In cooperation with the Rock River Coalition.

Ground-Water Flow in the Rock River Basin

An update on project status

The following slides were presented during a public meetings at the Jefferson County UW-Extension office in Jefferson, Wis., on December 14, 2007 by Paul Juckem and Charles Dunning

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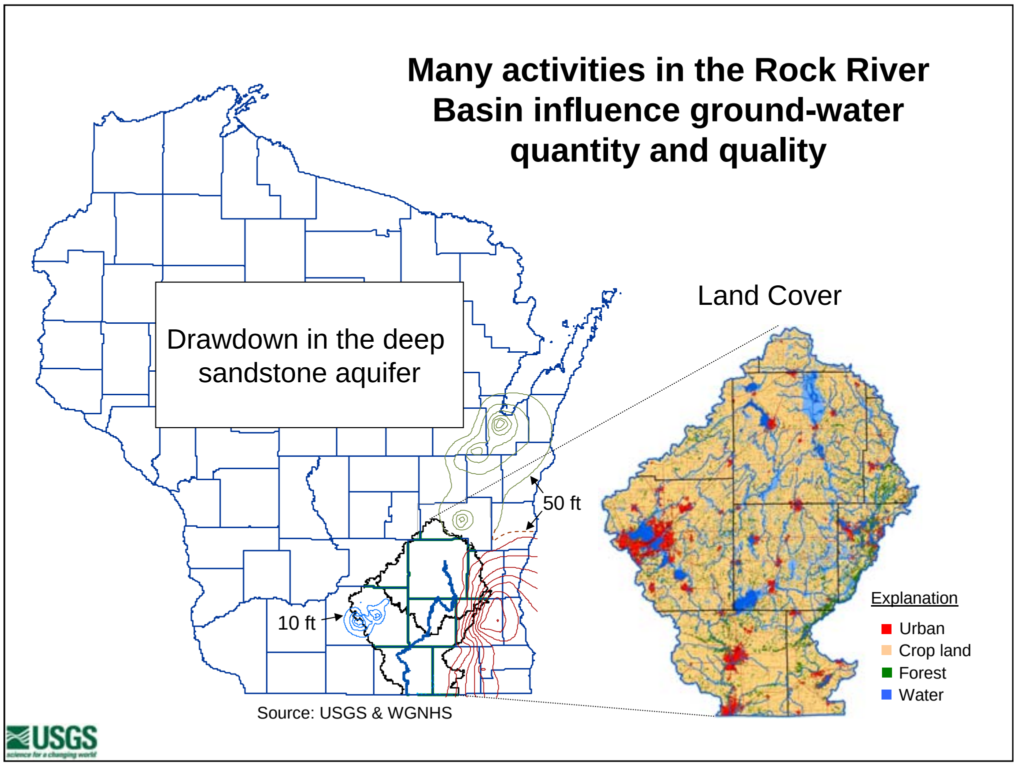
Ground-Water Flow in the Rock River Basin

An update on project status

December 14, 2007
UW-Extension office, Jefferson, WI

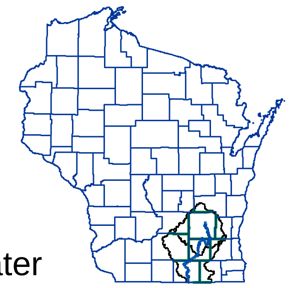
The following slide show provides an update on a study of ground-water flow in the Rock River Basin. Information may be added or removed from the ground-water flow model (described in subsequent slides) as the project proceeds.

Funding for this work has been from numerous stakeholders through the Rock River Coalition, with additional funding from the U.S. Geological Survey.



Many activities influence ground-water quantity and quality in the Rock River Basin. This slide shows two examples. The Rock River Basin encompasses or abuts areas with water-level drawdown in the deep Sandstone Aquifer. A map of land cover shows the influence of human activity in the form of urban and agricultural (Crop land) land uses. These examples are meant to illustrate the importance of understanding regional and local ground-water resources to facilitate proper management

Purpose



- Improve the understanding of ground-water flow and ground-water/surface-water interaction
- Identify sources of base flow to the Rock River and its tributaries
- Provide a basis to interpret previously collected water-quality data
- Provide a scalable framework for evaluating hydrologic stress to the system

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The purpose of the project has many aspects, which guide the project design and the construction of a ground water flow model (described in subsequent slides).

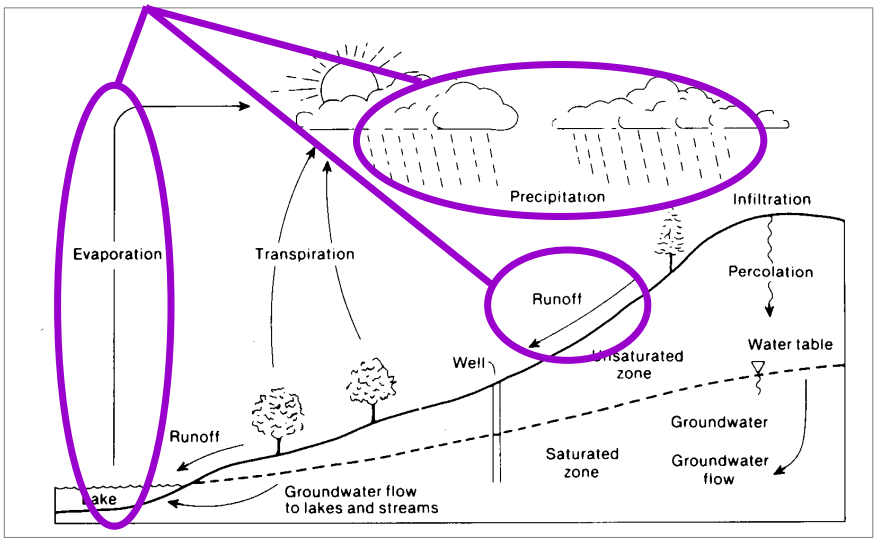
Project Approach

- Construct a regional ground-water-flow model based on general hydrogeologic principals
- Quantify average water use, water levels, and stream base flows for the period 1997-2006
- Customize the conceptual model and numerical model for the Rock River Basin
- Calibrate the model
- Simulate the flow system

The project approach focuses on the construction, customization and calibration of a regional ground-water-flow model. The model is founded on general hydrogeologic principals, which are described in the following slides.

