Water Management Analysis of Hydraulic Fracturing using System Dynamic Models

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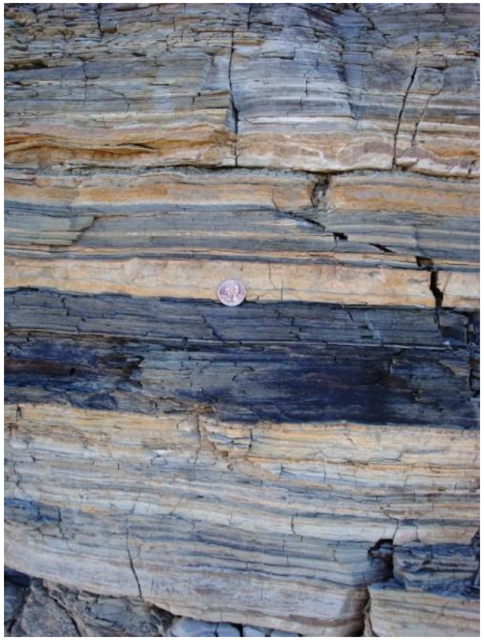

EPA Technical Workshop #4

Water Resource Management

Theme 1: Water Use and Sustainability

March 29-30, 2011

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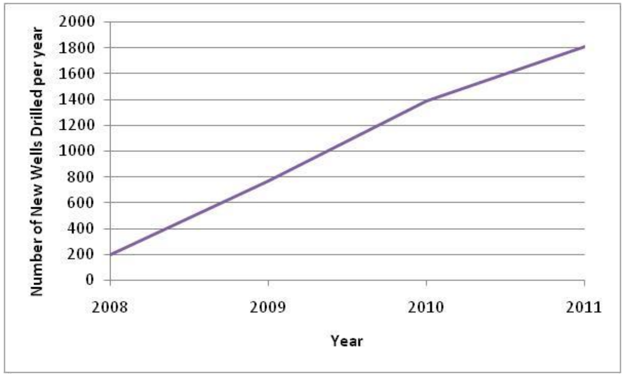
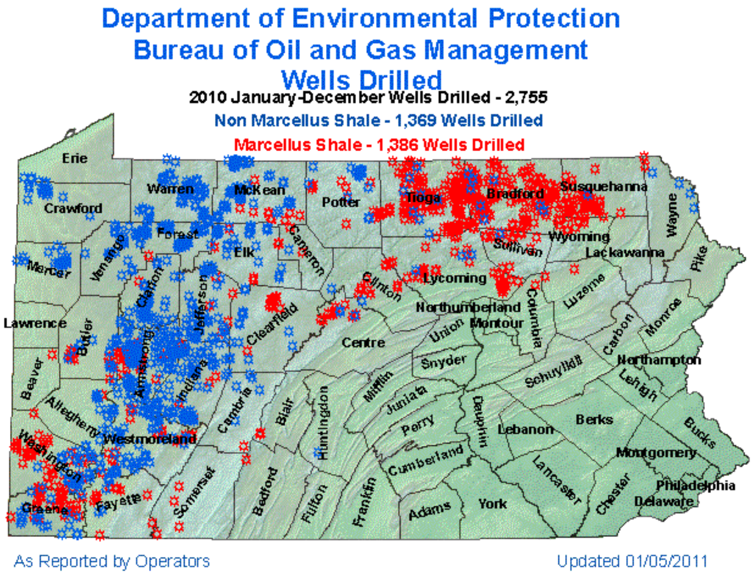
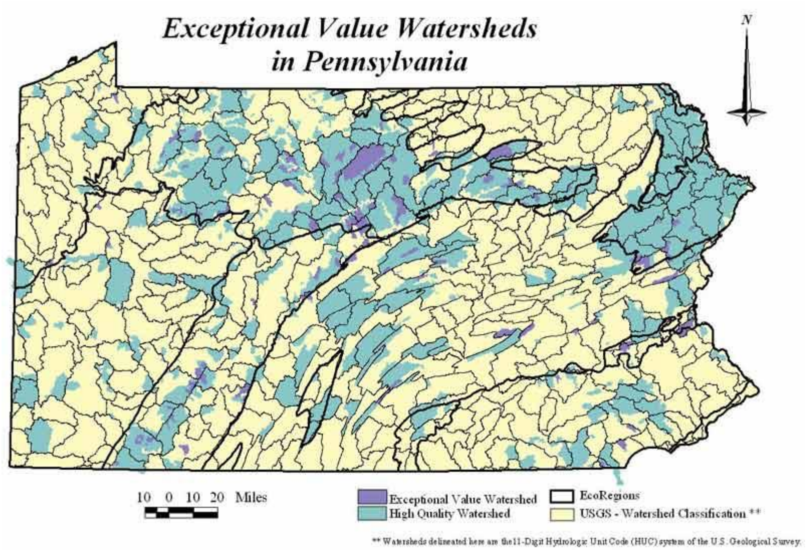
Water Impact from Shale Gas Development

- Growing Industry
- Multiple Operators (82 in PA)
- Multiple Watersheds
- Complex problem to integrate





From:
http://www.dep.state.pa.us/dep/deputate/minres/oilgas/BOGM%20Website%20Pictures/2009/2009%20%20Wells%20Drilled.jpg



From: http://www.dcnr.state.pa.us/wlhabitat/images/watersheds.jpg

Objective:

Present an outline on the potential use of System Dynamic Models to track water usage for hydraulic fracturing of shales and its integration into GIS models.

Hydraulic Fracturing Water Consumption Estimates

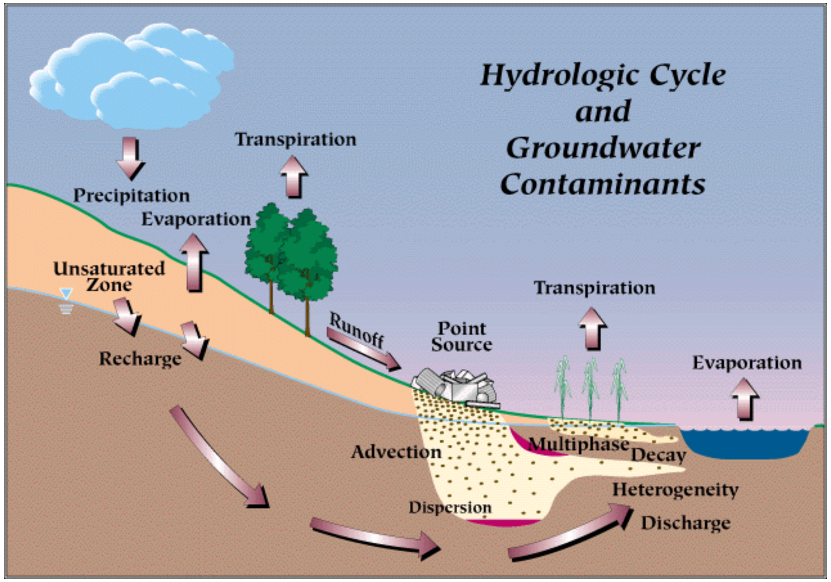
Shale Gas Play	Volume of Drilling Water per well (gal)	Volume of Fracturing Water per well (gal)	Total Volume of Water per well (gal)
Barnett	400,000	2,300,000	2,700,000
Fayetteville	60,000	2,900,000	3,060,000
Haynesville	1,000,000	2,700,000	3,700,000
Marcellus	80,000	3,800,000	3,880,000

Data from Modern Shale Gas A Primer

- No description of acquisition
- No estimate of return volume
- Based on historical data

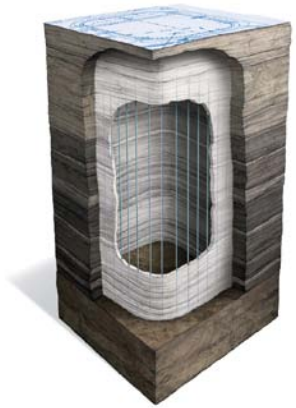
System Dynamics Modeling

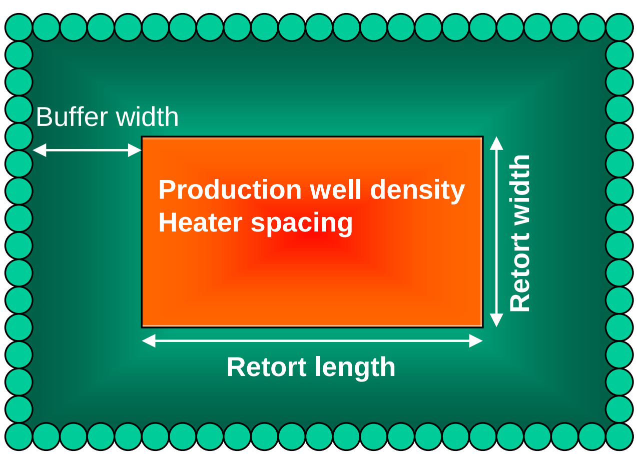
- A way to address complex problems involving diverse stakeholders
- Dynamic, non-linear simulation modeling with capacities to integrate “soft” and “hard” system components in one place.
- Provides a visual model of the system
- Receive immediate response to “what if” scenarios.



