Chapter 2
Integrated Simulation of Interactive Surface-Water and Groundwater Systems

Varut Guvanasen and Peter S. Huyakorn

Contents

V. Guvanasen (✉) · P. S. Huyakorn
HydroGeoLogic, Inc., 11107 Sunset Hills Road, Suite 400, Reston, VA 20190, USA
e-mail: dguvanasen@hgl.com

P. S. Huyakorn
e-mail: psh@hgl.com

C. T. Yang, L. K. Wang (eds.), *Advances in Water Resources Engineering,*
Handbook of Environmental Engineering, Volume 14, DOI 10.1007/978-3-319-11023-3_2

Abstract Effective management of watersheds and ecosystems requires a comprehensive knowledge of hydrologic processes, and the ability to predict and quantify reliably the impacts due to anthropogenic or natural changes in water availability and water quality. For integrated water resources management studies in which both surface water and groundwater are interactive, a technically rigorous and physically based approach is essential. Simulation models have been used increasingly to provide a predictive capability in support of water resources, and environmental and restoration projects. Often, simplified models are used to quantify complex hydrologic and transport processes in surface and subsurface domains. Such models incorporate restrictive assumptions relating to spatial variability, dimensionality, and interactions of components in flow and transport processes. During the past decade, with the advent of high-speed personal computers, a number of rigorous integrated surface-water/groundwater models have been developed to circumvent these limitations. In general, a typical model of an integrated hydrologic system may be divided into three interactive and interconnected domains: subsurface, overland, and channels/streams, in which water flow and transport of constituents can occur. In this chapter, the following are presented and discussed: a description of relevant processes relating to water flow and solute transport in conjunction with governing equations for all domains; procedures for model development and calibration; and two field application examples.

Keywords Integrated surface-water/groundwater modeling · Flow simulation · Transport simulation · Model calibration

Nomenclature

A_{C}	Wetted cross-sectional area of the channel segment (L^2)
A_{GO}	Area at the interface between overland and subsurface (L^2)
A_{IJ}	Area through which mass influx passes from domain J to domain I (L^2)
a_L	Longitudinal dispersivity (L)
a_T	Transverse dispersivity (L)

a_{ijmn}	Dispersivity tensor (L)
B_{C}	Top width of channel (L)
b	Thickness of channel bed (L)
b	Fitting parameter (dimensionless) (Eq. 2.4c)
b_{IJ}	Distance between two centroids in domains I and J (L)
C_1, C_2	Fitting parameters (dimensionless) (Eq. 2.14b)
C_3	Fitting parameters (dimensionless) (Eq. 2.14c)
C^i	Solute concentration of species *i* (M/L^3)
C^{k}	Solute concentration of component *k* (M/L^3)
C_{d}	Weir discharge coefficient (dimensionless)
C_{int}	Canopy storage parameter (L)
$\hat{C}_k$	Concentration for species *k* vector for the transport equation
C_{B}^k	Specified concentration of solute *k* at the boundary (M/L^3)
C_{C}^{*k}	Solute concentration of component *k* of the sources (or sinks) within the channel domain (M/L^3)
C_{G}^{*k}	Solute concentration of component *k* of the sources (or sinks) within the subsurface domain (M/L^3)
C_I^k	Solute concentration of species *i* (M/L^3)
$C_{\mathrm{J^+/I^-}}^k$	Directionally dependent concentration of component *k* in domain J, if v_{IJ} is positive, in domain I if v_{IJ} is negative (M/L^3)
C_O^{*k}	Solute concentration of component *k* of the sources (or sinks) within the overland domain (M/L^3)
C_{O}^i	Reference solute concentration of species i (M/L^3) corresponding to Δo and ∴$_{\mathrm{o}}$
C_S^i	Solute concentration of species i (M/L^3) corresponding to ρ_S^i and μ_S^i
C_{s}^k	Concentration of component k adsorbed to the soil (M/Msoil)
D_{d}^k	Molecular diffusion coefficient for component *k* (L^2/T)
D_{IJ}^k	Effective dispersion coefficient of component *k* between domains I and J (L^2/T)
D_{ij}^k	Apparent hydrodynamic dispersion tensor of component *k* (L^2/T)
$D_{ij\mathrm{B}}$	Dispersion coefficient tensor at the boundary (L^2/T)
d	Flow depth (L)
d_{C}	Depth of channel flow (L)
d_{O}	Depth of overland flow (L)
E_{can}	Canopy evaporation (L/T)
E_{P}	Reference evapotranspiration (L/T)
F_{F}	Forcing vector for the flow equation
F_{T}	Forcing vector for the transport equation
f_{Str}	Structure discharge per unit length (L^2/T)
g	Gravitation acceleration (L/T^2)
H	Specified hydraulic head at the boundary at x_{iB} (L)
h	Reference hydraulic head (or equivalent freshwater head) (L) $= \dfrac{p}{\rho_o g} + x_3$
h	Overland hydraulic head or water surface elevation (L) $= \mathrm{d_O} + \mathrm{z_{LS}}$
h	Hydraulic head or water surface elevation of the channel (L) $= \mathrm{d_C} + \mathrm{z_C}$
$\hat{h}$	Hydraulic head vector for the flow equation
h_{C}	Head in the channel domain (L)