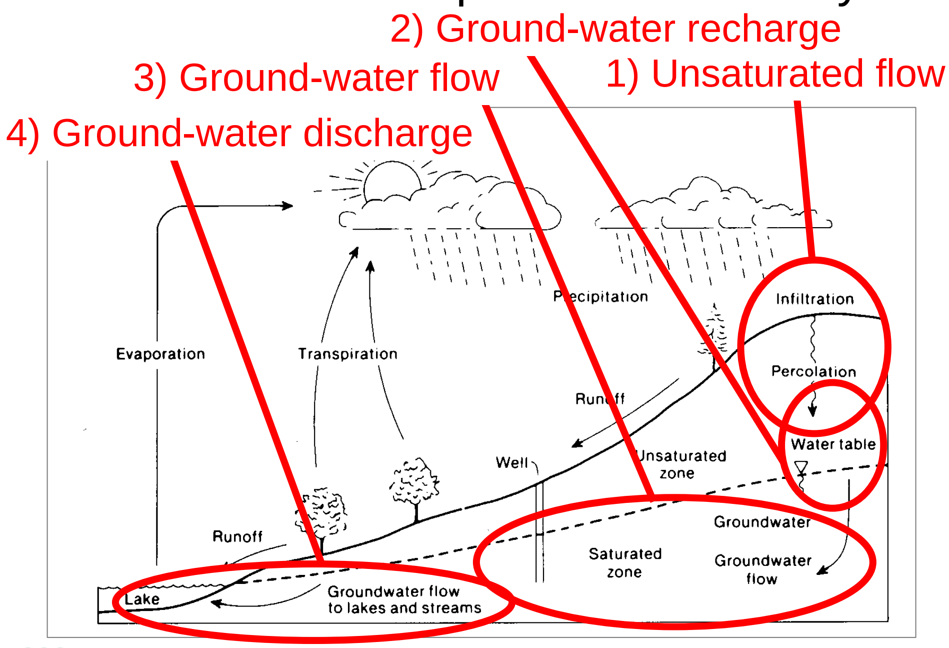
All water on earth is part of the water cycle

Surface processes



All water is part of a cycle. Some water moves on or above the land surface.

All water on earth is part of the water cycle



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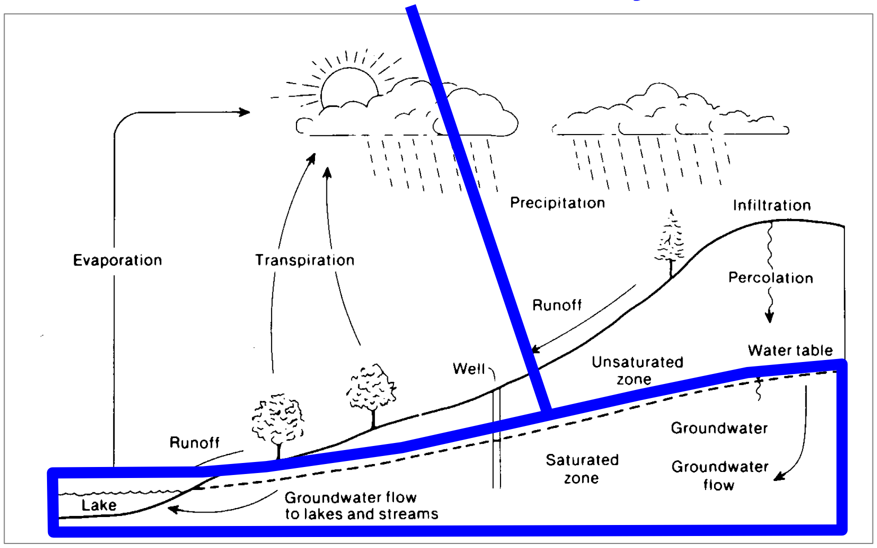
Some water moves below the land surface. Precipitation that infiltrates moves through the unsaturated zone (spaces between sand grains are filled with water and air) until it reaches the water table, which forms the top of the saturated zone (all spaces between sand grains are filled with water). Infiltration that reaches the water table is called "recharge". Water in the saturated zone is called ground water. Ground water flows toward features that remove, or "discharge", water from the ground (rivers, lakes, wells).

All water on earth is part of the water cycle

Ground-water-flow system



This project focuses on ground-water flow through the saturated zone, and does not incorporate surface processes or infiltration. Though other, more advanced tools are available for simulating the entire hydrologic cycle, use of such tools is beyond the scope of this project.

How Models Work:

- Plumbers' Rules
  - Water flows down-gradient, from high pressure to low pressure
  - Water can not be created or destroyed
- The Rules are formed into numerical equations that are solved by a computer model
- Properties of the rocks, rivers, recharge, etc., are entered into the model to quantify the system
- Simulated results are compared to field measurements, and properties are adjusted to improve the match
- Data requirements can be large *(results are as good as the data)*

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Models are a simplification of the physical world. Hydrogeologists use computer models to analyze large amounts of data. All computer models that simulate ground-water flow must obey two rules: 1) water flows from high pressure to low pressure, and 2) water can not be created or destroyed. There are a few types of computer model "programs" or "computer codes" available for use. Two common programs are GFLOW and MODFLOW. These computer model programs differ by how the two rules are formed into equations and then solved. To make the computer models represent a particular area, a Hydrogeologist enters numbers representing properties of the rocks, rivers, recharge, etc. into the computer model. This is how a model is customized for a particular area of interest. The computer then solves the equations using these input properties, and returns information on ground-water levels and the quantity of water moving through the system, from recharge at the water table to discharge at rivers and wells. The properties of the rocks, rivers, and recharge are then adjusted to improve the match between simulated and measured water levels and stream flows.

In this slide show, the word "model" generally refers to the GFLOW model that is being customized for the Rock River Basin, rather than the general "program" name.

Model Design

- Enter sources and sinks of water
  - Recharge (source, occurs everywhere)
  - Rivers and wells (sink)
- Construct and customize *(refined conceptual model)*
  - Flat, impermeable base
  - Quantify properties of the rocks, rivers, recharge, etc.
  - Uniform properties within zones
- Calibrate
  - Water levels
  - Stream base flows

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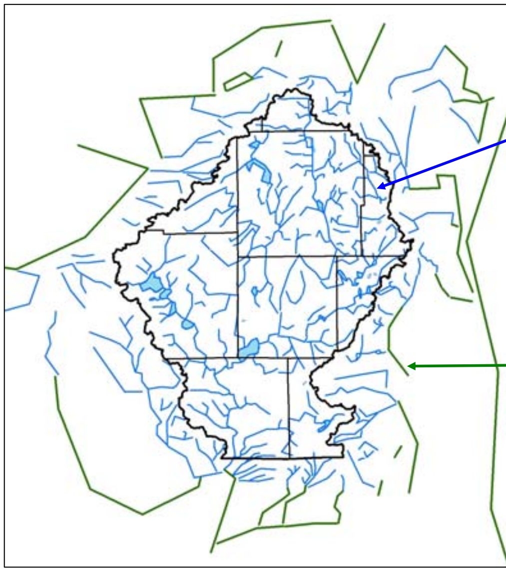
Sources (recharge) and sinks (rivers and wells) of ground water are entered into the model (shown in the next two slides).