- Links cause and effects relationships
- Captures the mental models of the domain experts.
- All model equations and data are “transparent”

Example of an in-situ retort similar to the Shell process

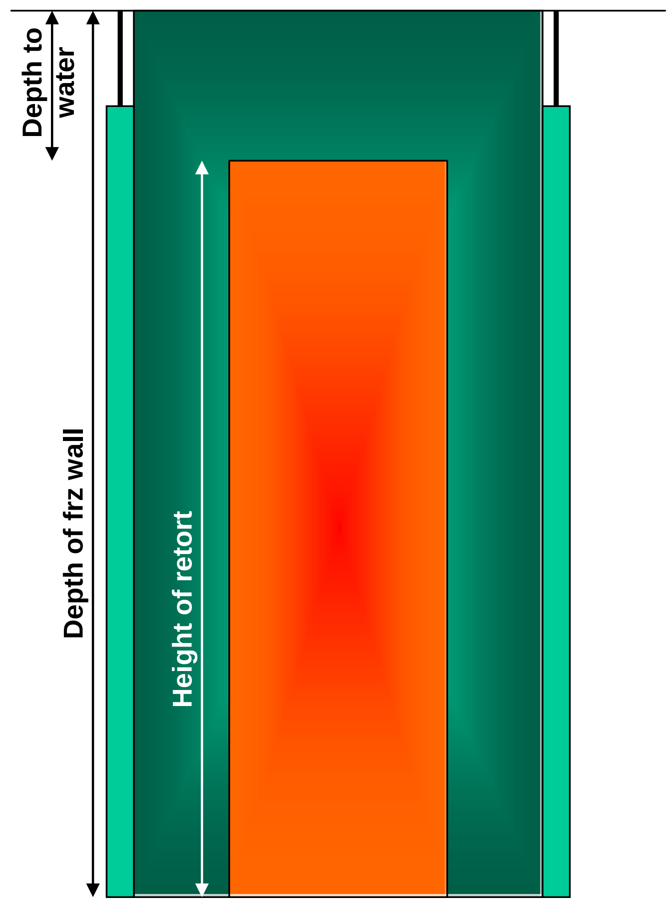




Freeze wall spacing

Well completion rate
Number of drill rigs

Plan View

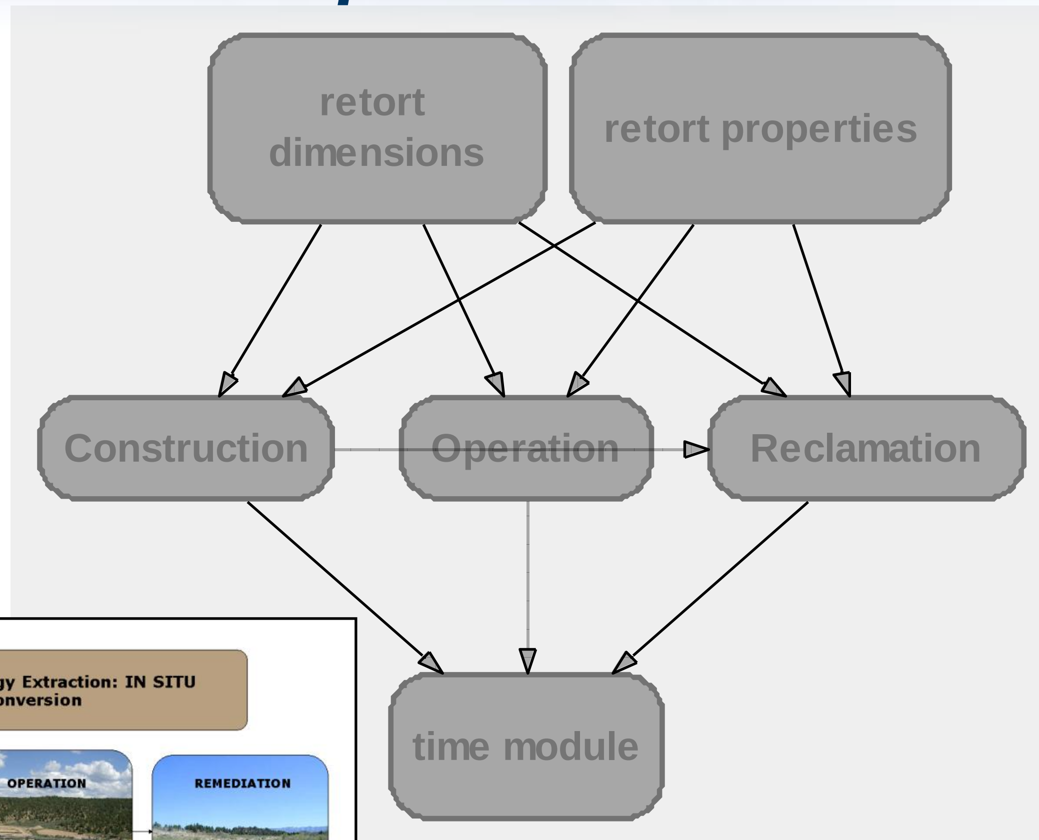


Cross Section

Building the Model

- The water usage can be scaled by:
  - Number of wells
  - Surface areas
  - Subsurface volumes
  - Product production rate
- The system can be represented by
  - Single subsurface shale
  - Sequential events
- The parameter distributions can be described by simple functions