h_{d} Downstream head between the two systems (L)
h_{G} Head in the subsurface domain (L)
h_{O} Head in the overland domain (L)
h_{u} Upstream head between the channel and overland domains (L)
LAI Leaf area index (dimensionless)
L_{R} Effective root length (L)
l_{UStr} Upstream reference location of the structure (L)
l_{DStr} Downstream reference location of the structure (L)
K Leakance (1/T)
K^{C} Conductance term along the length of the channel (L^3/T)
K_{ij} Hydraulic conductivity or conductance (L/T) in Eqs. (2.1), (2.5a), and (2.6a)
K_{ij}^{G} Hydraulic conductivity tensor (L/T) $= \dfrac{k_{ij}\rho_{\mathrm{o}} g}{\mu_{\mathrm{o}}}$
K_{ij}^{O} Overland conductance tensor (L/T)
K_{F} Conductance matrix for the flow equation
$K_{\mathrm{GC}}^{\mathrm{eff}}$ Effective leakance across the interface area between channel and subsurface (1/T)
K_{GO} Leakance across the interface area between overland and subsurface (1/T)
K_{T} Conductance matrix for the transport equation
k_{ij} Intrinsic permeability tensor (L^2)
k_n Manning's conversion factor ($\mathrm{L}^{1/3}$/T)
k_{rC} Relative channel conductance (dimensionless)
k_{rG} Relative permeability (dimensionless) which is a function of water saturation as provided by the relative permeability curve
k_{rGC} Relative leakance at the interface between channel and subsurface (dimensionless)
k_{rGO} Relative leakance at the interface between overland and subsurface (dimensionless)
k_{rO} Relative overland conductance (dimensionless)
k_{Str} Structure operation coefficient (dimensionless)
L_{C} Length of channel segment (L)
l Length along the direction of flow (L)
M_{B}^{k} Dispersive mass flux of species k per unit area ($\mathrm{M/L^3\,T}$)
M_{F} Mass matrix for the flow equation
M_{T} Mass matrix for the transport equation
m_{IJ}^{k} Mass influx rate per unit area from domain J to domain I of component k ($\mathrm{M/L^2\,T}$)
N_{P} Number of parent chemicals of solute k (dimensionless)
n_{C} Manning's roughness coefficient for channel (dimensionless)
n_i Unit vector (dimensionless), positive inward
n_{ij} Manning's roughness coefficient tensor for overland flow (dimensionless)
n_{R} Number of cells that contribute to the total root zone for each areal location (dimensionless)
n_{RT} Number of cells that lie within the depth interval from 0 to L_{R} at any areal location (dimensionless)