Perennial Rivers



Near field (area of interest)
- Route base flow down stream
- Ground-water / surface-water interaction depends on riverbed properties and elevation

Far field (bounds the near field)
-Pins the ground-water level at the river level

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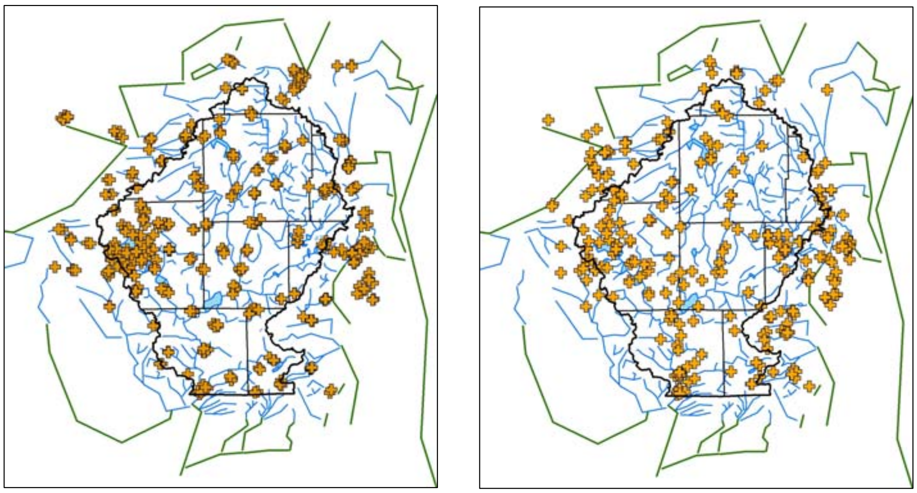
This slide shows the extent of the Rock River Basin GFLOW model. Rivers are simulated using "linesinks". In the "near field", or area of interest, special linesinks are used so that ground water that has discharged to a stream is routed down-river. The amount of ground-water discharge into an individual near field linesinks depends on the river elevation and the properties of the riverbed (sandy or silty sediments). Near field linesinks are also placed immediately around the basin to allow some flexibility for the model to simulate the ground-water divide that separates ground water in the Rock River Basin from ground water in adjacent basins. In the "far field", coarse linesinks are used to represent large regional rivers and lakes that control ground water levels. These far field linesinks form a "protective" boundary around the near field.

Pumping Data

Public Supply | Commercial / Agricultural



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These maps show the location of water withdrawal wells in and around the basin that have been incorporated into the model.

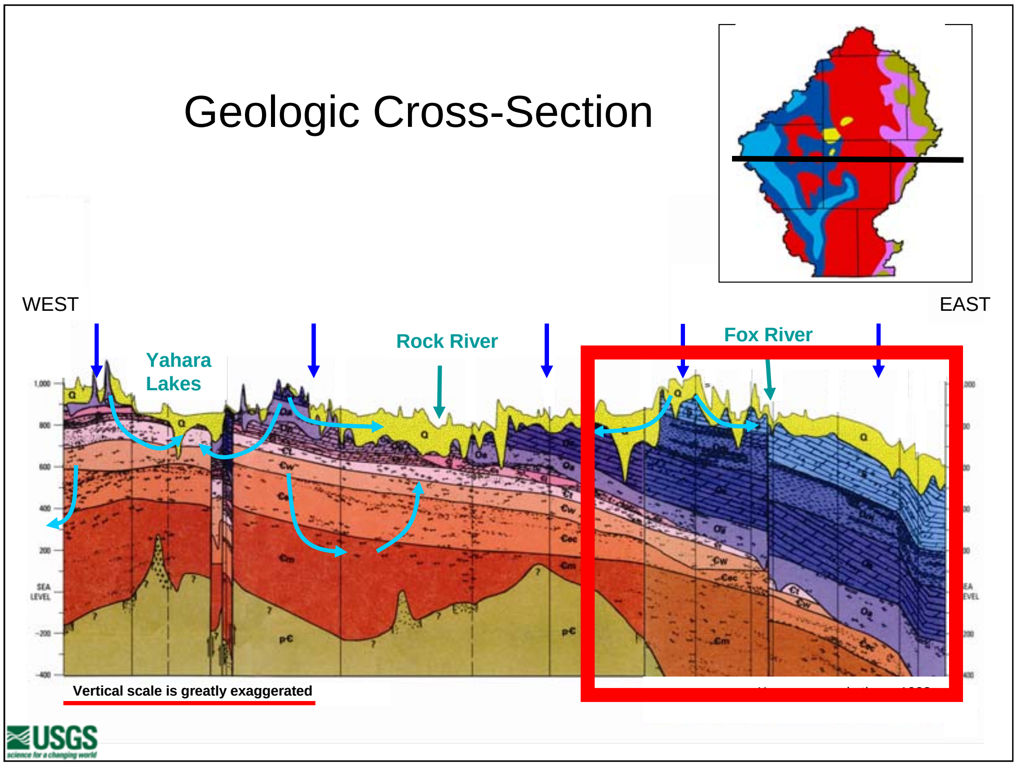
Model Design

- Enter sources and sinks of water
  - Recharge (source)
  - Rivers and wells (sink)
- Construct and customize *(refined conceptual model)*
  - Flat, impermeable base
  - Quantify properties of the rocks, rivers, recharge, etc.
  - Uniform properties within zones
- Calibrate
  - Water levels
  - Stream base flows

The construction and customization of the model requires hydrogeologists to balance the infinite amount of detail in our physical world with the capabilities and limitations of the model program (GFLOW and MODFLOW each have strengths and weaknesses) and the purpose for which the model is designed. A model, by definition, is a simplification of the real world. Some details (geology, rivers, etc.) may be important at a particular scale (regional or local) and for a specific purpose, while other details are less important. Thus, it is important to consider 1) the purpose of the study, 2) the capabilities of the modeling program, and 3) the physical properties of the area that are expected to have the most effect on ground-water flow.

