Model Verification

A mathematical model must be capable of simulating historical hydrologic events for which field data are available. A model is verified by comparing results to historical records. A transient response of the model is obtained and compared with a known transient condition in the aquifer. If the water levels through time and the locations and withdrawal rates from wells are known, the model should reproduce the known water-level changes. If the historical records are not reproduced to a desired degree of accuracy, the model parameters can be adjusted and the verification repeated. This process should eventually result in a verified model. Once the model has been verified against a transient event, it should be checked against the steady-state condition to ensure that it is still calibrated. Unfortunately, most mathematical models are not field verified, as this is time-consuming and expensive.

Limitations

While analytical modeling groundwater flow and transport of a single nonreactive contaminant in saturated porous media is a relatively simple process, it measures the mean of the average conditions. It is far more difficult to replicate exact conditions because the model parameters are by nature, averages over large areas. This makes calibration more difficult. Modeling becomes more complicated in aquifers of partial saturation, where there is fracturing or the existence of reactive contaminants, or if several mobile fluids are involved. Expert application of gridded numerical models allows much closer approximation to "real" conditions, especially with software that permits refinement of grid size and in some cases, shape.

Groundwater flow in fractured media is complex and can be difficult to predict at a given site unless extensive information is available about the fracture network. Recent research has made some advancement in the understanding of fracture and matrix flow in fractured media. Over-simplification, such as assuming that the effects of individual fractures will "average out," can produce errors, particularly when models are used in predicting the flow and movement of contaminants. However, long experience with extensively fractured aquifer media such as older North American mid-continent rock aquifers shows that they behave as quasi-porous media at the regional scale. At the well-field scale, defining structural influences (and certainly karstic features) is essential.

Modeling contaminant transport depends on the compound and its phase. Transportation of dilute, nonreactive aqueous phase solutes is well understood, with the exception of the effects of temporal and spatial variability within the aquifer. Studies indicate that real-world contaminant plumes have complex and difficult-to-predict three-dimensional structures in soils that are heterogeneous. Modeling reactive solutes is more complex because chemical rather than hydrologic process may govern the behavior and movement of plume.

It is easy, with modern software packages, to underestimate the task of aquifer modeling. This work should be conducted by qualified hydrologic modelers. Without a modeler's adequate understanding of the hydrogeologic setting, the groundwater system, chemical characteristics, and movement of contaminants, modeling results will provide uncertain predictions. Uncertainty in modeling includes

- numerical errors
- inability to precisely describe the natural variability of model parameters (e.g., hydraulic conductivity) from a finite and usually small number of measurement points
- inherent complexity of geologic and hydrogeologic processes over the long term

- inability to measure or otherwise quantify certain critical parameters (e.g., features of the geometry of fracture networks)
- conceptual deficiencies
- biases or measurement errors that are part of common field methods
- establishing values of controlling parameters such as velocity, effective porosity, diffusion coefficient, and dispersivity, which are difficult to measure or estimate because these features vary spatially

Because of these uncertainties, any single source of information should not be relied on when formulating regulations, evaluating water resources, cleaning up an aquifer, or protecting public health. The model provides results based on the conditions entered. Regulatory and groundwater protection have higher risks during more extreme conditions. Careful field work and confirmation of conditions are required to perform a quantitative and defensible assessment of the model's accuracy.

Applications

Properly applied models are useful tools to

- assist in problem evaluation
- conceptualize and study flow processes
- recognize limitations in data and guide collection of new data
- design remedial strategies
- provide additional information for decision making

Groundwater models are valuable tools that can be used to help understand the movement of water and chemicals in the subsurface. The results of model application are dependent on the quality of the data used as input for the model. Generally, site-specific data are required to develop a reliable model of a site. There are inherent inaccuracies and simplifying assumptions in the theoretical equations, the boundary and other conditions, and in the computer codes. Therefore, the results must be evaluated with other information about site conditions to make decisions about groundwater development and cleanup.

Federal and state or provincial and other regional agencies have guidelines that encourage the proper use of mathematical models. Some government regulations require modeling for long-term predictions of water resources and potential chemical migration. Models used in regulatory or legal proceedings should be available for evaluation to determine the application of the model to a particular site and quality of the model. Issues such as the extent to which equations describe the actual processes and the steps taken to verify that the code correctly solves the governing equations and is fully operational (i.e., code verification) should be considered.

Lists of published models are available that can be selected for a particular application and site. Government officials may be reluctant to accept a model that has not been approved previously by the agency. Getting governmental approval of an alternate model may be a lengthy process.

Published Mathematical Models

Many mathematical models have been developed, debugged, and applied to field situations. An existing appropriate model is more cost-effective than developing new models. Groundwater models do, and should, vary in complexity because of the variation in hydrogeology. While more complex models increase the range of situations that can be described, increasing complexity requires more input data, requires a higher level and range of skill of the modelers, and may introduce greater uncertainty in the output if input data are not available or of sufficient quality.