n_s	Number of solutes (dimensionless)
P_C	Wetted perimeter of the channel segment (L)
P_P	Precipitation rate (L/T)
p	Fluid pressure (M/LT^2)
p_o	Reference fluid pressure (M/LT^2)
Q_B	Volumetric water flux per unit area (L)
Q_{CG}	Flux across the area of the interface from subsurface to channel (L^3/T)
Q_{GC}	Flux across the area of the interface from channel to subsurface (L^3/T)
Q_{GO}	Flux across the area of the interface from overland to subsurface (L^3/T)
Q_{OC}	Flux across the total length of channel banks to/from the overland flow domain (L^3/T)
Q_i	Discharge per unit width normal to the flow direction (L^2/T)
Q_{OG}	Flux across the area of the interface from subsurface to overland (L^3/T)
Q_{Str}	Discharge rate (L^3/T) of the structure as a function of head, h
q_C	Volumetric flux per unit volume (1/T) of the overland domain and represents sources and/or sinks of water
q_{CO}	Flux per unit volume of channel flow domain from the overland flow domain (1/T)
q_{CG}	Flux per unit volume of channel flow domain from the subsurface (1/T)
q_G	Volumetric flux per unit volume (1/T) of the subsurface domain and represents sources and/or sinks of water
q_{GC}	Flux per unit volume of subsurface from the one-dimensional channel domain $=-q_{CG}$ (1/T)
q_{GO}	Flux per unit volume of subsurface from the two-dimensional overland flow domain (1/T)
q_O	Volumetric flux per unit volume (1/T) of the overland domain and represents sources and/or sinks of water
q_{OC}	Flux per unit volume of overland flow domain from channel (1/T) $=-q_{CO}$
q_{OG}	Flux per unit volume of overland flow domain from groundwater (1/T) $=-q_{GO}$
$r_F(z)$	Root extraction function (dimensionless) which typically varies logarithmically with depth
S_b	Bed slope (dimensionless) at the zero-depth gradient boundary
S_e	Effective water saturation (dimensionless)
S_G	Degree of water saturation (dimensionless) and is determined by the moisture retention curve as a function of the pressure head
S_{Gr}	Residual water saturation (dimensionless)
S_{int}	Canopy storage (L)
S_{int}^{max}	Canopy storage capacity (L)
S_{int}^{o}	Previous time step canopy storage (L)
S_{int}^{*}	Intermediate canopy storage (L)
S_O	Equivalent sediment depth (L)
S_{Str}	Structure unit function (dimensionless), equals unity along the length when a hydraulic structure is present, 0 otherwise
s	Length along the direction maximum local slope (L)
T_{ij}^{*}	Tortuosity tensor (dimensionless)

T_{pI}	Rate of transpiration for computational cell I (L/T)
t	Time (T)
V	Magnitude of the velocity vector (L/T)
V_{G}	Subsurface elementary volume (L^3)
V_{I}	Normalization volume in domain I (L3)
v_{IJ}	Water flow rate per unit area from domain J to domain I (L/T)
v_i	Darcy velocity along the ith direction (L/T)
$v_{i\mathrm{B}}$	Specified fluid velocity at the boundary (M/L^3)
x_i	Cartesian coordinate along the ith direction (L) with x_3 being vertically upward
$x_{i\mathrm{B}}$	Boundary coordinates (L)
Z_{Bank}	Bank elevation (L) which may be at or above the overland flow surface elevation
z	Depth coordinate from the soil surface (L) (Eq. 2.14d)
z_{C}	Channel bottom elevation (L)
z_{LS}	Land surface elevation (L)
α	Fitting parameter (1/L), (Eqs. 2.4a and 2.4b)
α_{G}	Bulk compressibility of aquifer (L^2T^2/M)
β	Fitting parameter (dimensionless) (Eqs. 2.4a and 2.4b)
β_{w}	Fluid compressibility (LT^2/M)
I^k_{CInt}	Mass transfer rate of component k between the channel and other domains (1/T)
I^k_{GInt}	Mass transfer rate of component k between subsurface and other domains (M/L^3 T)
I^k_{OInt}	Mass transfer rate of component k between overland and other domains (1/T)
γ	$1-1/\beta$ (dimensionless; Eqs. 2.4a and 2.4b)
δ	Total density factor (dimensionless) $=\dfrac{\rho_{\mathrm{f}}-\rho_{\mathrm{o}}}{\rho_{\mathrm{o}}}$
$\delta(\bullet)$	Dirac delta function (1/L)
δ_{ij}	Kronecker's delta (dimensionless)
ζ	Distance along submerged channel cross section (L)
θ_{an}	Moisture content at anoxic limit (dimensionless)
θ_C	Effective porosity in the channel domain (dimensionless)
θ_{e1}	Moisture content at the end of the energy-limiting stage (above which full evaporation can occur; dimensionless)
θ_{e2}	Limiting moisture content below which evaporation is zero (dimensionless)
θ_{eG}	Effective porosity in groundwater domain (dimensionless)
θ_{fc}	Moisture content at field capacity (dimensionless)
θ_{G}	Subsurface porosity (dimensionless)
θ_{O}	Overland porosity (dimensionless)
θ_{o}	Moisture content at oxic limit (dimensionless)
θ_{wp}	Moisture content at wilting point (dimensionless)
λ^k_s	First-order decay coefficient for component k in soil (1/T)
λ^k_w	First-order decay coefficient for component k in water (1/T)

