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Assessment of the current state of technology of water resource management in the Fayetteville Shale Gas region

Sustainable water resources are required for many industrial and agriculture applications in the Fayetteville Shale. While agriculture places the most demands on water in the Shale area, energy production also places significant demands on water resources. Water has competing uses. Water is used in producing energy and energy, in turn, is needed to produce water. Water is used in natural gas exploration and production for drilling fluids, dust suppression, cleaning and flushing and for hydraulic fracturing. Developing unconventional gas reservoirs like the Fayetteville Shale involve horizontal drilling and hydraulic fracturing. Hydraulic fracturing involves the pumping of a fracturing fluid under high pressure into a shale formation to generate fractures or cracks in the target rock formation. For shale gas development, fracture fluids are primarily water based fluids mixed with additives that help the water to carry sand proppant into the fractures. Water and sand make up over 98% of the fracture fluid, with the rest consisting of various chemical additives that improve the effectiveness of the fracture job. The amount of water needed to drill and fracture a horizontal shale gas well generally ranges from about 2 million to 4 million gallons, depending on the basin and formation characteristics. While these volumes may seem very large, they are small by comparison to some other uses of water, such as agriculture, electric power generation, and municipalities, and generally represent a small percentage of the total water resource use in each shale gas area. Calculations indicate that water use for shale gas development will range from less than 0.1% to 0.8% of total water use by basin. [1]

Produced water is water trapped in underground formations that is brought to the surface along with oil or gas. Because the water has been in contact with the hydrocarbon-bearing formation for centuries, it contains some of the chemical characteristics of the formation and the hydrocarbon itself. It may include water from the reservoir, water injected into the formation, and any chemicals added during the production and treatment processes. Produced water is also called "brine" and "formation water." [2]

After a hydraulic fracture treatment, when the pumping pressure has been relieved from the well, the water-based fracturing fluid, mixed with any natural formation water present, begins to flow back through the well casing to the wellhead. This produced water may also contain dissolved constituents from the formation itself. The dissolved constituents are naturally occurring compounds and may vary from one shale play to the next or even by area within a shale play. Initial produced water can vary from fresh (<5,000 ppm Total Dissolved Solids (TDS)) to varying degrees of saline (5,000 ppm to 100,000 ppm TDS or higher). The majority of fracturing fluid is recovered in a matter of several hours to a couple of weeks. In various basins and shale gas plays, the volume of produced water may account for less than 30% to more than 70% of the original fracture fluid volume. In some cases, flow back of fracturing fluid in produced water can continue for several months after gas production has begun. [3] Table 1 below shows how produced water is currently managed in the Fayetteville Shale region.

Table 1: Current Produced Water Management System in the Fayetteville Shale

Water Management Technology	**Availability**	**Comments**
Class II injection wells	Non-commercial	Water is transported to two injection wells owned and operated by a single producing company
Recycling	On-site recycling	For re-use in subsequent

		fracturing jobs

Source: US Department of Energy. Modern Shale Gas Development in the United States: A Primer

Water modeling[4]

The use of computers has provided the opportunity to better understand and assess our water resources through comprehensive numerical model simulations and testing of various schemes or options. A numerical model is a combination of an equation that represents physical structures and their hydraulic impact upon lake and stream flow. It allows the user to assess the hydraulic conditions in the basin and thus, establish a better understanding of human impacts upon a natural or modified river and lake system.

In terms of regulation modeling, the modeler can incorporate various user interests, as well as historical uses, to generate operating scenarios to verify the variations, alternatives of interest to the basin community, as well as the physical environment, that has been changed. Assessments of operating policy changes, impacts of floods, and changes in water quality are just a few examples where numerical models are used. Physically based models determine the flow and level changes that are currently being employed to determine the impact of man-made changes upon the river and its active biological community.

Steady-State and Dynamic (Transient) Models

Steady-state models assume constant discharges (flow, effluent), which very seldom occur in nature. However, the assumption of steady-state conditions is usually on the conservative side, especially in flood plain hydrotechnical studies. Advances in computer hardware and software are increasing the popularity of the more physically based dynamic (transient) models, which compute variable values as a function of time.

Expert Systems (ES)

ES is a special field of artificial intelligence, which is used in water management for decision-making. ES uses a collection of facts, rules of thumb, and other knowledge to help make inferences on how to deal with the water management problem under consideration. Expert systems differ substantially from conventional computer programs in that their goals may have no mathematical solution, and they must make inferences based on incomplete or uncertain information. They are called expert systems because they address problems normally thought to require human specialists for solution. Their success lies in their ability to analyze large amounts of information according to pre-established rules resembling the reasoning of a human expert or group of experts.

Hybrid Expert Systems

Hybrid expert systems are now appearing in water management modeling. These models are characterized by a heuristic database (intuitive data and information garnered from experts) and a combination of mathematically and physically based simulation and operational research techniques.