For more information on published models in the public domain and readily available, go to www.usgs.gov or www.epa.gov.

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Chapter 6

Well Pumps and Pumping

Pumps produce flow by transforming mechanical energy to hydraulic energy. Pump designs and applications are numerous, and energy specifications and ratings for pumps range from less than one to thousands of horsepower per pump. To understand pumps and how they work, understanding the basic terminology is helpful.

Capacity is the rate of flow delivered by a pump, in units such as gallons per minute, cubic feet per second, or barrels per hour. To calculate the power needed or the size of prime mover required to produce a desired capacity, the rate of flow and total dynamic head must be determined (Hicks and Edwards 1971; Jones 2006).

Dynamic head is resistance to flow produced by a system, equal to the sum of static head, velocity head, and friction head (Jones 2006).

- *Static head* is the sum of the static suction head and the static discharge head (Figure 6-1; Jones 2006). To calculate static head, all measurements in pumping are vertical and the maximum drawdown is used as a reference. Measurements above this level are positive; those below, negative. The same measuring procedure can be used for both submersible and surface-mounted pumps.
  - *Static suction head* is the vertical measurement, in feet, of the distance from the water level in a well to the pump centerline.
  - *Static discharge head* is the distance measured vertically from the pump centerline to the water level in storage.
  - *Velocity head* is the height through which a buoy must fall freely to attain its velocity. In most cases, the velocity head is small and can be ignored. Table 6-1 provides a way to determine velocity head.
  - *Friction head* is the loss of energy due to fluid motion along the inner surfaces of pipe and through fittings (Dougherty and Franzini 1977). With no change in

elevation, friction head is the amount of head necessary to push fluid through pipe and fittings at the required velocity. Table 6-2 can be used to determine friction head when various steel pipe sizes and different flow rates are used. Friction head loss through fittings must be included (Table 6-3). Head losses for fittings are expressed in equivalent feet of pipe (Dougherty and Franzini 1977). For example, the loss through a regular 4-in. 90° elbow is equivalent to the loss through 13 ft of 4-in. pipe at the measured flow rate.

To accurately calculate head loss, pressure expressed in pounds per square inch (psi) must be converted to pressure expressed in feet of head

$$\text{head, in feet} = \text{psi} \times \frac{144}{w} \qquad \text{(Eq. 6-1)}$$

Where:

w = specific weight, in pounds per cubic foot

The specific weight of water at temperatures less than 85° F is 8.34 lb/gal or 62.4 lb/ft^3; each foot of water causes a change in pressure of 0.433 psi. To change from feet of water to pounds per square inch, multiply by 0.433 or divide by 2.307. For example, the pressure in pounds per square inch at the bottom of a storage tank containing a 10-ft depth of water is

$$\begin{aligned} \text{pressure, in psi} &= 10 \times 0.433, \text{ or} \\ &= 10 \div 2.307 \\ &= 4.33 \text{ psi} \end{aligned}$$