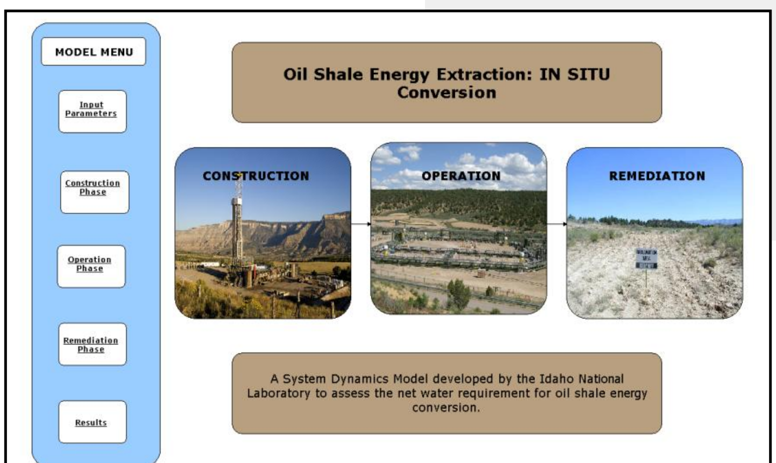
Oil Shale Model Components



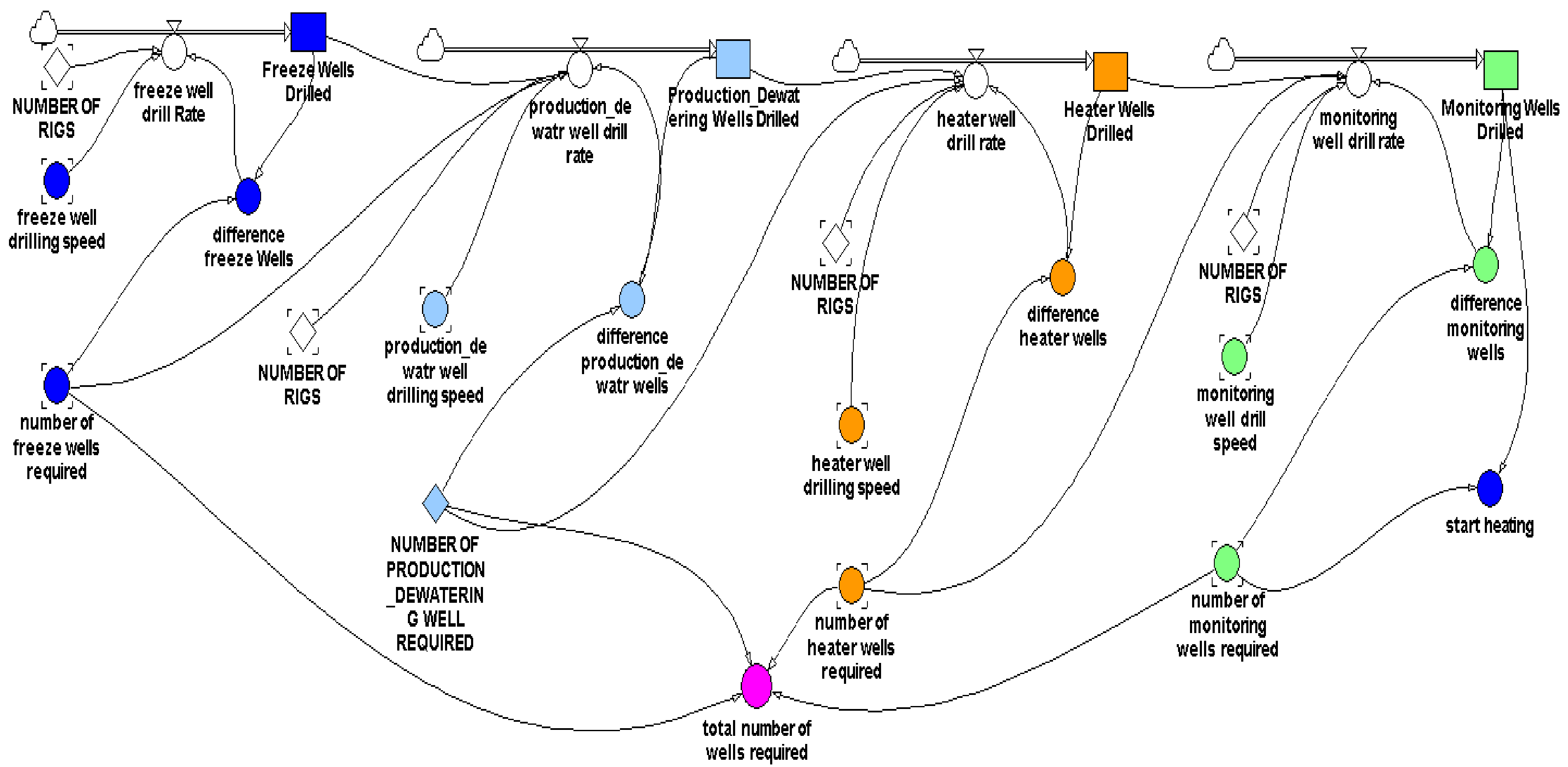
Model inputs

Model calculations

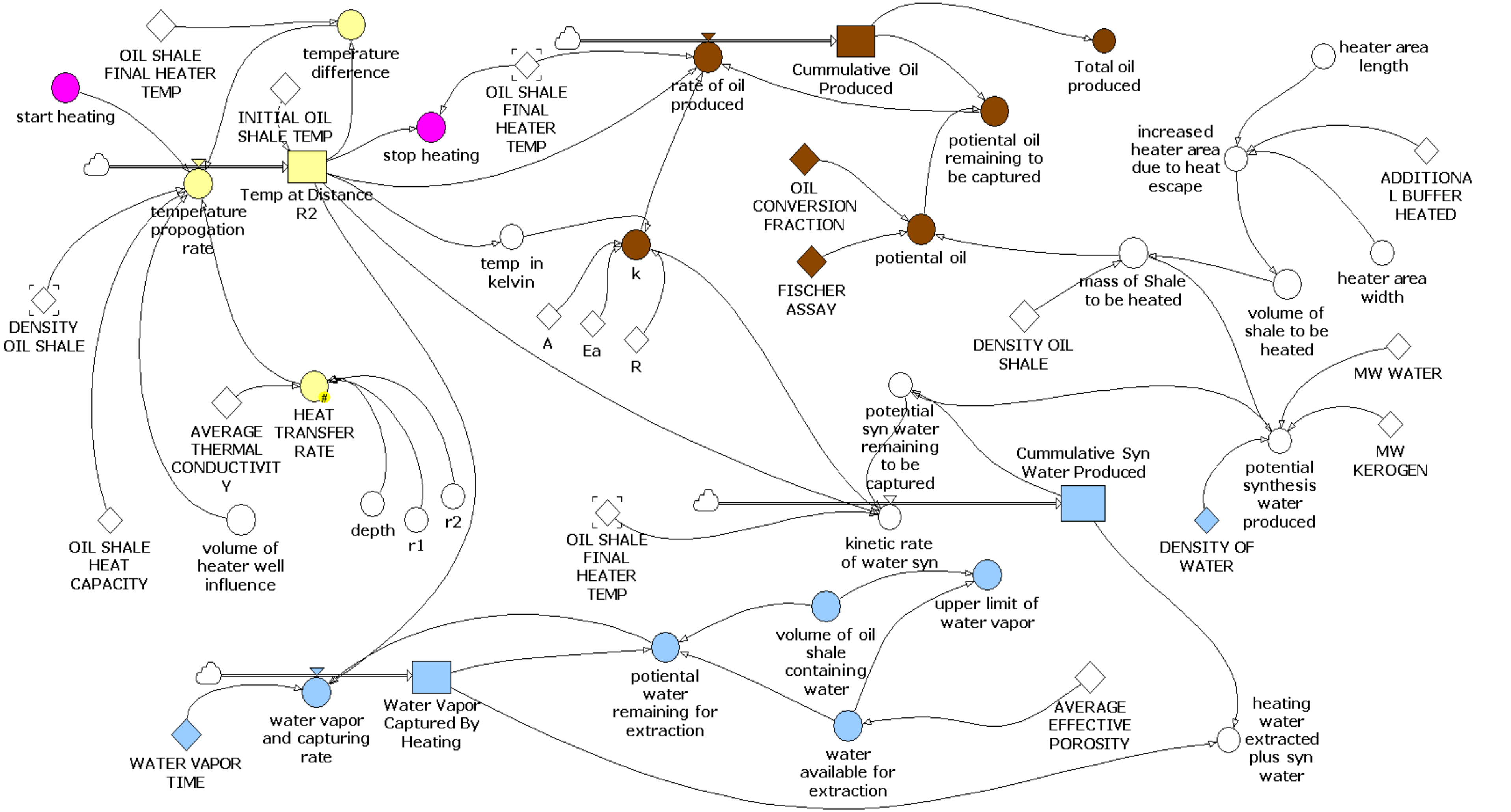
Model outputs



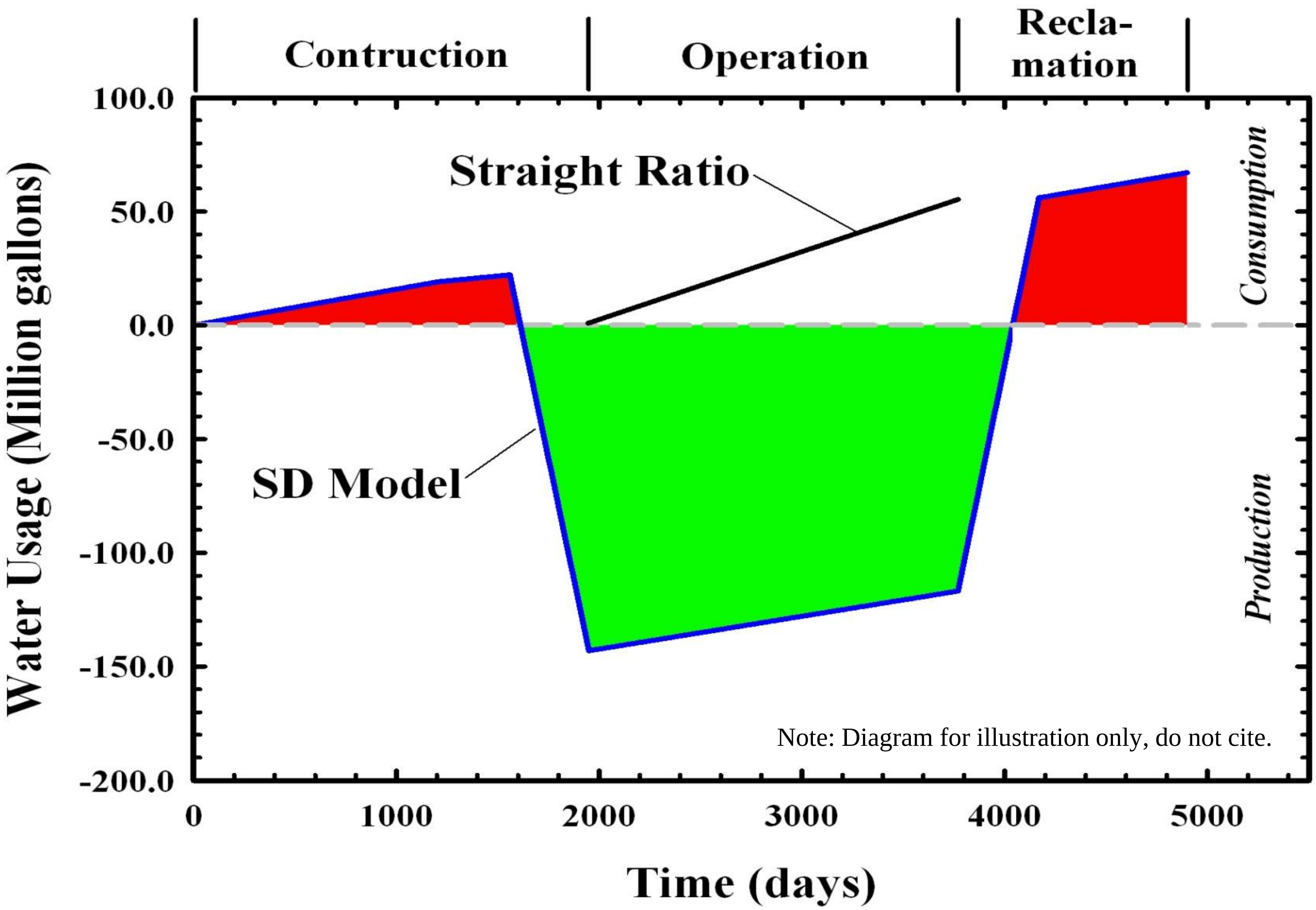
Oil Shale Construction Module



Oil Shale Operation Module



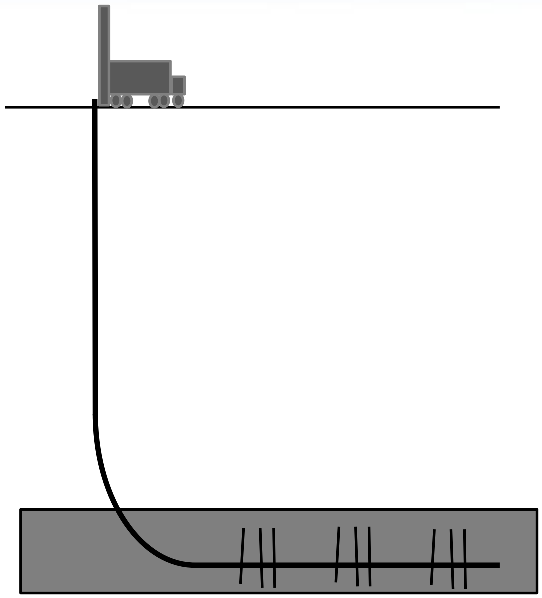