Examples of Hydraulics and Hydrology Models used in Managing Water Resources

1. **Agricultural Non-Point Source Pollution Model (AGNPS)**[5]
   AGNPS is a tool for use in evaluating the effect of management decisions impacting a watershed system. The input programs include: (1) a GIS-assisted computer program (TOPAZ with an interface to AGNPS) to develop terrain-following cells with all the needed hydrologic & hydraulic parameters that can be calculated from readily available DEM's. Included are procedures to associated management, soils, and climate shape files with the

derived AnnAGNPS cells. Additional features of the GIS interface provide ephemeral gully input information required by AnnAGNPS to describe the location of gully mouths and the associated input information for each gully; and (2) an Input Editor to initialize, complete, and/or revise the input data. Options are now available in the Input Editor to export and import files in a comma-delimited format for many of the data sections. This provides a convenient approach to developing input data sections in spreadsheet programs and then importing those into the Input Editor. Less description of how to use and more on what it does and why it is not completely relevant to FSP water issues
Outputs related to soluble & attached nutrients (nitrogen, phosphorus, & organic carbon) and any number of pesticides are provided. Water and sediment yield by particle size class and source are calculated. A field pond water & sediment loading routine is included for rice/crawfish ponds that can be rotated with other land uses. Nutrient concentrations from feedlots and other point sources are modeled.

2. **Windows Based Technical Release 20 (WinTR-20)** [6]
   The Computer Program for Project Formulation Hydrology (WinTR-20) is a single event watershed scale runoff and routing model. It computes direct runoff and develops hydrographs resulting from any synthetic or natural rainstorm. Developed hydrographs are routed through stream and valley reaches as well as through reservoirs. Hydrographs are combined from tributaries with those on the main stream. Branching flow (diversion) and baseflow can also be accommodated. WinTR-20 may be used to evaluate flooding problems, alternatives for flood control (reservoirs, channel modification, and diversion), and impacts of changing land use on the hydrologic response of watersheds.
3. **EFH2** [7]
   EFH2 is a computer program used to predict runoff volume and peak discharge from small single subarea watersheds. EFH2 predictions are based on design rainfall events associated with specific design rainfall intensity storm patterns, or distributions. **EFH2** is applicable to single subarea watersheds where: the watershed can accurately be represented by a single runoff curve number between 40 and 98; the watershed drainage area is between 1 and 2,000 acres; the watershed hydraulic length is between 200 and 26,000 feet; the average watershed slope is between 0.5 and 64 percent; no valley or reservoir routing is required; urban land use within the watershed does not exceed 10 percent and the rainfall is between 0.0 and 26 inches. How is swat better?

4. **Soil and Water Assessment Tool (SWAT)**[8]

   The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Arnold and Fohrer, 2005) has proven to be an effective tool for assessing water resource and nonpoint-source pollution problems for a wide range of scales and environmental conditions across the globe. In the U.S., SWAT is increasingly being used to support Total Maximum Daily Load (TMDL) analyses (Borah et al., 2006), research the effectiveness of conservation practices within the USDA Conservation Effects Assessment Program (CEAP) initiative, perform “macro-scale assessments” for large regions such as the upper Mississippi River basin and the entire U.S. (e.g., Arnold et al., 1999; Jha et al., 2006), and a wide range of other water use and water quality applications. Similar. SWAT application trends have also emerged in Europe and other regions of the world (UNESCO-IHE, 2007).

   The SWAT model is a continuation of 30 years of non-point source modeling. SWAT is a continuous time model that operates on a daily time step at basin scale. The objective of such a model is to predict the long-term impacts in large basins of management and also timing of agricultural practices within a year (i.e., crop rotations, planting and harvest dates, irrigation, fertilizer, and pesticide application rates and timing). It can be used to simulate at the basin scale water and nutrients cycle in landscapes whose dominant land use is agriculture. It can also help in assessing the environmental efficiency of best management practices (BMP's) and alternative management policies. SWAT uses a two-level disaggregation scheme; a preliminary sub basin identification is carried out based on topographic criteria, followed by further discretization using land use and soil type considerations. Areas with the same soil type and land use form a Hydrologic Response Unit (HRU), a basic computational unit assumed to be homogeneous in hydrologic response.

The overall hydrologic balance is simulated for each HRU, including canopy interception of precipitation, partitioning of precipitation, snowmelt water, and irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers. A storage routing technique is used to calculate redistribution of water between layers in the soil profile. Recharge below the soil profile is partitioned between shallow and deep aquifers. Return flow to the stream system and evapotranspiration from deep-rooted plants can occur from the shallow aquifer. Water that recharges the deep aquifer is assumed lost from the system.

5. **Water Erosion Prediction Project (WEPP)** [9]
   The Water Erosion Prediction Project (WEPP) is a computer simulation that predicts soil erosion. WEPP is a process-based, distributed parameter, continuous simulation, erosion prediction model. It is used to help land users understand and evaluate the impacts of land management practices on soil loss and sediment yields from their land. It is also used by scientists and others to inventory the amount of erosion which is occurring across agricultural regions, which provides information for developing national and regional soil conservation policy.
   WEPP is based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics. The WEPP erosion model is applicable at the field scale using input from the following areas: climate - this includes rainfall amounts, intensity, temperature; management - what management practices are done on the field including crops grown and soil disturbance operations; soil - soil properties; and topography - slope description including length, steepness of different sections, width, orientation.

