundwater to overland flow to surface water, thereby allowing a better simulation of the variability of lake stages and streamflows, and their sensitivity to fluctuations or trends in climatic conditions.

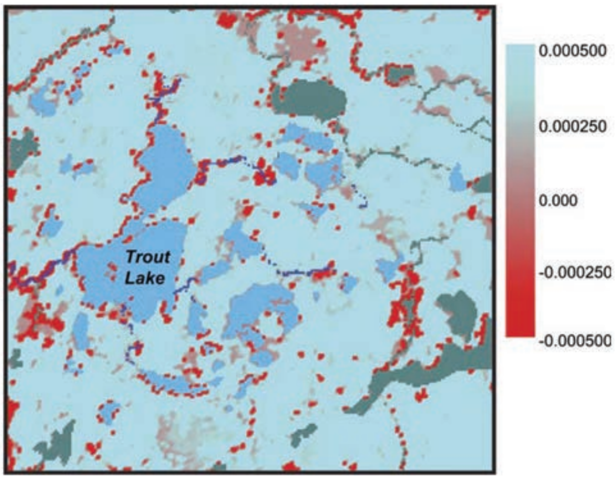

Fig. 4 - Application of the Streamflow Routing (SFR), Lake (LAK), and Unsaturated-Zone Flow (UZF) Packages to study area in northern Wisconsin: net flux (recharge minus discharge) across the water table, showing areas in red where wetlands form by groundwater discharge (from Hunt et al., 2008).

Fig. 4 - Applicazione dei Packages Streamflow Routing (SFR), Lake (LAK), e Unsaturated-Zone Flow (UZF) ad un'area di studio nel Wisconsin settentrionale: flusso netto (ricarica meno deflussi) verso la tavola d'acqua, con in rosso le aree umide formate dal recapito di acque sotterranee (da Hunt et al., 2008)

Balancing well discharge against stream depletion with MODFLOW-GWM

Although tools for groundwater optimization modeling have been available for about 25 years, the technique has yet to be routinely applied to groundwater studies (Barlow and Harbaugh, 2006). The availability of the GWM version of MODFLOW-2005 facilitates the use of models to support communities, for example, that are seeking ways to balance the often conflicting goals of groundwater resource development and streamflow protection. Reduction of streamflow caused

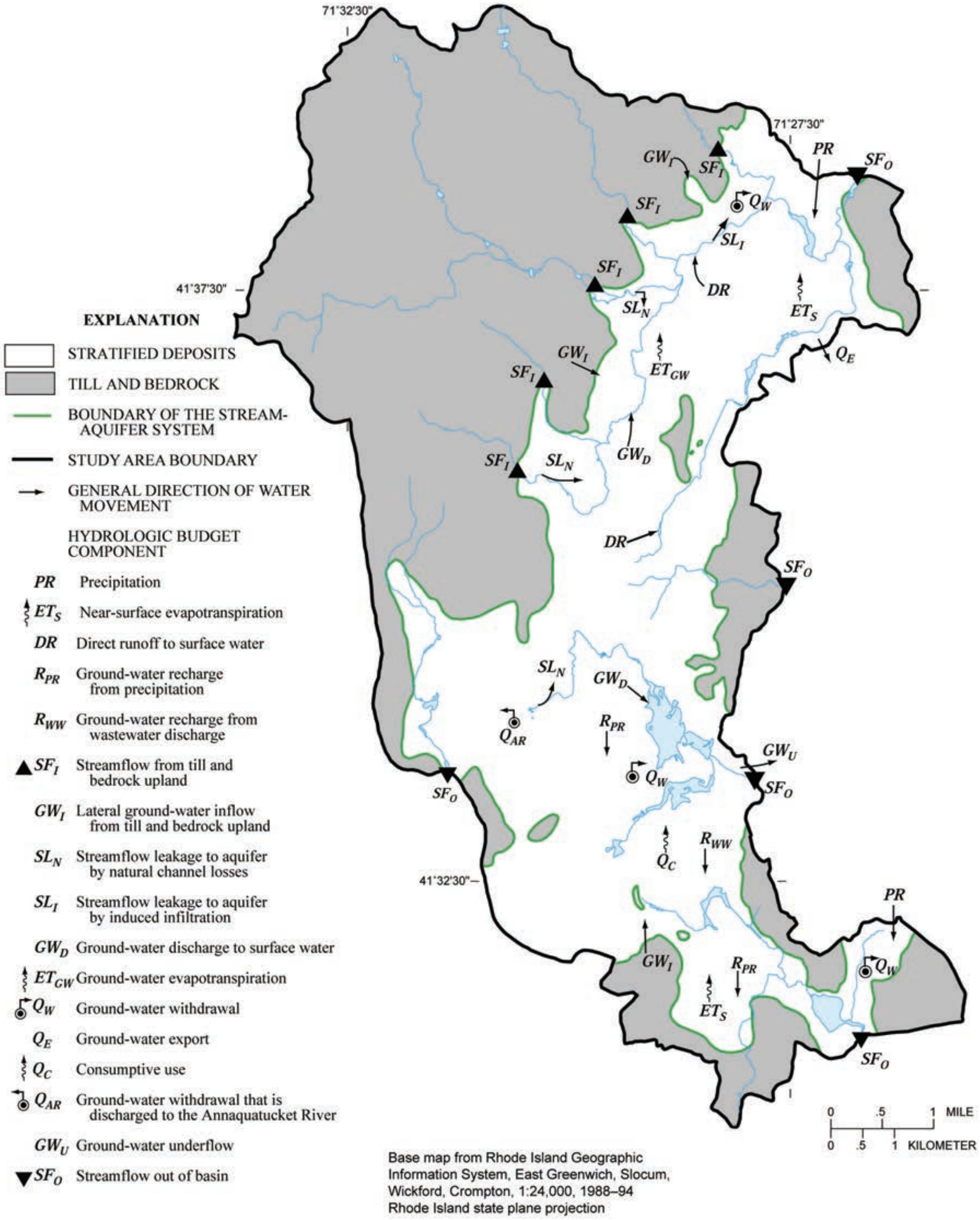

Fig. 5 - Optimization application using MODFLOW to watershed in Rhode Island: groundwater and surface-water budget components (from Barlow and Dickerman, 2001)