Model Output



Potential Hydraulic Fracturing Modules

Source
Groundwater
Surface water
Reuse

Pre-fracture Storage
Ponds
Pipelines
Tankers



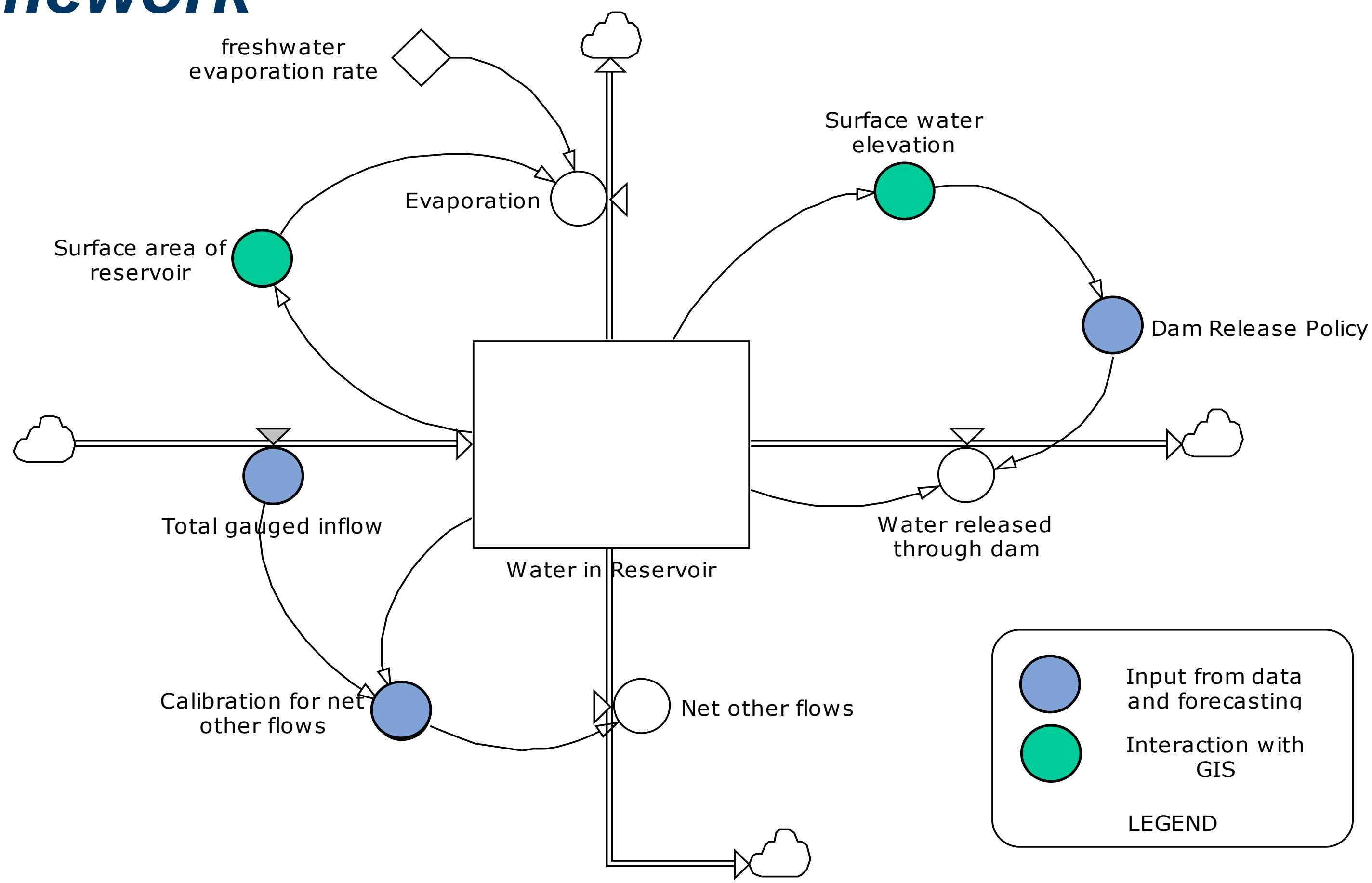
Fracture Design
Injection rate
Injection pressure
Young's Modulus
Possion ratio
Stress conditions
# of fractures
Leakoff rate