μ_f	Fluid dynamic viscosity (M/LT)
μ_o	Reference fluid dynamic viscosity (M/LT) corresponding to C_o^i
μ_S^i	Fluid dynamic viscosity of species i (M/LT) corresponding to C_S^i
ξ_{kj}	Fraction of parent component j transforming into component k (dimensionless)
ρ^C_f,	Fluid density (M/L^3) associated with q_C
ρ^{CG}_f,	Fluid density (M/L^3) associated with q_{CG}
ρ^{CO}_f,	Fluid density (M/L^3) associated with q_{CO}
ρ^G_f,	Fluid density (M/L^3) associated with q_G
ρ^{GC}_f,	Fluid density (M/L^3) associated with q_{GC}
ρ^{GO}_f,	Fluid density (M/L^3) associated with q_{GO}
ρ^O_f,	Fluid density (M/L^3) associated with q_O
ρ^{OC}_f,	Fluid density (M/L^3) associated with q_{OC}
ρ^{OG}_f,	Fluid density (M/L^3) associated with q_{OG}
ρ_B^C	Bulk density of sediment in the channel domain (M/L^3)
ρ_B^G	Bulk density of soil in the subsurface domain (M/L^3)
ρ_B^C	Bulk density of sediment in the overland domain (M/L^3)
ρ_f	Fluid density (M/L^3)
ρ_o	Reference fluid density (M/L^3) corresponding to C_o^i
ρ_S^i	Fluid density of species i (M/L^3) corresponding to C_S^i
ψ	Pressure head (L) $=p/(\Delta_o g)$

1 Introduction

As the global population grows, more demands are placed on one of the world's precious resources: water. With the rate of population increase of 70 million people per year, corresponding global water use is rising at an approximate rate of 30 billion m^3 per year [1]. Increased water demands give rise to global water stress. Causes that lead to global water stress include: excessive withdrawal from surface-water bodies, excessive withdrawal of groundwater from aquifers, pollution of freshwater resources, and inefficient use and management. Water resources consist of two integral systems, surface water and groundwater, both of which require rigorous management and protection. Groundwater in pristine aquifer systems usually requires little or no treatment before it is drinkable. However, if contaminated, these resources are expensive and difficult to remediate and restore. No less important is surface water in rivers, lakes, estuaries, and coastal systems, which is more visibly abundant. Surface water can have a strong impact on our everyday lives through flooding, transport, drinking water, etc. Surface-water and groundwater resources are interconnected. Baseflow in streams and rivers is derived from the contributing groundwater. Agricultural chemicals in surface water may enter into groundwater, which subsequently may emerge into streams. For these reasons, both groundwater and surface-water resources need to be protected and properly managed.