Fig. 5 - Procedura di ottimizzazione con MODFLOW applicata ad un bacino di Rhode Island: componenti del bilancio per le acque sotterranee e superficiali (da Barlow and Dickerman, 2001).

by groundwater withdrawals may adversely affect aquatic and riparian habitats, particularly during periods of lower streamflow in the summer months. A case study performed in Rhode Island (Barlow and Dickerman, 2001; Galloway et al., 2003), which linked MODFLOW to a separate optimization code, demonstrates the ability of the simulation-optimization modeling approach to quantify trade-offs between groundwater development for public supply and protection of streamflow. The groundwater/surface-water model accounts for the many types of exchanges that occur in the study area (fig. 5). The optimization model calculates response coefficients that characterize the link between decision variables (e.g. wells) and physical-system state variables (e.g., streamflows). The results are in the form of graphs that show trade-offs in the context of the maximum stream depletion that can be tolerated (fig. 6). Heavy groundwater use in areas of irrigated agriculture can also stress surface water. The current GWM code has been used in a study of an important agricultural zone in Nebraska to balance the benefits of withdrawals against the cost of stream depletion (Stanton et al., 2010).

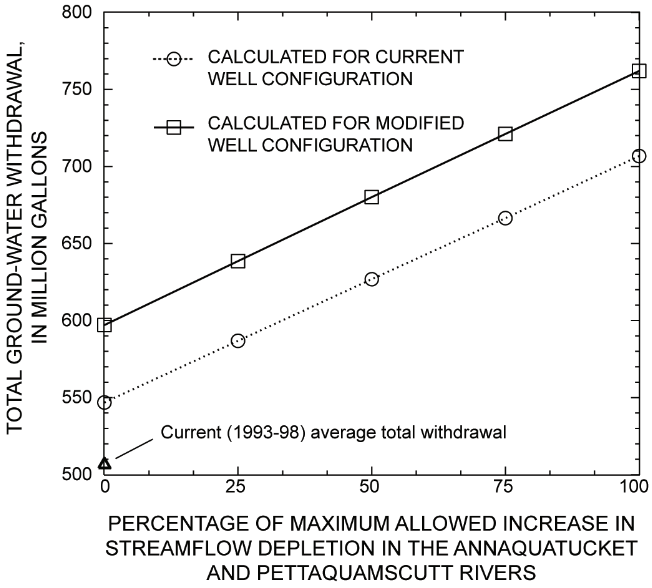

Fig. 6 - Results from optimization application using MODFLOW: Balancing well withdrawlas and allowable streamflow depletion (from Barflow and Dickerman, 2001)

Fig. 6 - Risultati da una applicazione di ottimizzazione con MODFLOW: bilanciamento dei prelievi con una diminuzione ammissibile del deflusso del corso d'acqua (da Barlow and Dickerman, 2001).

Grid refinement and climate change scenarios with MODFLOW-LGR

The flow in headwater tributaries (that is, the most upstream part of the surface-water network) are particularly vulnerable to small changes in water-table elevation. Drawdown due to pumping or variations in recharge can cause the headwater tributaries to go dry, with possible effects on aquatic habitat and ability to sustain well withdrawals. Regional groundwater models typically require too large a grid size to accurately reflect the subtle effects that occur at the headwater interface. However, it is often convenient to downscale from an existing regional model to a local inset model that is sufficiently focused to include the features and mechanisms necessary to study processes such as the transient flow in headwater streams. The Local Grid Refinement (LGR) version of MODFLOW-2005, in combination with packages such as SFR, is one way to perform this downscaling. An application to a watershed in Michigan (Hoard, 2010) involves three scales – a previously constructed regional model of the Lake Michigan Basin with cells 1500 m on a side (Feinstein et al, 2010), an intermediate model with cells 150 m on a side, and a local model with cells 20 m on a side (fig. 7). The stepped refinement of model scale is accompanied by increased accuracy in the representation of the stream network, particularly headwater tributaries. The intermediate model is embedded in the regional model by conventional telescopic mesh refinement (TMR) techniques; whereas the intermediate model is treated as the parent of the local, or child, model. That is, the intermediate and local models use the LGR code to share an active boundary condition which responds to seasonal changes in recharge and streamflow – in this way the local model is sensitive to changes outside its restricted area. The flow models are linked to a forecasting climate model in order to simulate possible changes in recharge into the future. The recharge is affected by the balance between anticipated 1) increases in precipitation and 2) increases in temperature and evapotranspiration. The simulated cumulative effect of these processes on a headwater stream selected for study indicates that by the middle of this century this tributary could go dry for part of the year (fig. 8).

Overcoming dry cells in unconfined simulations with MODFLOW-NWT

The optimal way to simulate exchange between groundwater and surface water in a finite-difference groundwater-flow model is often to use thin shallow layers in combination with a fine horizontal mesh. The fine vertical discretization enables the model to more accurately simulate vertical gradients that are especially important in the vicinity of discharge areas such as rivers. However, modelers have often shied away from using this technique because over part of the model domain the thin shallow layers tend to go dry (that is, the water-table elevation is below the cell-bottom elevation). Drying of model cells can provoke instabilities for the Picard-type solvers generally used with MODFLOW (for example, the PCG2 Solver Package), sometimes resulting in wildly inaccurate solutions (fig. 9). The MODFLOW-NWT code substitutes an upstream weighting approach for the standard MODFLOW formulation to smooth the horizontal-conductance function and the storage-change function during wetting and drying of a cell to provide continuous derivatives for solution by the Newton method (Niswonger et al., 2011; Bedekar et al., 2012; Hunt and Feinstein, in press). The smoothness of the transition allows a cell to remain active even when it has completely dewatered, thus helping to avoid numerical instabilities. Instead of converting abruptly to zero as the unconfined cell dries, conductance and storage values approach zero along a gradu-