Water Injected
Fracture volume
Leakoff volume

Operation
Operating pressure
Fracture rinse
Flow back water
Produced water
Water in matrix

Post-fracture Storage
Volume
Treatment

An example of a basic system dynamics reservoir model with direct plug-in to GIS framework



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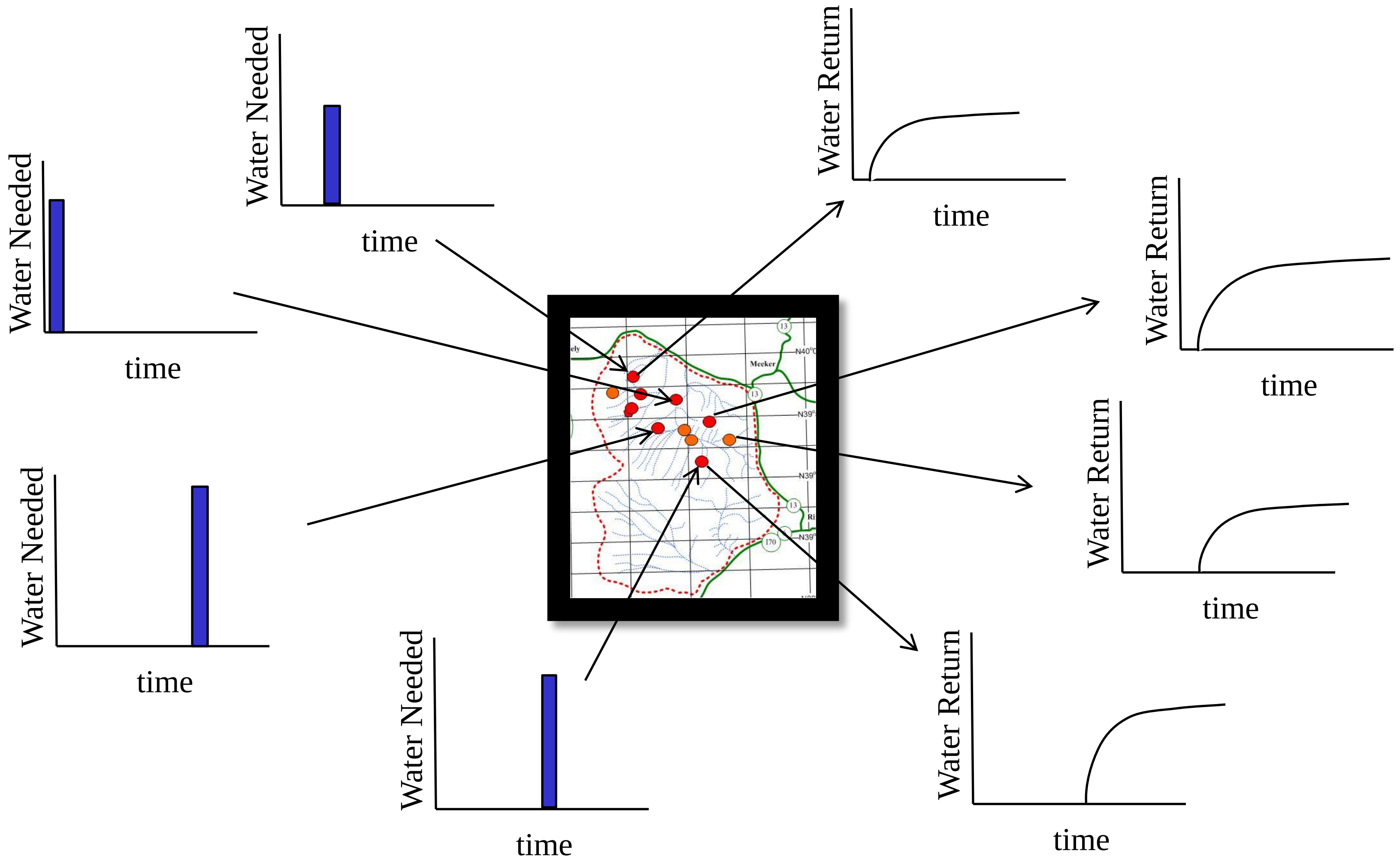
Summary



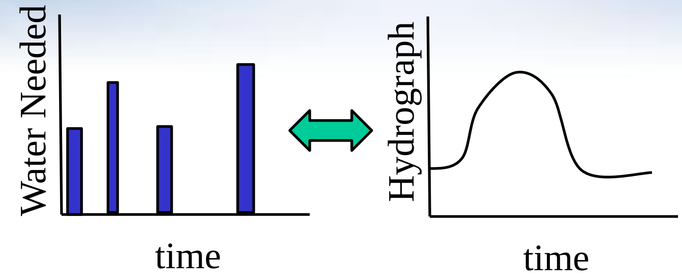
Inputs

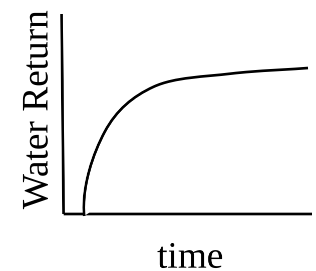
GIS Location

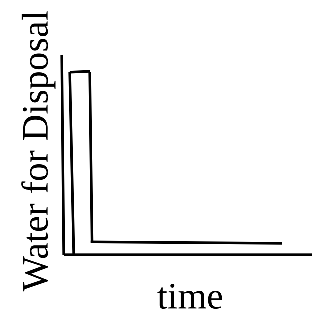
Outputs

Summary

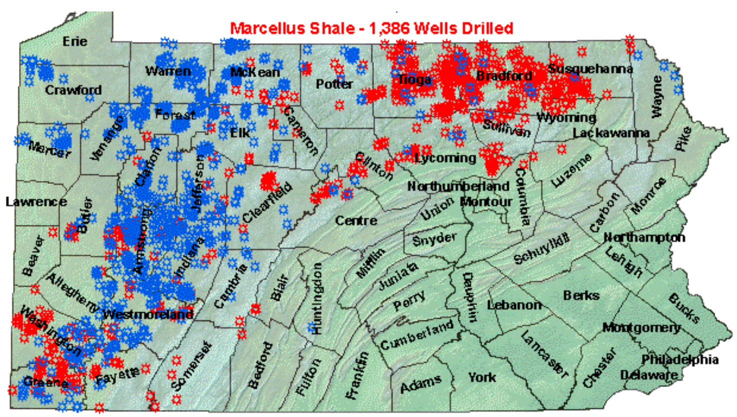
- Theme 1: Water Use and Sustainability
  - Identify sources of water needed for HF
  - How to integrate this water use with surrounding communities
- Theme 2: Flowback Recovery and Water Use
  - Quantify amount of flowback
  - Extended towards reuse
- Theme 3: Disposal Practices
  - Quantifies volume of waste disposal