It is apparent that each water resource system is a set of interdependent water bodies and structures, each impacting on the state and performance of the others, and together contributing to the overall performance of the system [2]. There are many water resource problems that display a strong linkage between surface-water and groundwater systems. Therefore, understanding how surface-water levels are related to adjacent aquifer systems is crucial, for example, for the management of wetlands and river habitat restoration. Pollution of groundwater may influence surface-water resources and vice versa. Whether a river might flood at times of heavy rain or not will often depend on the surrounding groundwater levels. For these situations, it is desirable to consider surface-water and groundwater domains in an integrated manner and to develop appropriate tools to describe the interactions between the two domains. Therefore, water resources problems cannot be treated as isolated systems and it may be necessary to treat the entire water pathway, including overland, channel and river network, groundwater, and urban pipe and drainage systems. Those involved in the design and operation of each structure, which could be a reservoir, a diversion canal, a control structure affecting the input or output of a natural lake or wetland area, a hydropower plant, a groundwater extraction plant or an artificial recharge basin, a water or wastewater treatment plant, or a flood control levee, must examine the impacts resulting from those individual components in the system. Integrated water resource systems planning and management focus not only on the performance of individual components but also on the performance of the entire systems of components.

Computer modeling of both water resource systems has long been used as an aid to the planning and management of water resources. In 1969, Freeze and Harlan [3] proposed a blueprint for the digital modeling of the hydrologic cycle based on their assessment of the feasibility of the development of a rigorous, physically based mathematical model of the complete hydrological system. In this original blueprint, it was argued that if each of the component processes within the hydrological cycle can be described by an exact mathematical representation, then it should be possible to model the different flow and transport processes using their governing partial differential equations. Following this vision, there have been a number of models that attempt to simulate the interactions between surface water and groundwater.

Historically, groundwater and surface-water flow and transport processes were modeled separately, as their behaviors are represented by different mathematical equations and over very different time scales [4]. The interaction between them was usually taken into account as boundary conditions at respective interdomain interfaces. The simplest method, but also the least accurate, is by independently solving the surface and subsurface flow equations in succession without iteration [5, 6]. The next level of coupling is to solve the surface and groundwater flow and transport equations separately but iteratively at the same time step, interlinked by common internal boundary conditions representing the exchange between the surface and groundwater domains [7, 8]. Solution for the water flow and solute transport equations at a time step is achieved when the iteration errors fall within respective specified tolerances before the computation is advanced to the next time step. The highest level of coupling is realized by numerically solving all the flow and transport equations for surface water, groundwater, and the common internal boundary condition between the two as a set of simultaneous equations for each time step [4, 9–11]. Since this approach requires intensive computation efforts, restrictive assumptions relating to dimensionality and interaction of components of flow and transport processes were initially necessary. However, during the last decade, along with the advent of high-speed personal computers, a number of rigorous integrated surface-water/groundwater models have been developed to circumvent these limitations. This approach has been increasingly accepted and utilized by the technical community. Recent application examples reported in the literature based on this approach include: water resources evaluation and management in Florida [12], and western Australia [13]; and studies relating to the impact of water quality on water resources in Florida [14, 15], California [16], and China [17].

An integrated view of water resource systems takes into account a multitude of interactions between surface-water and groundwater components in both water quantity and quality aspects. The modeling approach described herein will attempt to address these interactions in a comprehensive and rigorous manner. In this chapter, in order to describe the flow and transport processes in a systematic manner, a typical integrated hydrologic system is divided into three interconnected domains in which flow and transport occur: the subsurface domain, the overland domain, and the channel domain. The following are presented and discussed: governing equations for the flow and transport processes in the integrated three domains; interdomain interactions; solution techniques, model development and calibration; and application examples.

2 Governing Processes and Equations

As shown Fig. 2.1, an integrated system consists of two interactive components: surface water and subsurface water. From the simulation consideration, the surface-water component is divided into two domains: stream/channel domain and overland domain. The flow and transport along streams/channels and overland are approximated by one-dimensional and two-dimensional processes, respectively. Below the ground surface is the subsurface domain. In this domain, there are two distinct but continuous zones: above the water table and below the water table. The zone above the water table is called the vadose zone (the unsaturated zone), and the zone below the water table is called the saturated zone (Fig. 2.2).

In this section, fundamental equations describing the flow and transport of water, and mass in an integrated subsurface and surface environment are described, along with boundary and initial conditions, interdomain communication, relevant process, and solution techniques. Derivation details of fundamental equations may be found in [18–21].