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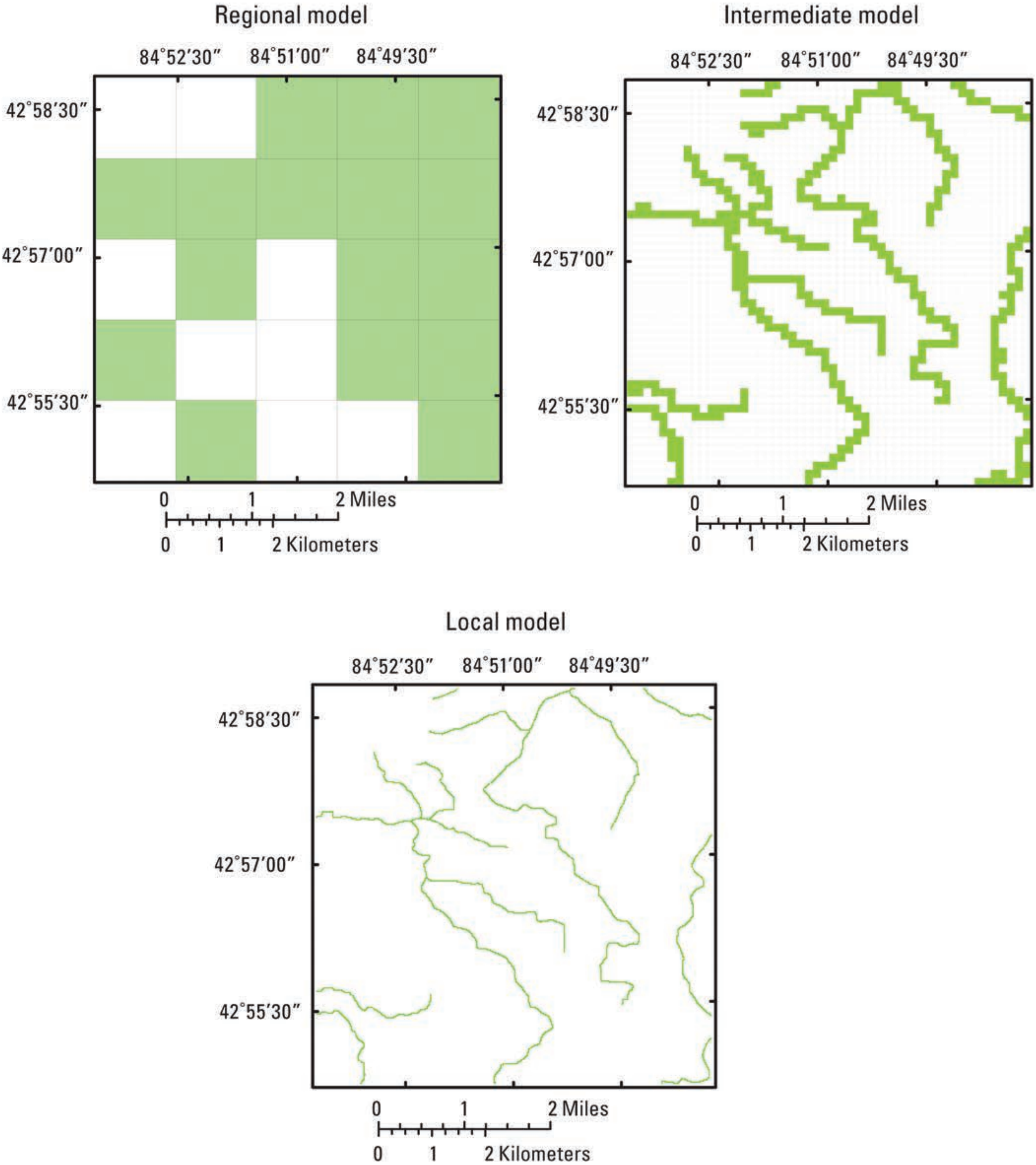

Fig. 7 - Application of the Local Grid Refinement (LGR) version of MODFLOW-2005 to basin near Lansing, Michigan: grid spacing for regional (upper left), intermediate (upper right), and local (lower) models (from Hoard, 2010).

***Regional model**: 64% of layer 1 = RIV cells.; **Intermediate model:** 14% of layer 1 = SFR cells.; **Local model:** 2% of layer 1 = SFR cells.*

{Grid spacing too dense to be shown for local model, but dimensions correspond to SFR cells.}

Fig. 7 -Applicazione della versione MODFLOW-2005-LGR ad un bacino nei pressi di Lansing, Michigan: discretizzazione della griglia per il modello regionale (in alto a sinistra), intermedio (in alto a destra) e locale (in basso) (da Hoard, 2010).

Modello regionale: celle RIV = 64% del layer 1; **Modello intermedio:** celle SFR = 14% del layer 1; **Modello locale:** celle SFR = 2% del layer 1

{La griglia e` troppo densa per essere visualizzata nel modello locale, ma le dimensioni corrispondono alle celle tipo SFR.}