One characteristic of the GFLOW program is that properties of the rocks, rivers, and recharge, (and the impermeable base of the model) are represented with zones that have a constant value. Where properties change, a zone can be added to the model to represent this detail. A minimal number of zones is desired, because these zones add more computational effort to the solution than do rivers and streams (linesinks), and because numerous zones, or poorly constructed zones, can produce an unstable (unreliable) solution.

Hydrogeologists commonly develop a conceptual model (picture) of the study area to help guide construction of the computer model. This is commonly done by using a geologic cross-section as a background, as illustrated in the following slide.

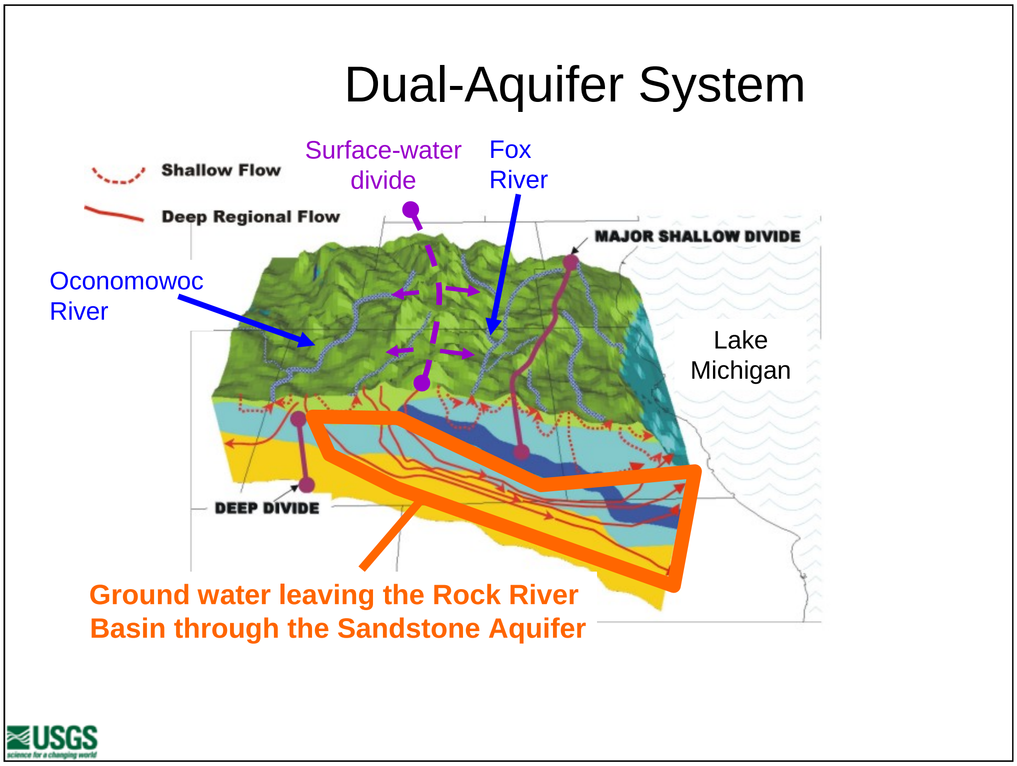


A geologic map in the upper-right-hand corner shows that various rock types underlie the Rock River Basin. The black line roughly corresponds with the cross-section shown below. The Yahara Lakes (Madison), the Rock River, and the Fox River are identified for reference.

The cross section shows several layers of bedrock and glacial deposits. The brown/tan rock at the bottom of the cross section is a Precambrian (pC) crystalline rock (granite, quartzite) with very low permeability. The reddish to pinkish layers above include sandstones and shales, which as a group are referred to as the Sandstone Aquifer. The overlying purple rocks consist of sandstones, dolomites (limestone) and a thick shale layer. The yellow material on top represents quaternary (Q) deposits, which are sands and gravels deposited by glaciers.

The vertical scale of the cross section is greatly exaggerated – on the order of 150 fold. The vertical scale spans hundreds of feet; the horizontal distance spans hundreds of miles. This is important to note because the cross section exaggerates the thickness of the rocks and the magnitude of vertical ground water flow in the Rock River Basin.

Conceptual ground-water flow is illustrated with blue arrows. Ground-water flow starts as recharge (dark blue arrows) at the water table. The light blue arrows illustrate ground water flowing from the water table, through the aquifers and to the rivers, where the ground water discharges. Most of the ground-water flow occurs entirely within the Rock River Basin. That is, most of the water that recharges the water table within the Rock River Basin will eventually discharge to the Rock River or one of its tributaries, regardless of which aquifer (shallow or deep) the water flows through. There is an exception to this pattern in south-eastern Wisconsin (red rectangle), where the Sandstone Aquifer is isolated from the shallow aquifer by a thick layer of shale called the Maquoketa Shale. The importance of this shale layer for simulating ground-water flow in the Rock River Basin is shown in the next slide.



The block diagram shown here is from a three-dimensional ground-water-flow model of southeastern Wisconsin. Lake Michigan is identified to the east. Counties are shown with thin grey lines. From east to west, the central counties include Milwaukee County, Waukesha County, and eastern Jefferson County. Geologic layers in the model are illustrated from bottom to top as the Sandstone Aquifer (yellow), a limestone aquifer (light blue), the Maquoketa Shale (dark blue), another limestone aquifer (light blue), and the glacial aquifer on top (green). Rivers are shown as thick grey lines; the Oconomowoc and Fox Rivers are identified for reference. A surface-water divide is shown, which separates the Rock River Basin from the Fox River Basin. A shallow ground-water divide (not shown) mimics the surface-water divide between the Rock and Fox River Basins. Similarly, the "Major Shallow Divide" identifies the boundary between the Mississippi River Basin (including the Fox River) and the Lake Michigan Basin.

Shallow ground-water flow is illustrated with dotted lines; solid lines illustrate ground-water flow in the deep sandstone and limestone aquifers. The shallow flow lines (dotted) illustrate that shallow ground water flow does not cross the divides, but rather travels a relatively short distances to local tributary streams within the basin. Commonly, deep ground water also discharges to rivers within the basin (western-most solid line/arrow). However, in south eastern Wisconsin, the Sandstone Aquifer is isolated from the shallow aquifer by the Maquoketa Shale. Ground water in the deep aquifer below the Maquoketa Shale flows generally to the east toward Lake Michigan and municipal wells. This difference between flow patterns in the shallow and deep systems is important because the GFLOW program simulates one system; it can not simulate flow patterns that are drastically different in a deep aquifer. This is also important for the Rock River Basin ground-water model, because ground water in the Sandstone Aquifer below the Maquoketa Shale is leaving the basin, and will not be a source of water to the Rock River.