2.1 Flow

Flow equations for the three interactive domains are described below. The state variable that continuously spans over the three domains is hydraulic head, defined

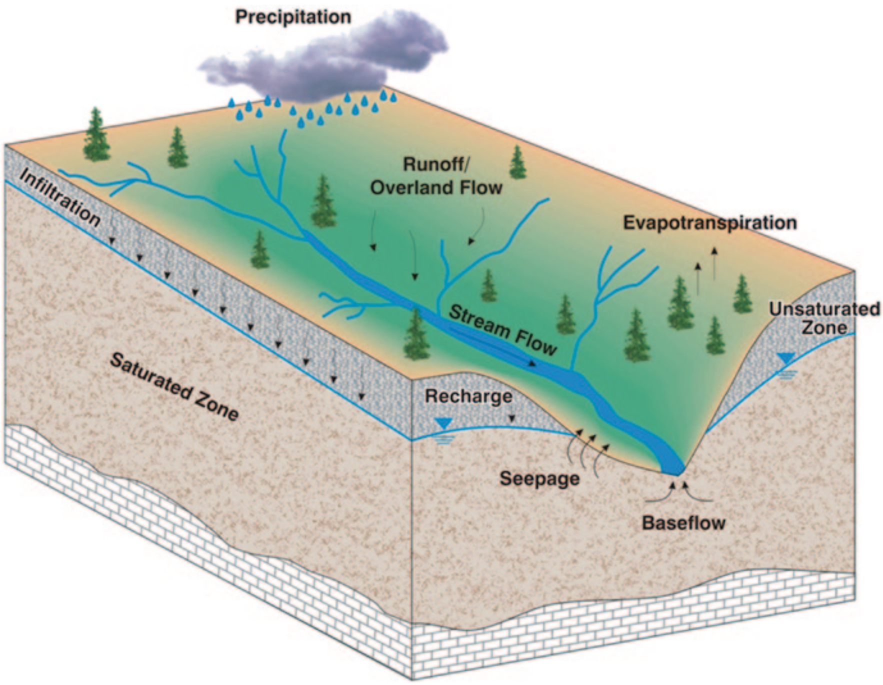

Fig. 2.1 Distribution, flow, and interaction of water on the land and in the subsurface

in the subsection below. Three capitalized prefixes and suffixes are: *G, O, and C* which denote the subsurface (groundwater), overland, and channel domains, respectively. For fluxes between any two domains, two letters are used. The domain of interest is determined by the first letter and the domain adjacent to it is denoted by the second letter. The flux is positive when the direction of the flux is from the adjacent domain to the domain of interest. As an example, *GO* indicates that the domain of interest is the subsurface domain and is communicating with the overland domain. In this case, the flux is positive from the overland domain to the subsurface domain. This convention is used throughout this chapter.

2.1.1 Subsurface Flow

In a variably saturated environment in the subsurface domain, isothermal flow may be expressed by the mixed form of the Richard's equation as (Adapted from Refs. [16, 18, 22]):

$$\frac{\partial}{\partial x_i}\left(\rho_{\mathrm{f}}\, k_{\mathrm{rG}}\, K_{ij}^{\mathrm{G}}\left(\frac{\mu_{\mathrm{o}}}{\mu_{\mathrm{f}}}\right)\frac{\partial\left(h+\delta x_3\right)}{\partial x_j}\right)=\frac{\partial}{\partial t}\left(\rho_{\mathrm{f}}\, S_{\mathrm{G}}\, \theta_{\mathrm{G}}\right)-\rho_{\mathrm{f}}^{\mathrm{G}} q_{\mathrm{G}}-\rho_{\mathrm{f}}^{\mathrm{GO}} q_{\mathrm{GO}}-\rho_{\mathrm{f}}^{\mathrm{GC}} q_{\mathrm{GC}} \quad (2.1)$$

http://www.springer.com/978-3-319-11022-6

Advances in Water Resources Engineering
Yang, C.T.; Wang, L.K. (Eds.)
2015, XXVIII, 556 p. 223 illus., 122 illus. in color.,
Hardcover
ISBN: 978-3-319-11022-6