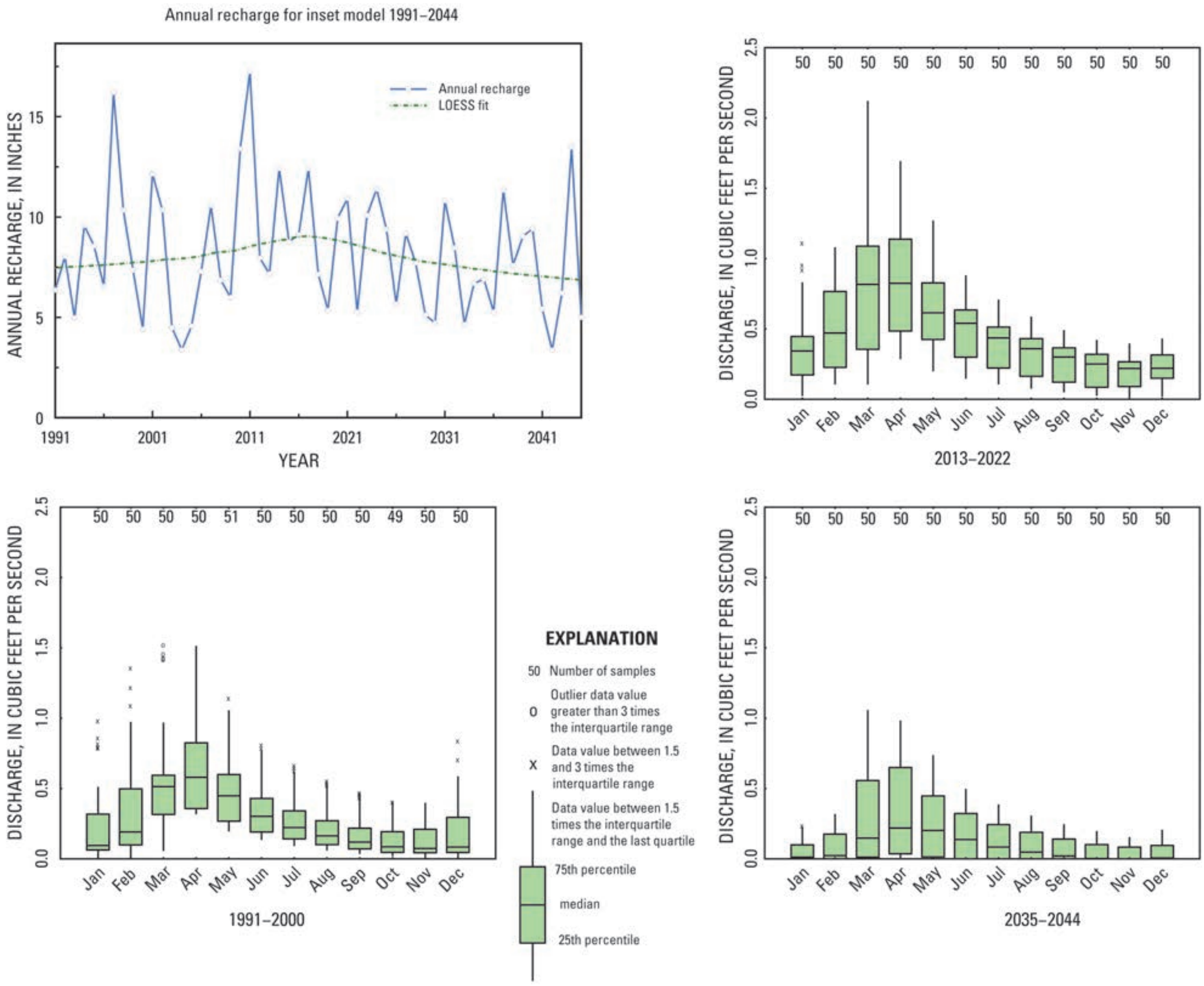

Fig. 8 - Application of the Local Grid Refinement (LGR) version of MODFLOW-2005: results of climate change scenarios, showing changes in base flow to headwater stream (from Hoard, 2010).

Fig. 8 - Applicazione della versione MODFLOW-2005-LGR: risultati di scenari di cambiamento climatico, cambiamenti nel deflusso di base di un corso d'acqua (da Hoard, 2010).

al slope at small saturated thicknesses. Other aspects of the solution method (including reduction of pumping from unconfined cells at low saturated thicknesses) also promote numerical stability, allowing MODFLOW models to be used to investigate water-supply strategies such as riverbank inducement, whereby shallow wells are located adjacent to streams in order to recirculate water from surface water, to groundwater, to upstream wastewater treatment plants, and back to surface water, in a potentially sustainable loop. This idea has been tested, for example, in southeastern Wisconsin. A model that combines MODFLOW-NWT with the SFR and LAK Packages to represent flow through heterogeneous glacial deposits (Feinstein et al., 2012) shows that a hypothetical system of wells located along a river (fig. 10) can, by taking advantage of preferential pathways in shallow deposits, induce about a third of a city's needed water supply from the river and then recycle it, thereby reducing drawdown and stream depletion considerably relative to what would occur without riverbank inducement.

Future Directions

The accelerated pace of research at the USGS on methods to simulate the coupling of groundwater and surface-water systems has increased the potential for model applications. In this section, three proposed approaches that hold promise for expanding the power of models to simulate the combined water resource are presented.

GSFLOW

The USGS has been developing and testing a fully integrated groundwater and precipitation-runoff model that can be applied to water-resource problems at the scale of a watershed (Barlow and Harbaugh, 2006; Marskstrom et al., 2008). The basic components of the integrated model are MODFLOW-2005 and MODFLOW-NWT, and the USGS precipitation-runoff modeling system (PRMS) (Leavesley et al. 1983). PRMS is a modular, distributed-parameter modeling system that partitions daily precipitation in the form of