The following slides describe how the GFLOW model of the Rock River Basin has been customized to approximate this dual aquifer system.

What to do?

Problem:

- GFLOW model has 1 layer, but…
- Maquoketa Shale separates 2 flow systems (shallow aquifer and Sandstone Aquifer)

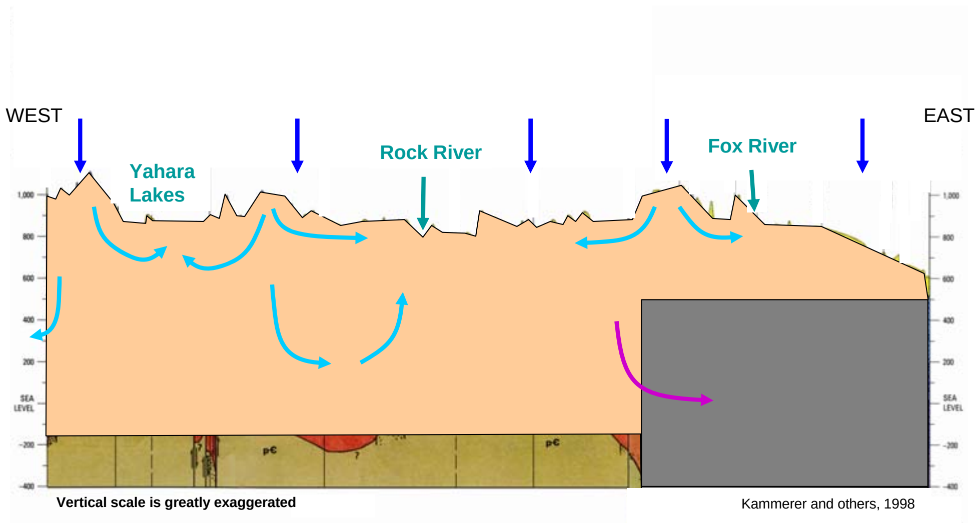
Solution:

- Simulate only the shallow aquifer system where the Maquoketa is present
- Simulate flow into the Sandstone Aquifer based on SEWRPC model results

Keeping in mind the capabilities and limitations of the GFLOW program, our solution to the dual-aquifer complexity is to simulate water levels and ground-water flow patterns only in the shallow aquifer system where ever the Maquoketa is present. Where the Maquoketa is absent (most of the basin), water levels and flow patterns will be simulated for the full aquifer thickness (shallow and deep).

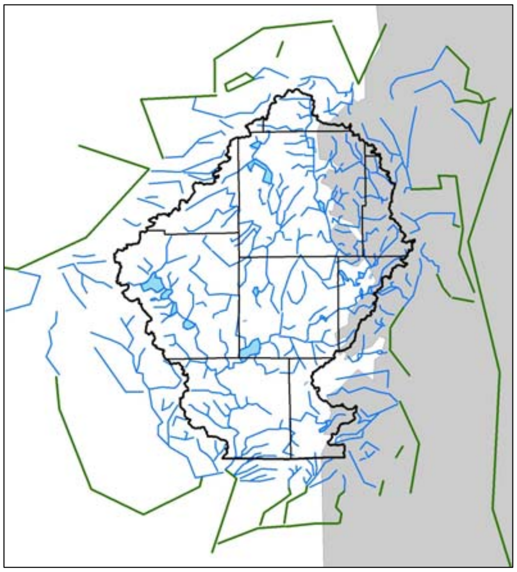
Ground-water flow out of the Rock River Basin through the Sandstone Aquifer will be removed from the GFLOW model based on results of the model shown in the previous slide, as described in the next slide.

Conceptual Model



The geologic cross section has been converted into a conceptual model in this slide. As shown by the grey box, the deep aquifer system below the Maquoketa Shale will not be explicitly simulated in the GFLOW model. However, the “effect” of this deep aquifer on the rest of the Rock River Basin model will be represented by removing water (pink arrow) from the model along the edge of the Maquoketa shale (as shown in the next slide). The tan area shows how the base of the model will be adjusted to simulate the shallow aquifer in the eastern portion of the Rock River Basin. The following slide shows how this conceptual model has been implemented in the GFLOW model.

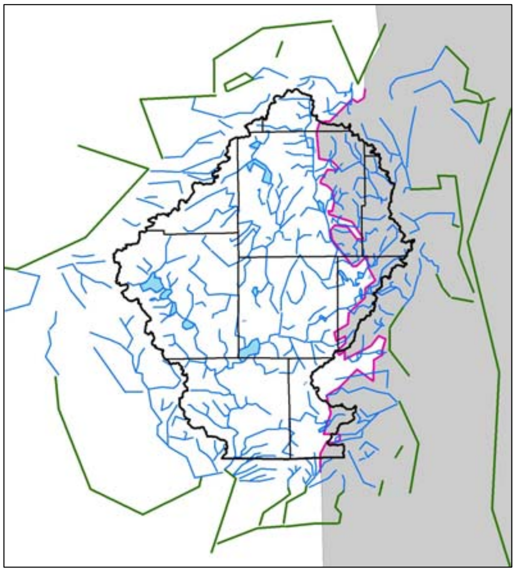
Model Construction



- Base elevation zones
  - Sandstone Aquifer (white)
  - Shallow aquifer (gray)

This slide shows the rivers and streams (linesinks) that make up the GFLOW model. It also shows the area where the full aquifer system will be simulated (white background), and the area where only the shallow aquifer system will be simulated (grey background). The irregular boundary between the two areas identifies the extent of the Maquoketa Shale.

Model Construction



- Base elevation zones
  - Sandstone Aquifer (white)
  - Shallow aquifer (gray)
- Flow into the Sandstone Aquifer
  - Remove water along the Maquoketa subcrop (pink)

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As explained earlier, ground water is removed from the Rock River GFLOW model along the edge of the Maquoketa Shale (pink line). The amount of water removed along this line varies based on the results of the three-dimensional model of southeastern Wisconsin.