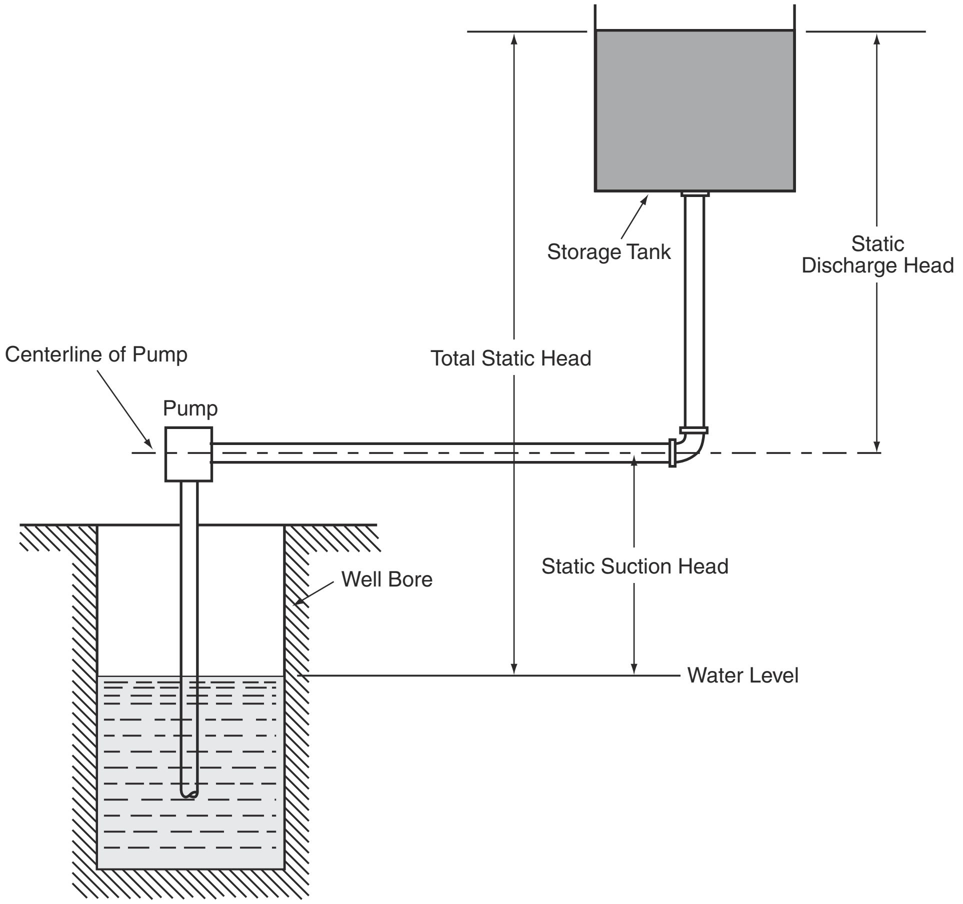

Figure 6-1 Schematic illustrating total static head

Table 6-1 Velocity-head data

Velocity (V) *fps*	Velocity Head (h_v)* *ft*	Velocity (V) *fps*	Velocity Head (h_v)* *ft*
1	0.02	11	1.87
2	0.06	12	2.24
3	0.14	13	2.62
4	0.25	14	3.04
5	0.36	15	3.49
6	0.56	16	3.97
7	0.76	17	4.44
8	1.00	18	5.03
9	1.25	19	5.61
10	1.55	20	6.21

*$h_v = V^2/2g$; g = acceleration due to gravity.

The net positive suction head (NPSH) is the amount of pressure that prevents water from vaporizing. The NPSH can cause cavitation (the formation and collapse of water vapor bubbles in the flowing water) and damage a pump. The required or minimum NPSH usually is stated by the pump manufacturer. The available NPSH is approximately equal to the distance from the eye of the pump impeller to the water level in the well while pumping. The available NPSH must be at least equal to the required NPSH to prevent cavitation. If necessary, the required NPSH can be satisfied by lowering the pump in the well.

PUMP CLASSIFICATIONS

Several types of pumps are used today. Only those pumps generally used to pump water from wells are described in the following sections. Table 6-5 at the end of this section (p. 152) provides a summary of the types of pumps discussed in this chapter.

Centrifugal Pump

The most important and most common pump for transmitting water from wells is the centrifugal pump (Driscoll 1986). A centrifugal pump uses centrifugal force to move a liquid through a change in elevation or against a total dynamic head. The pump consists of a suction nozzle, an impeller eye, an impeller (rotating element), a volute, and a discharge nozzle. As fluid is drawn through the suction nozzle to the impeller eye, rotation of the impeller gives the fluid a high-velocity radial motion. Centrifugal force throws fluid from the outer tips of the impeller into the volute or diffuser and into the discharge line.

In both volute and diffuser types of centrifugal pumps, velocity head and, consequently, pressure are developed entirely by centrifugal force. In the volute-type pump (Figure 6-2), the impeller discharges fluid into a gradually expanding case (Stewart 1977). The volute efficiently changes part of the velocity head of the fluid leaving the impeller to pressure head (Stewart 1977). In the diffuser-type pump (Figure 6-3), the impeller is surrounded by progressively expanding passages of stationary guide vanes. The diffuser pump does a more complete job of converting velocity head to pressure (Hicks and Edwards 1971), and consequently, is more efficient than the volute type.

Table 6-2 Friction loss for water in ft per 100 ft (Schedule 40 Steel Pipe)

	2 in.		2 ½ in.		3 in.		4 in.	
Flow *gpm*	*V* *ft/s*	h_f Friction	*V* *ft/s*	h_f Friction	*V* *ft/s*	h_f Friction	*V* *ft/s*	h_f Friction
25	2.39	1.29						
30	2.87	1.82						
35	3.35	2.42	2.35	1.00				
40	3.82	3.10	2.68	1.28				
45	4.30	3.85	3.02	1.60				
50	4.78	4.67	3.35	1.94	2.17	0.662		
60	5.74	6.59	4.02	2.72	2.60	0.924		
70	6.69	8.86	4.69	3.63	3.04	1.22		
80	7.65	11.4	5.36	4.66	3.47	1.57		
90	8.60	14.2	6.03	5.82	3.91	1.96		
100	9.56	17.4	6.70	7.11	4.34	2.39	2.52	0.624
120	11.5	24.7	8.04	10.0	5.21	3.37	3.02	0.877
140	13.4	33.2	9.38	13.5	6.08	4.51	3.53	1.17
160	15.3	43.0	10.7	17.4	6.94	5.81	4.03	1.49
180			12.1	21.9	7.81	7.28	4.54	1.86
200			13.4	26.7	8.68	8.90	5.04	2.27
220			14.7	32.2	9.55	10.7	5.54	2.72
240			16.1	38.1	10.4	12.6	6.05	3.21
260					11.3	14.7	6.55	3.74
280					12.2	16.9	7.06	4.30
300					13.0	19.2	7.56	4.89
350					15.2	26.1	8.82	6.55
400							10.10	8.47
450							11.4	10.65
500							12.6	13.0
550							13.9	15.7
600							15.1	18.6