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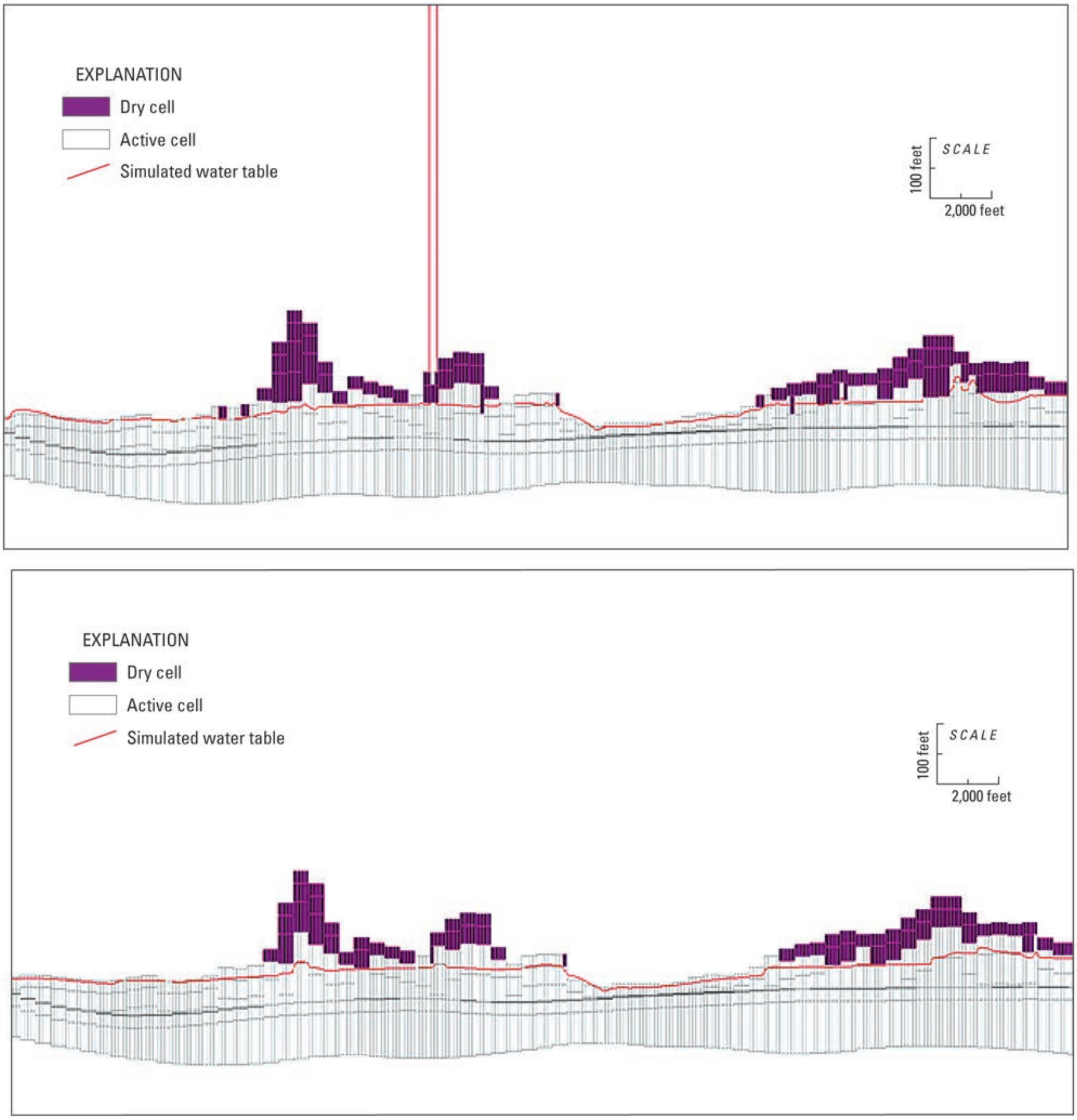

Fig. 9 - Application of the Newton formulation (NWT) version of MODFLOW-2005: Comparison of water-table solutions calculated by (a) the PCG solver and (b) the NWT formulation for unconfined system represented by thin shallow layers (from Feinstein et al., 2012).

Fig. 9 - Applicazione della versione con formulazione di Newton (NWT) di MODFLOW-2005: confronto della soluzione per la tavola d'acqua calcolata con (a) risolutore PCG e (b) la formulazione NWT per un sistema non confinato rappresentato da livelli superficiali di piccolo spessore (da Feinstein et al., 2012).

rain or snow (or a mixture of both) among several watershed hydrologic compartments (interception by vegetation, surface evaporation, overland flow, infiltration to the soil zone, and so forth). Hydrologic connections between the surface and subsurface zones are through the soil zone and surface-water bodies (fig. 11). The recent development of the SFR, LAK and UZF Packages for coupling saturated flow conditions simulated by MODFLOW's flow processes with surface-water flows and with unsaturated zone flow beneath streambeds and the soil zone has been an important part of the integrating all the watershed flows. Care is required to overcome the challenges of data management, spatial/temporal scale connections, and calibration which arise from the coupling PRMS and MODFLOW, but the rewards are great in terms of enhanced power to quantify the watershed response to a range of influences. An application to the Trout Lake watershed (fig. 4) shows the advantages of simulating together all the processes considered by GSFLOW when predicting watershed flows in the presence of climate change (Marsktrom et al., 2012; Walker et al, in review).