Model Design

- Enter sources and sinks of water
  - Recharge (source)
  - Rivers (sink)
  - Wells with average pumping from 1997-2006 (sink)
- Construct and customize *(refined conceptual model)*
  - Flat, impermeable base
  - Quantify properties of the rocks, river, recharge, etc.
  - Uniform properties within zones
- Calibrate
  - Water levels
  - Stream base flows

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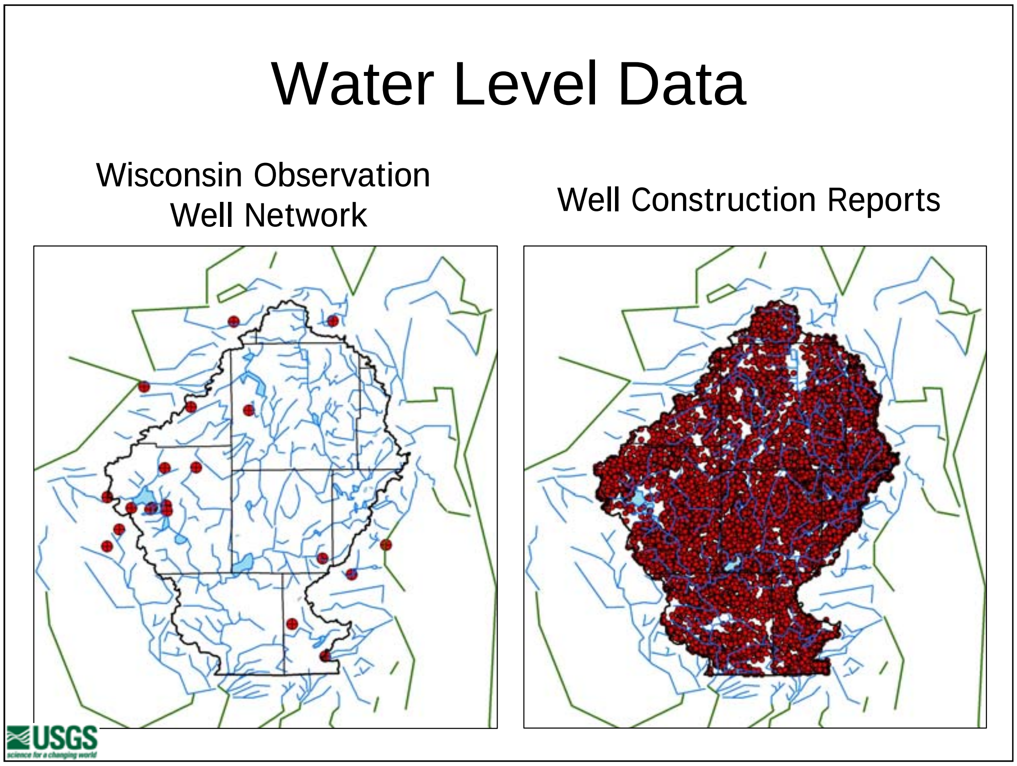
The previous slides described the current status of the study. The next step of the project will focus on calibrating the model (adjusting properties of the rocks, rivers, recharge, etc.) to match measured water levels and stream base flows.

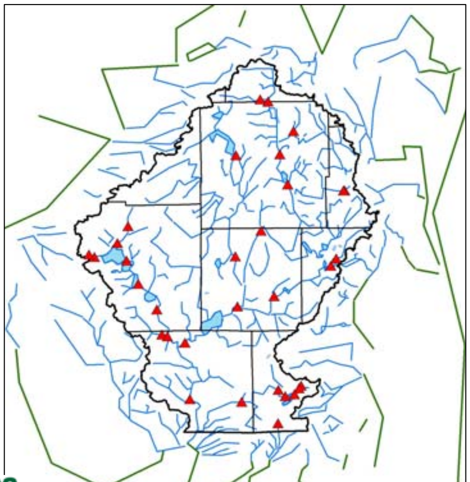


This slide shows the locations of wells with water level measurements that will be used to calibrate the model. Monitoring wells that are part of the Wisconsin Observation Well Network have water level data that span several years and decades. There is a high degree of confidence in these data because the wells are precisely located (horizontal and elevation), and because the historical data set can be used to compute a mean water level for the study period (1997 to 2006). Unfortunately, there are no monitoring wells in the center of the model area.

The slide on the right shows wells that are part of the Department of Natural Resource's Well Construction Report database. This database includes wells for which the water level was measured once, shortly after construction of the well. The level of confidence in this data set is less than that for the Network wells, but the broad distribution of these wells will be useful for calibrating the model.

Base flow Data

USGS long-term
streamflow gaging stations



Streamflow data are used to compare simulated and measured base flow in rivers. Base flow is defined as the part of total streamflow that comes from ground water. Stormflow, which comes from overland runoff, makes up the remainder of total streamflow; stormflow is not represented in this ground-water flow model.

Regional Model Capabilities

- A tool to process large quantities of variable data types *(geology, well pumping, water levels, stream flows)*
- A tool to evaluate regional ground-water flow and effects of stress on the system
- Framework for more detailed models

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This slide summarizes the capabilities that the model will provide, once completed. The following slides show examples of how the regional model can be used as a framework for more detailed models.

When to Refine the Model?

Answer: Depends on the question
(the purpose of the model)

Regional Model:

- What area contributes ground water to the ____ River?

Refined Model:

- What areas contribute water to our wells?
- How much would base flow decrease if pumping increased?
- What if 3D flow is important?

The question that a model (regional or refined) is used to answer is very important, because the GFLOW model can be refined differently depending upon the new question. While it is impossible to anticipate every question that the regional model might be used to evaluate, the GFLOW model is designed to be flexible and easily refined so that it can focus on information that may be important for evaluating a new question. For some questions, the GFLOW model may need little or no refinement. For others, the question can guide how the model is refined.

For example, questions seeking to understand regional dynamics, or those seeking to understand contributing areas to ground-water sinks, may be adequately evaluated by using the regional model with little or no refinement. Moreover, the regional model can be used as a scoping tool to provide a "first cut" at answering questions of local interest. This "first cut" could be used to evaluate how the model could be further refined, or what additional data would be most useful for constraining the simulated results. The three "refined model" examples listed above illustrate how a "first cut" simulation can guide refinement for various types of questions. But first, it is useful to understand the different ways that the regional GFLOW model could be refined (next slide).