NOTE: The table shows average values of pipe friction for new pipe. For commercial installations it is recommended that 15 percent be added to these values because no allowance for aging of pipe is included.

NOTE: Tables shown for Schedule 40 steel pipe are provided for example purposes only. For friction loss tables for other materials, consult the manufacturer.

Table continues on next page.

Table 6-2 Friction loss for water in ft per 100 ft (Schedule 40 Steel Pipe) (continued)

	5 in.		6 in.		8 in.	
Flow *gpm*	*V* *ft/s*	h_f Friction	*V* *ft/s*	h_f Friction	*V* *ft/s*	h_f Friction
160	2.57	0.487				
180	2.89	0.606				
200	3.21	0.736				
220	3.53	0.879	2.44	0.357		
240	3.85	1.035	2.66	0.419		
260	4.17	1.20	2.89	0.487		
300	4.81	1.58	3.33	0.637		
350	5.61	2.11	3.89	0.851		
400	6.41	2.72	4.44	1.09	2.57	0.279
450	7.22	3.41	5.00	1.36	2.89	0.348
500	8.02	4.16	5.55	1.66	3.21	0.424
600	9.62	5.88	6.66	2.34	3.85	0.597
700	11.2	7.93	7.77	3.13	4.49	0.797
800	12.8	10.22	8.88	4.03	5.13	1.02
900	14.4	12.9	9.99	5.05	5.77	1.27
1,000	16.0	15.8	11.1	6.17	6.41	1.56
1,100			12.2	7.41	7.05	1.87
1,200			13.3	8.76	7.70	2.20
1,300			14.4	10.2	8.34	2.56
1,400			15.5	11.8	8.98	2.95
1,500					9.62	3.37
1,600					10.3	3.82
1,700					10.9	4.29
1,800					11.5	4.79
1,900					12.2	5.31
2,000					12.8	5.86
2,100					13.5	6.43
2,200					14.1	7.02

NOTE: The table shows average values of pipe friction for new pipe. For commercial installations, it is recommended that 15 percent be added to these values because no allowance for aging of pipe is included.

Table continues on next page.

Table 6-2 Friction loss for water in ft per 100 ft (Schedule 40 Steel Pipe) (continued)

	10 in.		12 in.		14 in.	
Flow *gpm*	*V* *ft/s*	h_f Friction	*V* *ft/s*	h_f Friction	*V* *ft/s*	h_f Friction
650	2.64	0.224				
700	2.85	0.256				
750	3.05	0.294				
800	3.25	0.328				
850	3.46	0.368				
900	3.66	0.410	2.58	0.173		
950	3.87	0.455	2.72	0.191		
1,000	4.07	0.500	2.87	0.210	2.37	0.131
1,100	4.48	0.600	3.15	0.251	2.61	0.157
1,200	4.88	0.703	3.44	0.296	2.85	0.185
1,300	5.29	0.818	3.73	0.344	3.08	0.215
1,400	5.70	0.940	4.01	0.395	3.32	0.217
1,500	6.10	1.07	4.30	0.450	3.56	0.281
1,600	6.51	1.21	4.59	0.509	3.79	0.317
1,700	6.92	1.36	4.87	0.572	4.03	0.355
1,800	7.32	1.52	5.16	0.636	4.27	0.395
1,900	7.73	1.68	5.45	0.704	4.50	0.438
2,000	8.14	1.86	5.73	0.776	4.74	0.483
2,500	10.2	2.86	7.17	1.187	5.93	0.738
3,000	12.2	4.06	8.60	1.68	7.11	1.04
3,500	14.2	5.46	10.0	2.25	8.30	1.40
4,000	16.3	7.07	11.5	2.92	9.48	1.81
4,500			12.9	3.65	10.7	2.27
5,000			14.3	4.47	11.9	2.78
6,000			17.2	6.39	14.2	3.95
7,000					16.6	5.32
8,000						

NOTE: The table shows average values of pipe friction for new pipe. For commercial installations, it is recommended that 15 percent be added to these values because no allowance for aging of pipe is included.

Table continues on next page.