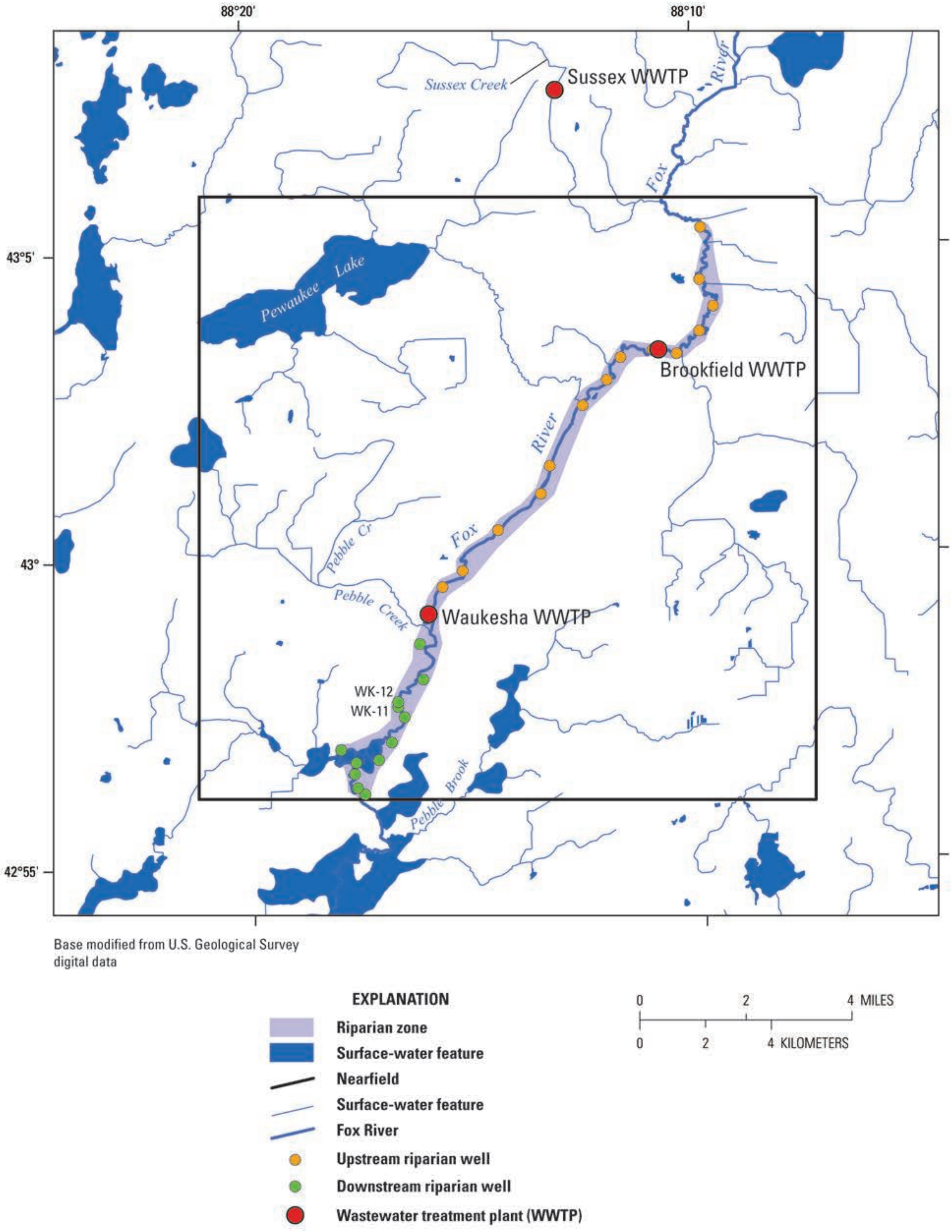

Fig. 10 - Application of the Newton formulation (NWT) version of MODFLOW-2005: Hypothetical system of riparian wells to test effectiveness of riverbank inducement (from Feinstein et al., 2012).

Fig. 10 - Applicazione della versione con formulazione di Newton (NWT) di MODFLOW-2005: sistema ipotetico di pozzi presso il fiume per verificare l'attendibilità dell'infiltrazione indotta dal corso d'acqua (da Feinstein et al., 2012)

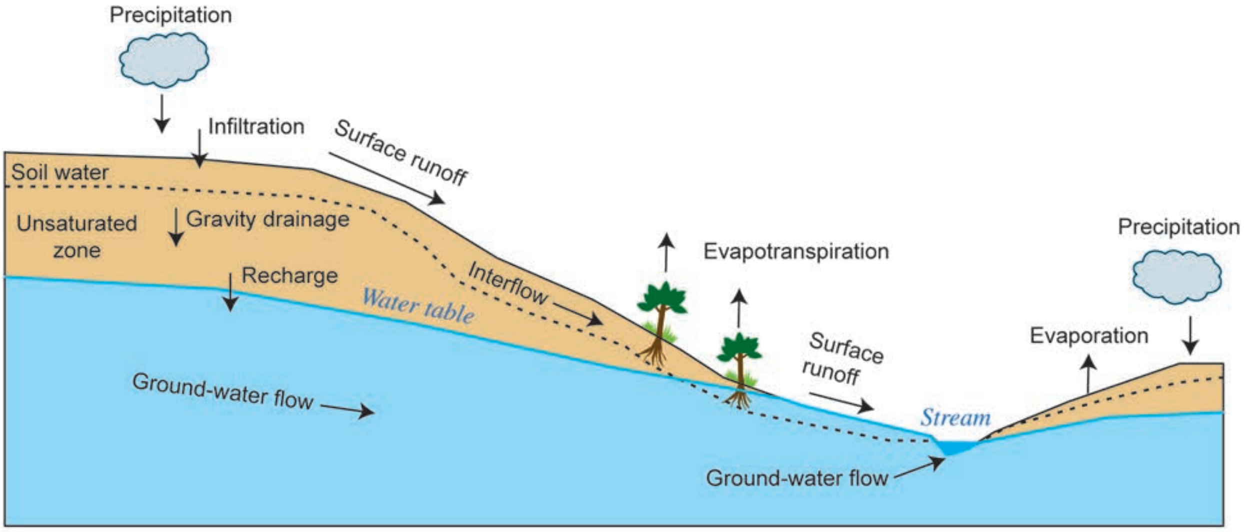

Fig. 11 - Elements and mechanisms incorporated in GSFLOW (from Markstrom et al., 2008)

Fig. 11 - Termini e processi inclusi in GSFLOW (da Markstrom et al., 2008).

GFLOW and MODFLOW

Reference has already been made to a practical limitation in using MODFLOW to simulate groundwater/surface-water interactions: the size of the grid cells. In particular, regional finite-difference models typically have cell sizes on the order of 1-2 km on a side. Although the regional flow pattern may be adequately represented by such a model, the intricate surface-water and groundwater exchanges in the shallow part of the system are not, partly because the surface-water network is represented too grossly, partly because hydraulic gradients are not simulated with sufficient precision. Several researchers (Haitjema et al., 2010) have proposed to replace the upper MODFLOW layer or layers in which the groundwater and surface-water interactions occur by an analytic element model (GFLOW, Haitjema, 1995) that does not employ a model grid; instead it represents wells and surface water directly as point-sinks and line-sinks, precisely located and acting as superimposed analytic elements. Experiments with a hybrid code combining GFLOW and MODFLOW show that for many cases it suffices to provide GFLOW with the vertical leakage rates calculated in the original coarse MODFLOW model (fig. 12) in order to obtain a good representation of surface and groundwater interactions, involving for example, wells and headwater streams. However, experiments have also shown that when the transmissivities in the deeper (MODFLOW) layers dominate, the accuracy of the GFLOW solution for shallow flows diminishes. It appears that this hybrid method is a promising alternative to local grid refinement models under circumstances when the shallow material transmits most of the flow and yet the regional component is still important for a reliable solution or is needed to fulfill model objectives. Planned applications of the hybrid code to glacial sediments in the northern U.S. should help to standardize the approach and show its relative advantages for addressing groundwater/surface-water problems.

Fig. 12 -Coupling between MODFLOW and GFLOW: leakage rates between the two MODFLOW layers are applied at the bottom of the GFLOW model, then GFLOW recalculates the heads and flows in the shallow part of the system using detailed surface-water and groundwater interactions {circled heads and fluxes are the ones calculated in each model} (from Haitjema et al., 2010).

Fig. 12 - Accoppiamento tra MODFLOW e GFLOW: i tassi di drenanza tra i due layer di MODFLOW sono applicati alla base del modello GFLOW, quest'ultimo ricalcola i carichi ed i termini di flusso nella parte superficiale del sistema utilizzando interazioni di dettaglio tra acque superficiali e sotterranee [i carichi ed i flussi cerchiati sono calcolati in ciascun modello] (da Haitjema et al., 2010).