Ways to Refine the Model

- Refine the regional GFLOW model
  - Well contributing areas
  - Base flow depletion due to pumping
  - Other ground-water / surface-water problems
- Extract a MODFLOW model
  - Three-dimensional problems
  - Transient (time-dependant) problems
  - Contaminant transport problems

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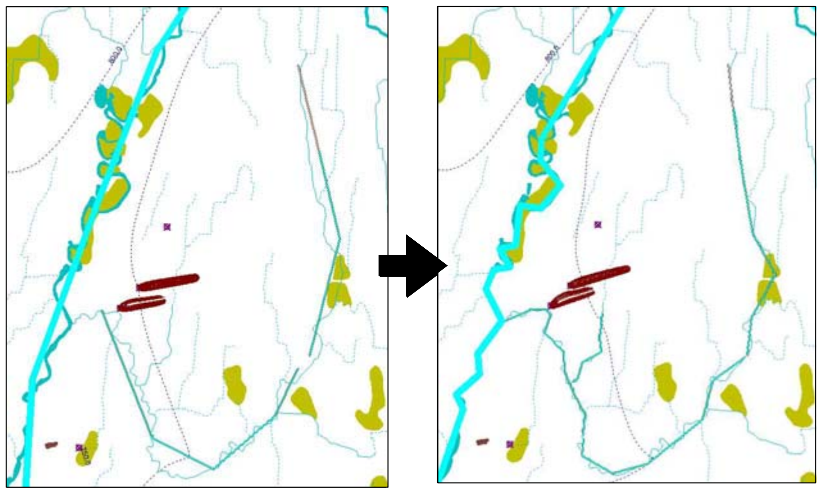
The GFLOW program was chosen for this study partially because of its flexibility. In the future, the regional Rock River GFLOW model itself could be refined locally to focus on local details that may be important for local ground-water flow, such as the examples listed at the top of this slide. In other cases where three-dimensional flow, transient flow, or contaminant transport issues are important, a MODFLOW model could be extracted from the GFLOW model (MODFLOW is a ground-water flow program that differs from GFLOW in how the 2 “Plumber's Rules” described earlier are formed into equations and then solved).

The following examples demonstrate how the GFLOW model could be refined locally. These examples are for demonstration purposes only.

Example: What areas contribute water to our wells?



This example compares simulated contributing areas for wells based on an example from the regional model (left), and an example from a refined version of the regional model (right). Note: these images are examples and meant for educational purposes only; they should not be used for decision making purposes.

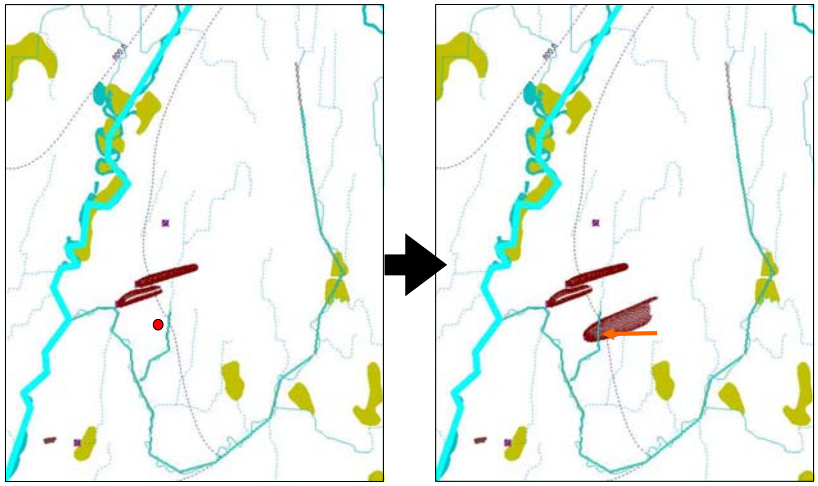
The image on the left shows coarse linesinks (light blue) that represent rivers in the regional model. The Rock River is the large light-blue linesink that runs primarily north and south. Ground-water flow is generally from east to west, toward the Rock River. The background map shows the detailed geometry of the rivers, and also shows wetlands (pale green) and tributary streams (dotted where ephemeral, which indicates zero base flow). The areas contributing ground water (brown) to two wells extend up-gradient (east) of the wells (purple crosses).

The image on the right shows refined linesinks, including the addition of a small tributary stream southeast of the wells. No geologic or other detail has been added.

Comparing both images, the areas contributing water to the wells are somewhat similar in their orientation, shape and extent. This is expected because the regional ground-water flow direction is toward the Rock River (largest light blue linesink), and this regional flow direction will only be “tweaked” by local refinement. That is, local refinement (including the addition of geologic or other details) may alter the shape and extent of contributing areas, but local refinement generally has less effect on the orientation (east to west toward the Rock River) of ground-water flow patterns, especially near large regional features such as the Rock River.

This example illustrates how the regional model could be used as a scoping tool to provide a generalized “first cut” of contributing areas to ground-water sinks (rivers and wells). For situations in which the shape, extent and refined orientation of contributing areas are desired at a higher degree of confidence, re-calibration of a locally refined model may benefit from information on local geologic detail as well as water level, base flow and other calibration data.

Example: How much would base flow decrease if pumping increased?