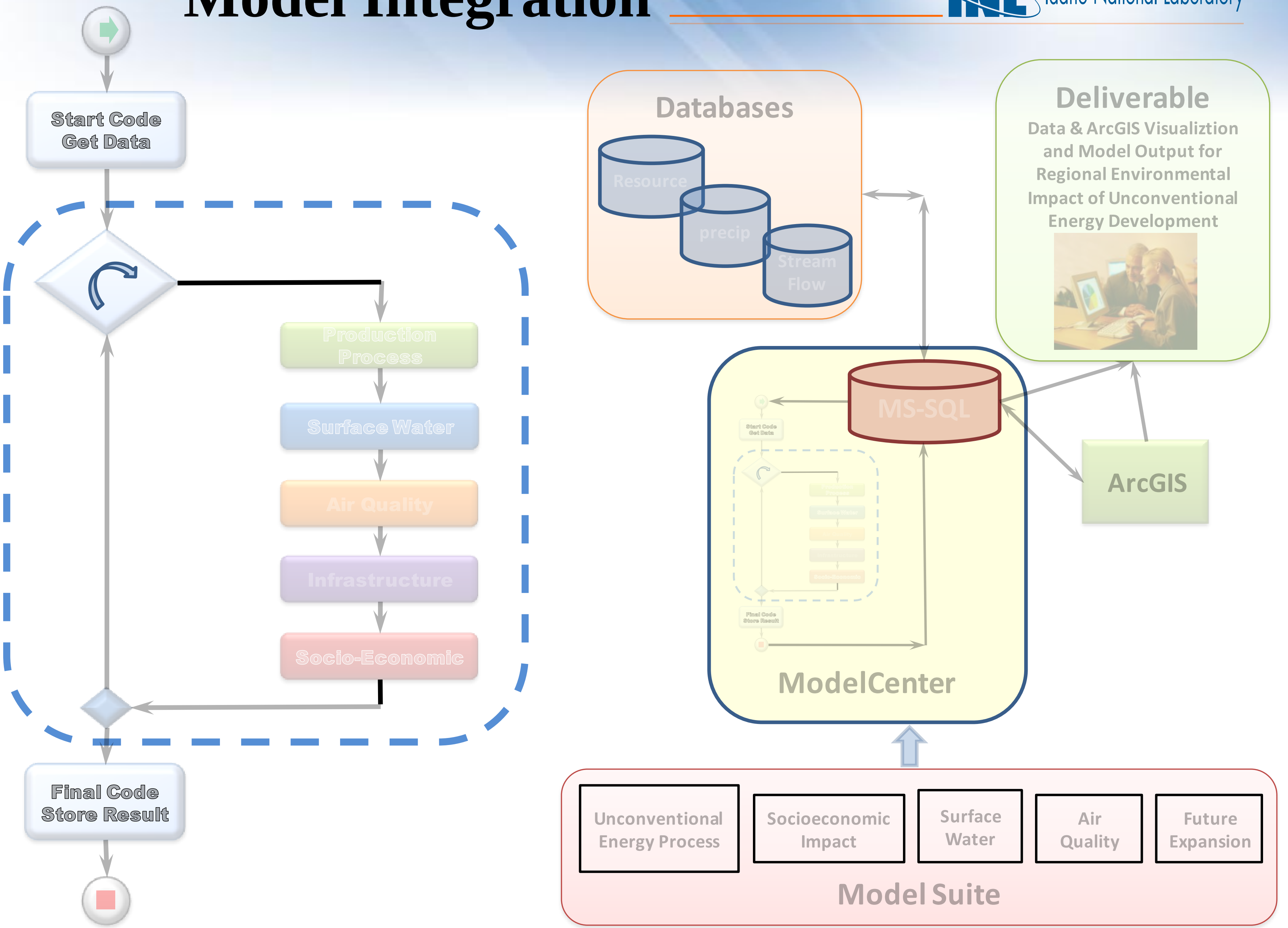




Integrate water use into single predictive tool for water management decisions



Model Integration



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Introduction

The recent increased production of natural gas from tight gas reservoirs has lead to public concern of the protection and use of subsurface water resources. Although the water consumption to perform hydraulic fracturing of these tight reservoirs often accounts for a small percentage of the total water consumption of the region, the rate of water consumption is rising, leading towards potential conflicts of water availability even in the "water abundant" eastern states associated with the Marcellus Shale.

The amount of water needed is directly tied to the increase in the amount of natural gas production and hence to the number of wells that are hydraulically fractured. Hydraulic fracturing for the Marcellus requires approximately 4,000,000 gallons of water for each well that is fractured (GWPC, 2009). Drilling in Pennsylvania Marcellus Shale has been increasing by

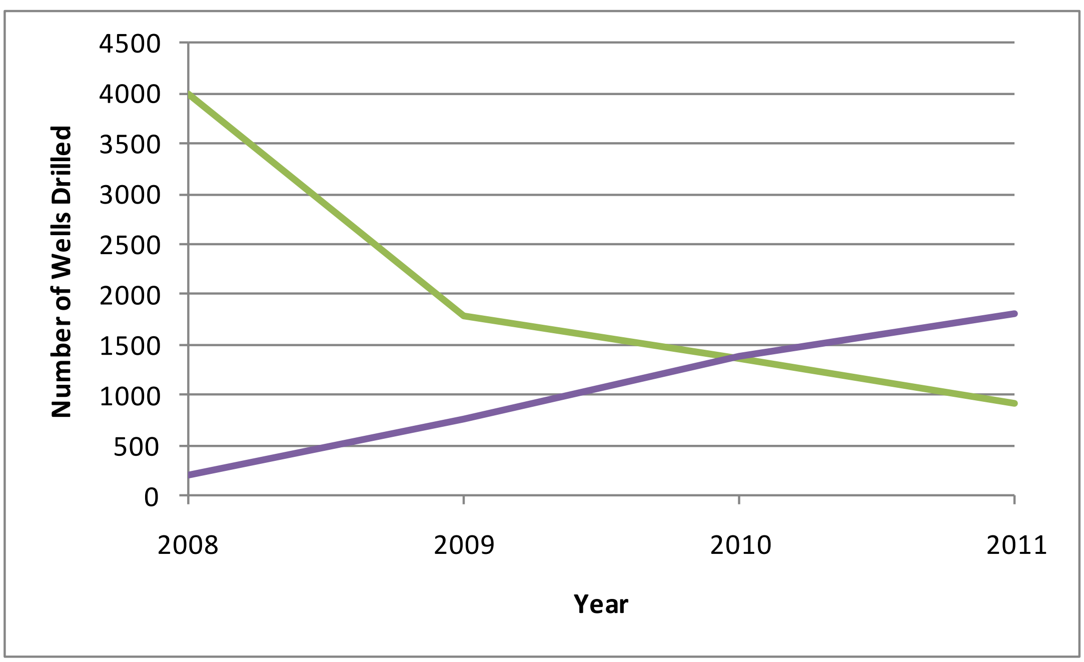

Figure 1. New oil and gas wells drilled in Pennsylvania by year. Green line is represents non-Marcellus Shale, Purple line represents Marcellus Shale wells. 2011 data is projected from January-February 2011 values.

about 500 wells per year (Pennsylvania Department of Environmental Protection, 2011) (Figure 1). The resulting water demand for hydraulic fracturing of these wells requires approximately 6000 acre feet of water each year.

Furthermore, the location of the Marcellus gas drilling activity is not uniformly distributed. This drilling activity tends to be concentrated along available leasing, access to distribution pipelines, and overall profitability. Using Pennsylvania as an example, the most active areas tend to be near Bradford County in the north and Washington County in the Southwest, (e.g., Figure 2). These areas have been the focus of drilling in the Marcellus Shale since 2008, and will likely be the preferred areas for some time.

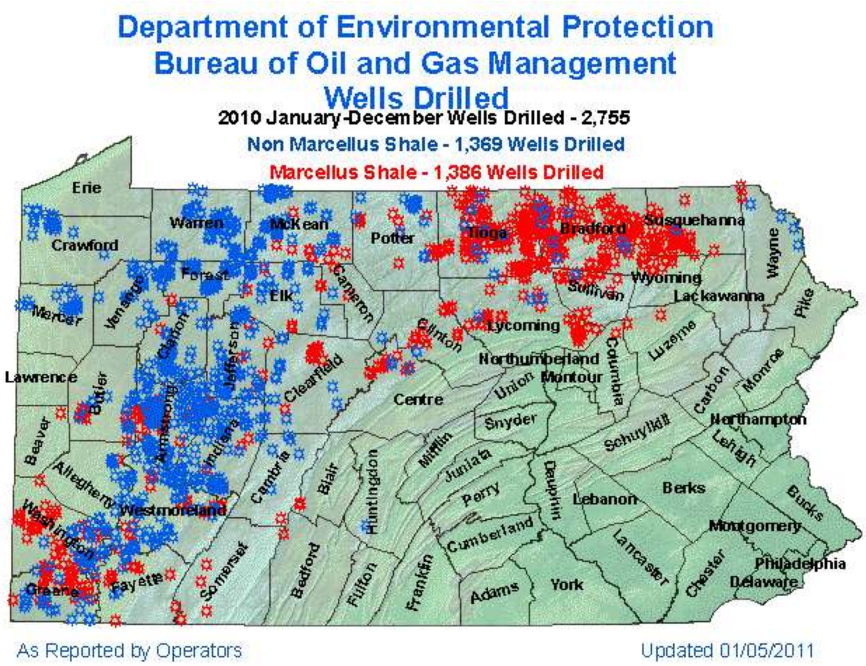

Figure 2. Location map of oil and gas drilling activities in Pennsylvania in 2010 (from PA Dept of Environmental Protection web page).