MODFLOW-USG

On the horizon is the transformation of MODFLOW-2005 from a structured finite-difference code (fixed row and column dimensions) to an unstructured code (Panday, et al., 2011; Langevin et al., 2011; Panday et al., in review). This reformulation of the equations in MODFLOW dramatically extends its power. The domain can be discretized into cells of different sizes and shapes, allowing any number of nested grids, including vertical sub-discretization within layers. The new code supports flow through linear networks of connected conduits (for example, fractures, tunnels, karst features, multi-layer wells) embedded into the groundwater system. It also allows for flow corrections at "ghost node" locations via interpolation from adjacent nodes – offering a new way to increase model precision. A preliminary version of this code has been used to test its power to simulate local groundwater/surface-water interactions over a large area. A 20-layer model of shallow and deep groundwater flow in the Lake Michigan

Basin with cells 1500 m on a side (Feinstein et al., 2010) has been converted into a 4-layer model of the same lateral and vertical extent, but with cell sizes varying by layer. In this "semi-structured" approach, the top layer is more finely discretized than underlying layers: it is composed of cells 150 m on a side, thereby allowing much more accurate simulation of exchanges with the surface-water network than with the original model (fig. 13). The availability of a regional model with capabilities for simulating local flow opens the way to a research strategy for statistically testing the importance of stream depletion as a source of water to shallow wells (fig 14). Using the flexible grid structure, it is possible to simulate thousands of realizations of the system's response to pumping with a single simulation. By then employing Bayesian networks to analyze the relations between surface-water depletion as the dependent variable and local factors (such as minimum distance from wells to surface water, density of local surface water, local recharge and shallow transmissivity) as causal variables, researchers are aiming to build transfer functions that will allow managers to balance well withdrawals and protection of surface water by considering local conditions only - with the need to construct, calibrate, and apply a numerical flow model.

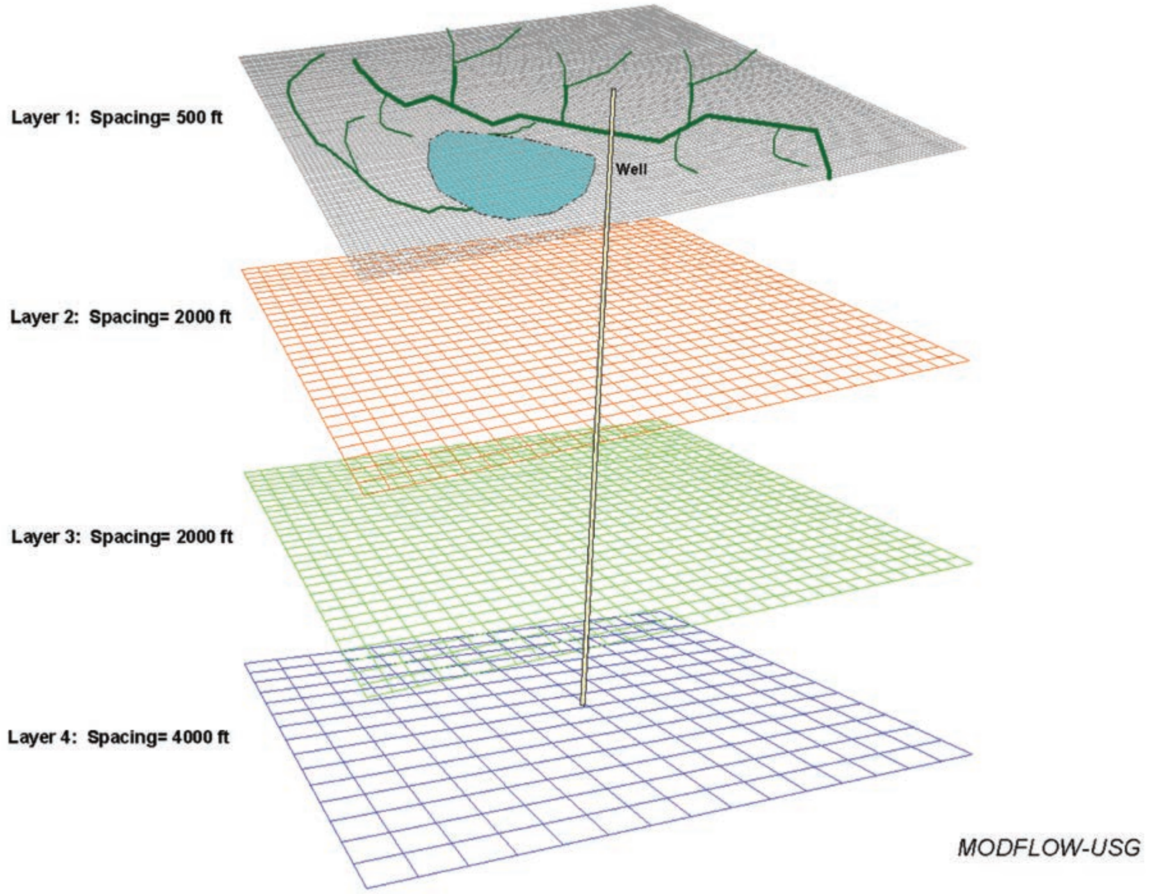

Fig. 13 -Semi-structured approach using MODFLOW-USG (from Feinstein, USGS, written communication).

- *decreasing refinement with depth, but uniform spacing within each layer*
- *top layer accommodates detailed surface-water network*
- *layer bottoms shown flat in schematic but can be uneven*

Fig. 13 - Approccio semi-strutturato utilizzando MODFLOW-USG (da Feinstein, USGS, comunicazione scritta).

- raffinamento decrescente con la profondità, ma spaziatura uniforme in ogni layer;
- griglia del layer superficiale che "segue" l'andamento del reticolo idrografico
- i layer di letto sono visualizzati nella figura come piani, ma in generale possono essere irregolari.