Why SWAT

Design and construction practices used for oil and gas development may potentially alter the volume and intensity of water moving through the watershed making management practices critical to the preservation of sustainable water storages and fluxes. SWAT is designed to evaluate water runoff from various agricultural landscapes, but has never been applied for oil and gas assessments. However, SWAT has great potential for measuring combined and/or alternative practices comparatively for the development and production of oil and gas as well, given their similar characteristics and associated management practices. In addition, SWAT successful modeling efforts are due to the combination of the process based components and the geo-spatial features associated to them. SWAT is used as part of GIS frameworks (Di Luzio et al., 2004; Olivera et al., 2006) in which topography is considered the main water drainage force. Processing DEM data, a spatially explicit hydrological analysis is used to define the direction of water flow across the landscape and its surface slope. Finally, this adopted approach, which is supported by the data exchange and storage power of relational databases, allows for segmenting watersheds, defining and dimensioning composing hydro-geomorphic units (sub-basins, response units, streams, floodplains, etc.), and assigning to them the hydrologic attributes necessary for the simulations. Since simulations are time-continuous, using a daily time-step, the models can cover periods ranging from a few days to hundreds of years. The model input can include scheduled and scenario of management operations related to agricultural management practices, thereby paralleling similar events in oil and gas management operations (e.g hydraulic fracturing and produced water). Responses are returned for each identified computational unit at the same time resolution covering a complete range of landscape units. This means that any problem can be evaluated on both historical and recent inputs, and these inputs may be either from point or non-point sources. As such, the simulations using SWAT and the associated GIS technology, provide potential for responses across spatial and temporal scales related to oil and gas operations in a variety of water resources problems and related to the various stages of the operations, from the initial permit request through acquisition and production to final divestiture.

References

1. Modern Shale Gas Development in the United States: A Primer http://www.gwpc.org/e-library/documents/general/Shale%20Gas%20Primer%202009.pdf.
2. Veil, J., 2007, Testimony of John A. Veil, Argonne National Laboratory, Before the House Committee on Science and Technology Subcommittee on Energy and Environment Concerning: "Research to Improve Water-Use Efficiency and Conservation: Technologies and Practice"

3. US Department of Energy. Office of Fossil Fuel. National Energy Technology Laboratory http://www.gwpc.org/e-library/documents/general/Shale%20Gas%20Primer%202009.pdf
4. http://www.ec.gc.ca/water/en/manage/model/e_intro.htm
5. Natural Resources Conservation Service http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/tool_mod.html
6. ibid
7. ibid
8. S.L. Neitsch; J.G. Arnold; J.R. Kiniry; J.R. Williams; K.W. King (2002), "Soil Water Assessment Tool Theoretical Documentation"
9. United States Department of Agriculture. http://www.ars.usda.gov/Research/docs.htm?docid=10621
10. Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. J. American Water Resour. Assoc. 34(1): 73-89.
11. Arnold, J. G., R. Srinivasan, R. S. Muttiah, P. M. Allen, and C. Walker. 1999. Continental-scale simulation of the hydrologic balance. J. American Water Resour. Assoc. 35(5): 1037-1052.
12. Arnold, J. G., and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. Hydrol. Process. 19(3): 563-572.
13. Borah, D. K., G. Yagow, A. Saleh, P. L. Barnes, W. Rosenthal, E. C. Krug, and L. M. Hauck. 2006. Sediment and nutrient modeling for TMDL development and implementation. Trans. ASABE 49(4): 967-986.

14. Di Luzio, M., R. Srinivasan, and J. G. Arnold. 2004. A GIS-coupled hydrological model system for the watershed assessment of agricultural nonpoint and point sources of pollution. Trans. GIS 8(1): 113-136.
15. Jha, M., J. G. Arnold, P. W. Gassman, F. Giorgi, and R. Gu. 2006. Climate change sensitivity assessment on upper Mississippi river basin steamflows using SWAT. J. American Water Resources. Assoc. 42(4): 997-1015.
16. Mausbach, M. J., and A. R. Dedrick. 2004. The length we go: Measuring environmental benefits of conservation practices. J. Soil Water Cons. 59(5): 96A-103A.
17. Olivera, F., M. Valenzuela, R. Srinivasan, J. Choi, H. Cho, S. Koka, and A. Agrawal. 2006. ArcGIS-SWAT: A geodata model and GIS interface for SWAT. J. American Water Resour. Assoc. 42(2): 295-309.
18. UNESCO-IHE. 2007. 4TH International SWAT conference: Book of abstracts. Delft, Netherlands: United Nations Educational, Scientific and Cultural Organization, Institute for Water Education.