At some point in the future, the increase in hydraulic fracturing activity and the concentration of these activities in certain geographic locations could lead to over-allocation of the local water supply. The ability to understand, predict and minimize the impact of shale gas energy resource development on water supply within the local watersheds needs to be addressed.

System dynamic modeling is a potential tool that can provide a better understanding of the present and future water consumption for a diverse set of stakeholders (the multiple energy development operators, federal and state regulators, and the surrounding communities). This model is a dynamic non-linear simulation model with the capability to integrate “soft” and “hard” system components in a single tool. System dynamic modeling has been used to better understand river basin models, fuel cycles, and population dynamics on resources. Although the connection of this set of information can be accomplished through the use of multiple software packages, one great advantage of system dynamic modeling package is that it provides a visual model of the system that allows non-technical stakeholders a better understanding of the complex system.

To develop a system dynamic model for hydraulic fracturing, the water cycle is first broken up into a number of sub-models that describe the potential water flows. Figure 3 illustrates a potential structure for a system dynamic model. The source water may be from surface water sources, shallow groundwater and other recycle/reuse sources. Due to the nature of hydraulic fracturing, this water is typically stored on-site in tankers, or storage lagoons. The fracture design module would either use data from the operators or from idealized fracture geometries (e.g. PKN planer fracture models) to determine water use for the fracture. Water distribution from the injection could be segregated into that contained in the fracture, leakoff volume, pre-treatment water use volumes. Finally, flowback and produced water could be accounted for via numerical approximations of physical phenomena or via operators' best judgment information on a specific location. Produced and flowback water returned to the surface can to examined for quantity (and potentially quality) allowing for decisions of treatment options and reuse.

Researchers at the Idaho National Laboratory are currently conducting an assessment for another unconventional fossil energy resource, oil shale. The following example describes how an *in-situ* oil shale retorting operation was modeled and used as input data for a GIS based groundwater consumption model of the Piceance Basin in Colorado.

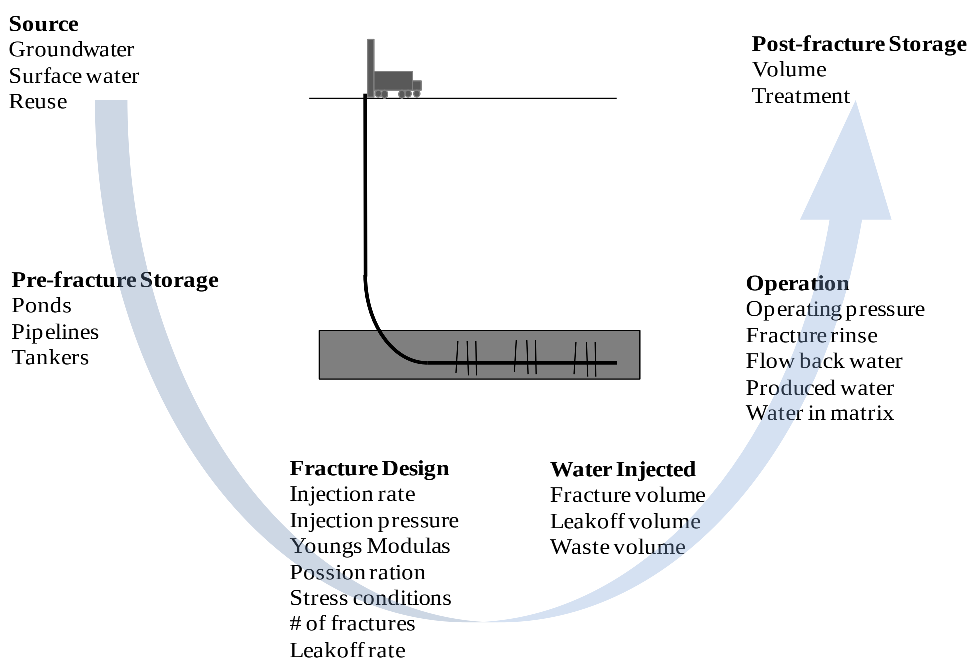

Figure 3. Potential components of System Dynamic Model for Hydraulic Fracturing to better understand the water cycle.

Oil Shale Water Model Example

The use of oil shale as a supplemental energy source is rapidly emerging as an answer to increasing energy demand and cost. Oil shale is a sedimentary rock which contains a high content of kerogen. When subjected to high temperatures in an anoxic environment, oil shale decomposes into a mixture of liquid and gaseous substances similar to petroleum fuels (Brandt, 2007).Oil shale energy conversion is achieved by two basic methodologies: *ex-situ* retorting and *in-situ* retorting. *Ex-situ* processes involve mining oil shale in large open pits or subsurface mines, then applying heat in an above ground or surface retort. *In-situ* retorting process use subsurface heaters or steam to apply heat below ground. While still under development, an advantage of *in-situ* retorting is the reduction of environmental impacts caused by eliminating the mining process. Both processes are water intensive and consume large quantities of water for construction, operation, and remediation (Lee, 1991). Accurately modeling water requirements and consumption will greatly aid in the assessment of water availability and the potential to utilize oil shale deposits as a viable energy source in a region.

To assess the impact of water availability as a limiting factor for *in situ* oil shale conversion, a PowerSim^{TM}, system dynamic, model was developed. A pilot study conducted by Shell Oil Company, was used as a template for the theoretical model since *in situ* retorting is highly developmental. Patents, literature, and engineering principles were referenced where appropriate.

Model architecture for an in situ oil shale development was developed in three stages: construction, operation and remediation. Figure 4 illustrates the model interface and the three stage design architecture.

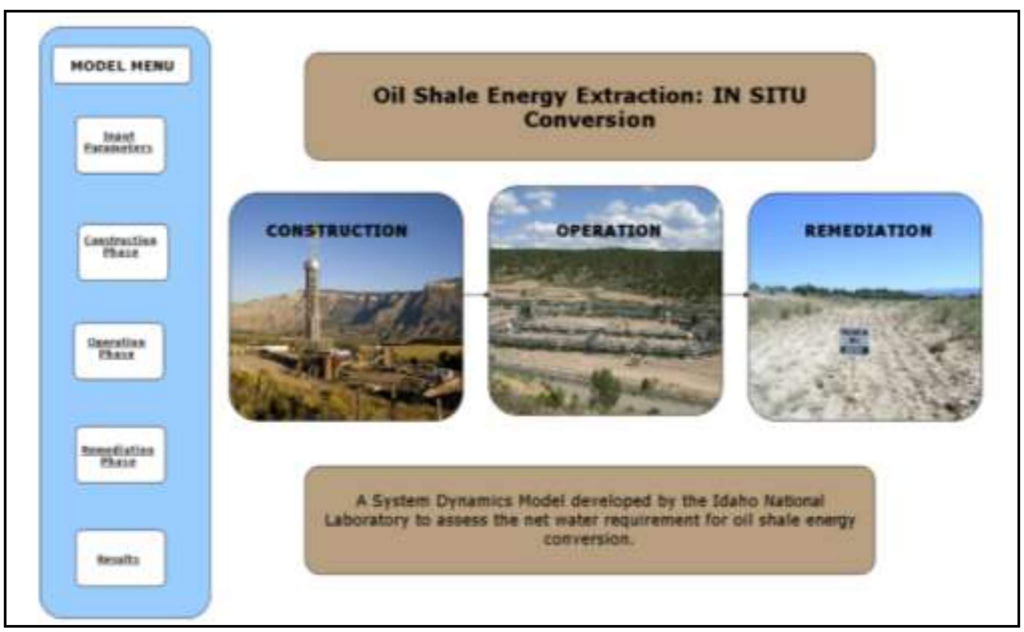

Figure 4. Model Interface of an in situ-oil shale development

Each oil shale stage has a system dynamic model that describes the water use during each stage. For example, the construction stage of the *in situ* retorting process was assumed to consist of any site preparation and development prior to oil production (Figure 5). An average well drilling rate of 8 ft/hr was estimated from average limestone and sandstone drilling rates. Drilling mud and seepage losses were estimated to be 30 barrels/hr and 1.5 barrels/hr (Devereux, 1999). Pilot study saturated porosities and effective porosities of 10.7% and 3.8% were assumed (Brandt, 2007).