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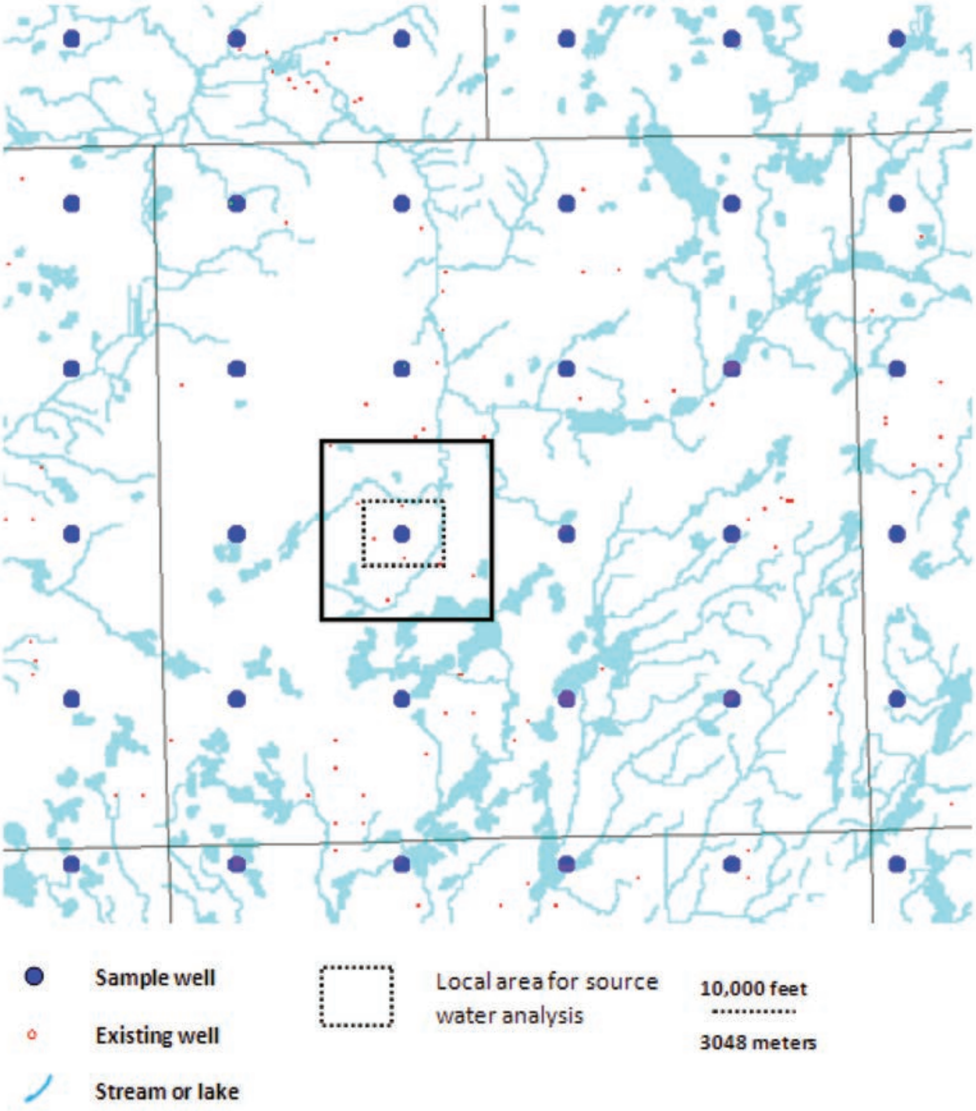

Fig. 14 Semi-structured approach using MODFLOW-USG: Sampling relation between pumping and stream depletion over part of the regional model (from Feinstein, USGS, written communication).

Fig. 14 - Approccio semi-strutturato utilizzando MODFLOW-USG: analisi a campione delle relazioni tra prelievi e diminuzione dei deflussi su una parte di un modello regionale (da Feinstein, USGS, comunicazione scritta).

Conclusions

Field research and numerical experiments performed by T.C. Winter and his colleagues at the USGS, summarized in the 1998 publication "Groundwater and Surface Water – A Single Resource," laid the ground for computing advances in the simulation of groundwater flow centered on the code MODFLOW. The scope of MODFLOW has grown substantially since its first release in 1984; many of the innovations since 1998 have focused on coupling groundwater and surface-water systems. These changes have increased the power of hydrogeologists to confront practical questions of prediction and management arising from concerns such as safe yield to wells, the health of aquatic habitat, and climate change. The computing advances fall into two general categories. The first arise from increased ability to refine the representation of the groundwater/surface-water interface, by use of: 1) child grids embedded in regional models (MODFLOW-LGR); 2) new solver methods that insure stable results in the presence of thin unconfined layers (MODFLOW-NWT); 3) coupled analytic-element and finite-difference codes, which, under favorable conditions, allow unlimited resolution in representing surface-water features (GFLOW-MODFLOW); and 4) dramatically increased flexibility in representing all elements of MODFLOW by means of unstructured grids (MODFLOW-USG). The second set of advances revolve around added functionality for simulating groundwater/surface-water interactions, including: 1) routing of base flow, flood-wave propagation, and specified tributary flow through streams and calculation of stream stage for both connected and perched conditions (SFR Package); 2) full integration of lakes and wetlands into the surface-water network with calculation of stage and water budgets (LAK Package); 3) computing recharge as a function of infiltration and unsaturated flow, enabling the routing of rejected recharge to surface water (UZF Package); 4) routines for optimizing conjunctive-management decisions by balancing objectives against constraints (MODFLOW-GWM); and 5) a fully integrated model to address water-resource problems at the scale of a watershed that couples precipitation-runoff algorithms to all the other capabilities of MODFLOW (GSFLOW).

Practical applications have accompanied the computing advances. Case studies, restricted in this article to several U.S. Geological Survey studies, focus on stream depletion in the context of water supply, ecologic flows, and climate change. It is likely that future environmental studies will integrate surface and subsurface flows even more explicitly, using a range of methods involving not only MODFLOW and related codes, but also a variety of data and estimation techniques applied at different spatial and temporal scales. An example of this broad approach to studying overall water availability with respect to both groundwater and surface-water flow systems has recently been completed for the U.S. Great Lakes Basin (Reeves, 2010).

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