Base flow decrease: ~35%

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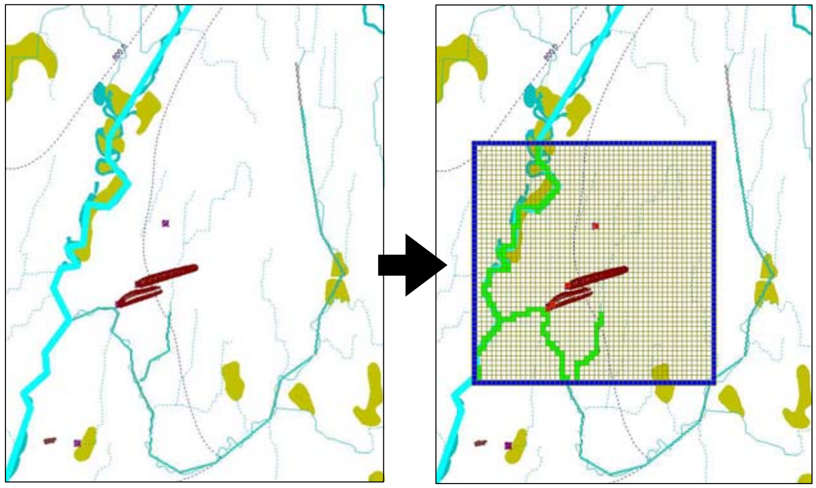
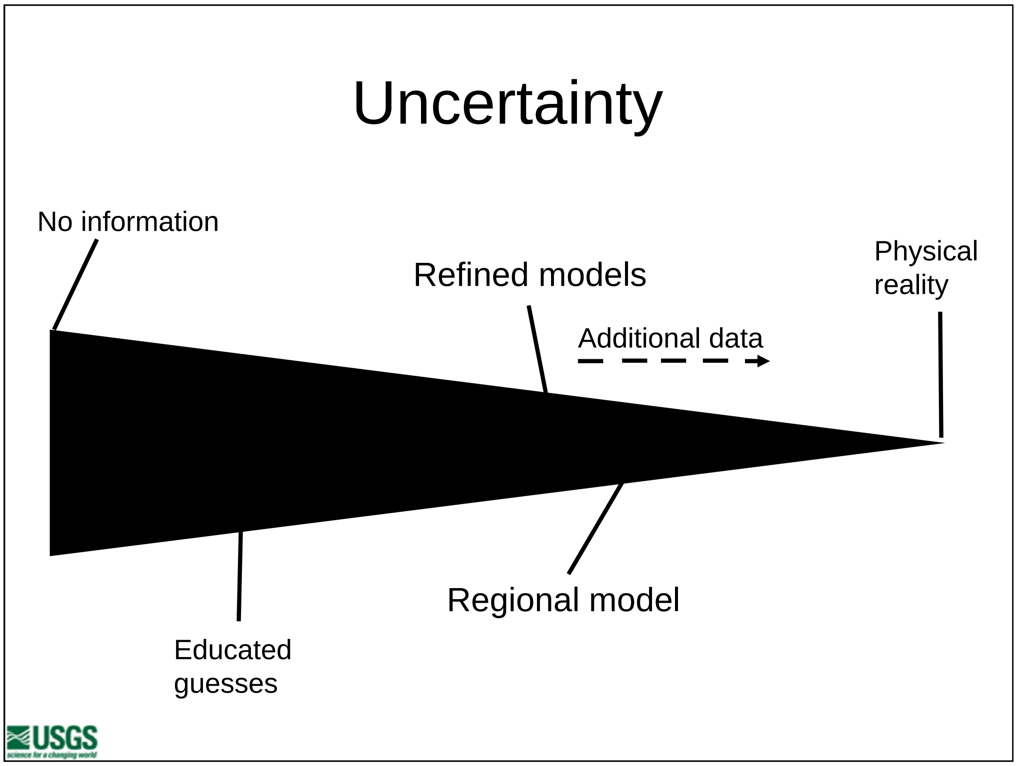
This example demonstrates the effect of adding a new well with additional ground-water withdrawal. The image on the left is the refined simulation from the previous slide. For demonstration purposes, a well withdrawing the same amount of water as the other two wells combined is added near a small tributary stream. As indicated by the well's contributing area, the new well captures ground water that would have previously discharged to the tributary stream. In this hypothetical example, base flow in the stream at the point closest to the well (orange arrow) decreased by about 35%.

This example illustrates how simple refinement of the regional model could be used to provide a generalized "first cut" estimation for a complex ground-water / surface-water interaction question. However, ground-water / surface-water interactions, such as the example shown here, can be sensitive to local geologic and other details. For situations in which the amount of base flow decrease is important (rather than an example), re-calibration of a locally refined model may benefit from information on local geologic detail, water level data, and especially base flow information for the tributary stream and potentially other local streams.

Example: What if 3D flow were important?



This example demonstrates the capability of extracting a local, three-dimensional, MODFLOW model from the regional, two-dimensional, model. MODFLOW has the capability to simulate ground-water flow in multiple layers. However, it uses a grid that can be difficult to refine once created, and has a finite perimeter of limited spatial extent. These limitations can be minimized for local simulations by transferring simulated results from the regional GFLOW model to the MODFLOW model (blue grid cells along the perimeter of the grid). Properties of the rocks, rivers, and recharge can also be transferred from the regional model to the MODFLOW model. For situations in which it is important to identify areas that contribute ground water to wells that intersect multiple aquifers separated by confining units, a refined MODFLOW model may benefit from hydraulic information for each geologic layer, as well as water level and other data that may indicate how individual layers transmit water within the layer and across layers.



All of the previous examples demonstrated *how* the model could be refined locally. The examples did not demonstrate uncertainty associated with the example solutions.

This slide illustrates a continuum of uncertainty, from relatively more uncertainty at the left to relatively less uncertainty at the right. Uncertainty indicates the confidence with which scientists can explain real-world processes or phenomena. With limited information and a basic understanding of a process, a person can make an educated guess for a particular question. Ground-water-flow models incur less uncertainty because they are physically based mathematical formulations of known ground-water flow processes. Uncertainty in the regional GFLOW model is generally low because the results (preliminary for this slide show) are constrained by numerous measurements of water levels and baseflows, which help to improve understanding of ground-water-flow patterns (the purpose of the study). Ironically, uncertainty in the previous examples may have increased despite refining the river geometry. This is partially because the purpose of a local simulations differed somewhat from the purpose for which the regional model was constructed. Increased uncertainty in the previous examples is also partially influenced by the fact that as the area of interest shrinks, local geologic details that were not important (and difficult to incorporate) at a regional scale may become more important for the new purpose or question. Nonetheless, uncertainty can be reduced for local simulations that incorporate and focus on new or existing local data (water levels, streamflows, geologic properties, etc.), provided that the data are appropriate for addressing the question for which the refined model is designed to answer.

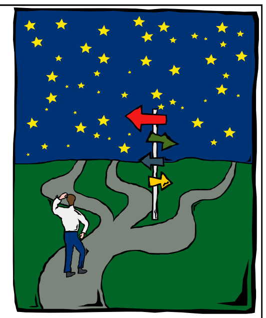
In summary, the regional model is well suited for the purposes that it is designed to address (next slide). It may also be useful as a scoping tool to evaluate the need for refinement and then guide how refinement should proceed. Refinement by itself may not decrease uncertainty of the results, especially if the question for which the model will be used to address differs from the purpose of the regional model. Nonetheless, uncertainty can be reduced by evaluating local details based on local geology, water levels, base flows, and other information.

Purpose

- Improve the understanding of ground-water flow and ground-water/surface-water interaction
- Identify sources of base flow to the Rock River and its tributaries
- Provide a basis to interpret previously collected water-quality data
- Provide a scalable framework for evaluating hydrologic stress to the system

Returning attention to the regional model and the current study, the items above describe the purpose and objectives of the study.

Moving forward…



- Calibrate the model
- Simulate regional water levels
- Map regional flow patterns
- Quantify the ground-water budget for the Rock River Basin

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The items above identify the tasks that need to be completed for this study.

Questions?