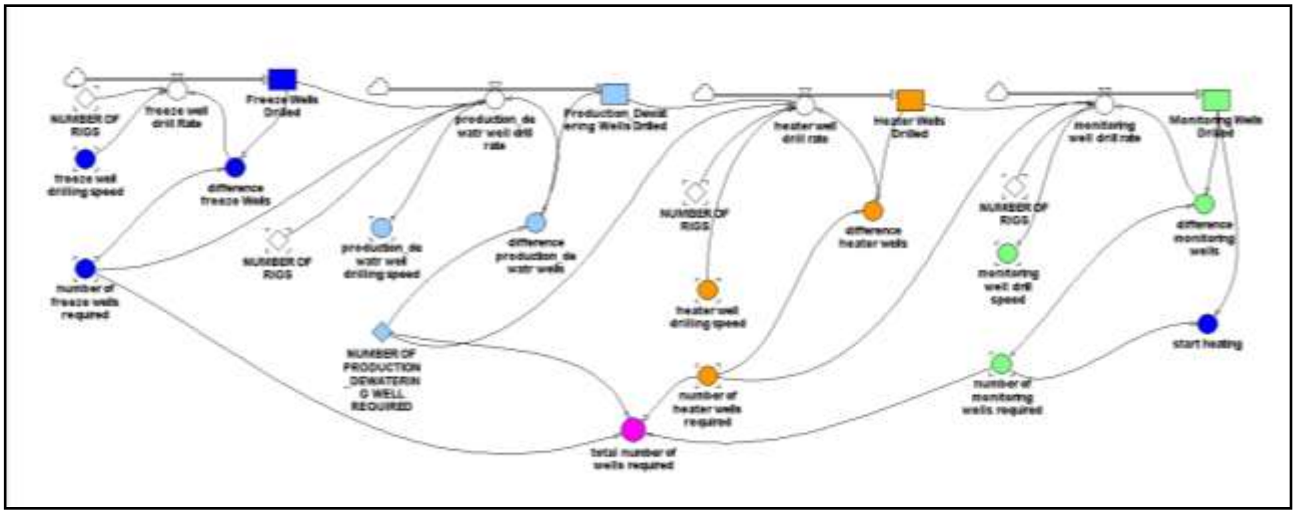

Figure 5. Construction phase model component of the in-situ oil shale example.

While the construction phase of the *in-situ* retorting process is controlled by physical activities like well drilling and site preparation, the operation phase involves the complex interaction of heat transfer, chemical reactions, and material conversion (Figure 6). A non-uniform heat transfer rate assuming cylindrical geometries was used to model the *in-situ* heat transport (Hendersen, 1997). An initial oil shale temperature of 20 °C and a pyrolysis temperature of 400°C were used to calculate heat transfer rates (Brandt, 2007). Homogenous material properties were assumed to simplify calculations. Important oil shale material parameters include: thermal conductivity (1.2 W/m°C), density (1.75g/cm^3), heat capacity (1.25J/g°C) (Lee, 1991).

The operation phase includes a process to describe the rate of oil production using kinetic factors for pyrolysis oil production published by Shell. Water synthesized during the pyrolytic conversion was modeled from chemical reactions, and kinetic factors published in patents and literature. An empirical formula for kerogen of $C_{421}H_{638}O_{44}S_4NCl$ was assumed. Modification of the *in-situ* porosity was accounted for due to the retorting of the kerogen.

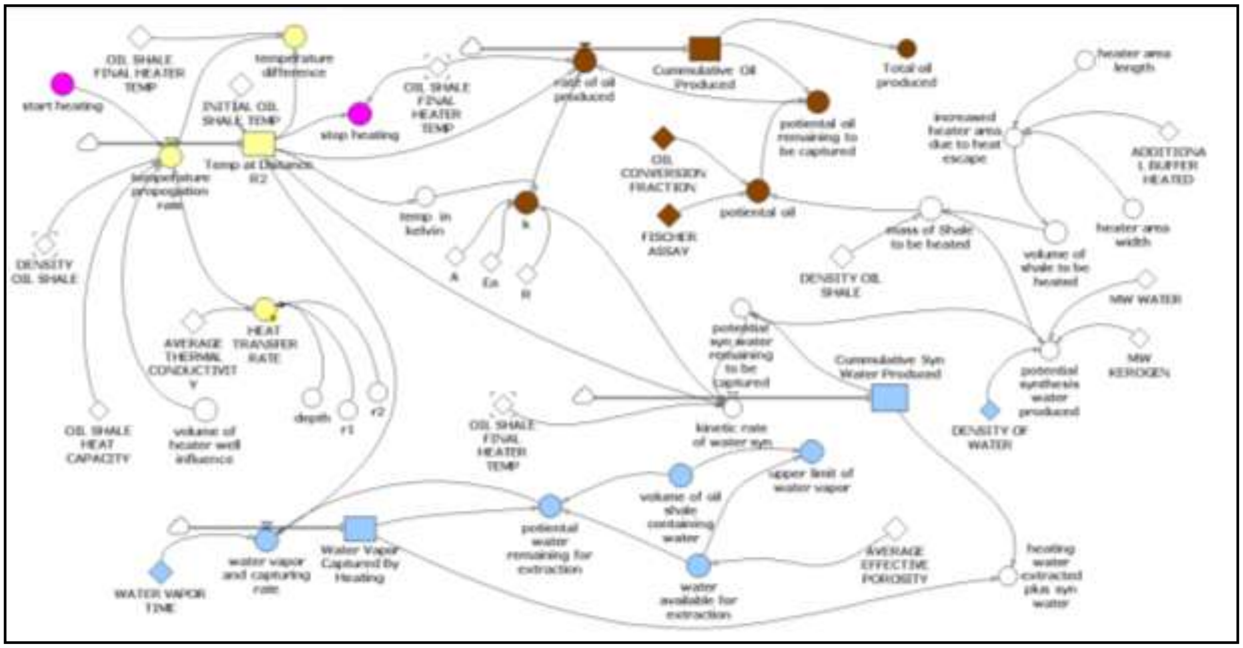

Figure 6. Operation phase model component of the in-situ oil shale example.

Summary

In many areas of the country shale gas development is rapidly growing. Hydraulic fracturing of shale typically injects two to four million gallons of water per well into the subsurface. Of this water, 10 to 70 percent is returned to the surface via flowback and produced water mechanisms. A predictive method is needed to assess the impact of the projected shale gas development on the local water resources in both quantity needed for the fracturing process and to develop adequate treatment plans for water to the surface.

System dynamic models offer a potential tool to assess water needs of the shale gas industry and allow its development to coexist with communities needs. The model components can be as simple or as sophisticated as necessary and tailored to the complexities of the development region. Some components will be based on operators' judgment. Other components will be based from engineering standards, thermodynamics, pilot scale tests, and the results from other processes models. These components when combined together, can describe the water consumption, losses, and returns to the surface for each hydraulic fracture as a function of time and scale. The model should be designed with the intent to be able to connect to GIS databases and other state regulatory management tools. Connecting to a GIS database will allow the models to access regional spatial data to support the model and allow its output to be effectively used in other tools to make water management decisions.

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