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Readily Available Hydrologic Models: Pertinence to Regulatory Application

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PURPOSE: Water is the driving force of wetlands. Hydroperiod represents both the frequency and duration of inundation or soil saturation whether it is from flooding or ponding. The formation of hydric soils and an expression of hydrophytic vegetation are evidence of the hydroperiod, which can be described along a gradient of hydrologic conditions (Figure 1).

Hydrologic modeling provides a means to establish wetland hydroperiod, including current wetland hydrologic conditions and forecasting future conditions in response to future with and without wetland impacts or restoration actions. Today, fast computer processing and hydrologic models allow the user to make a large number of computations very rapidly on potentially large volumes of data. Currently, there is a myriad of hydrologic models available that offer an array of applications. For regulatory application, accurate determination of wetland hydrology is paramount to the following:

- Confirm wetland hydrologic criteria in accordance to the US Army Corps of Engineers Wetland Delineation Manual (1987 Manual) and Regional Supplements.
- Establish frequency and duration (hydroperiod) of wetland ponding and flooding.
- Conduct wetland functional assessments including identification of predominant water source(s).
- Estimate wetland impacts from regulated activities.
- Determine ecological lift in response to restoration actions (compensatory mitigation).
- Establish performance standards and success criteria for compensatory mitigation.
- Facilitate development of a monitoring and adaptive management plan.

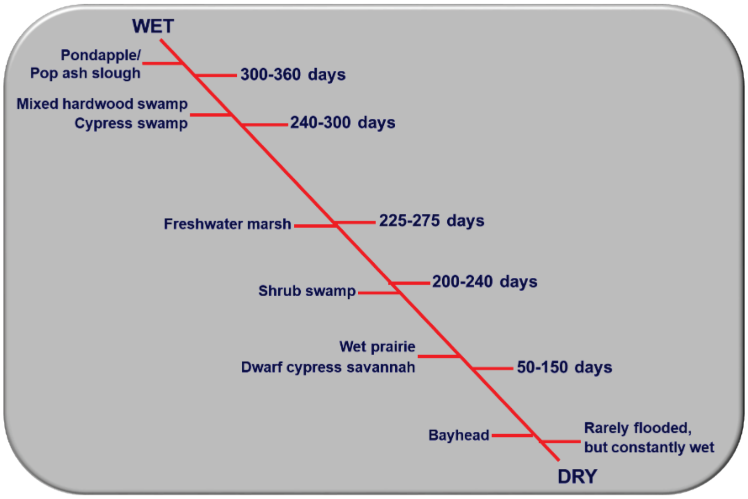


Figure 1. Wetlands distributed along a hydroperiod gradient depicting range of inundation and associated vegetation communities (from Duever [1989]).

The objective of this report is to provide a treatise of hydrologic models that offer specific application to establish wetland hydrology for existing and future conditions in response to regulated activities and restoration actions. The emphasis is on the suitability of existing hydrologic models to hydrogeomorphic (HGM) wetland classes. HGM subclasses are not addressed in this technical note. For more details on HGM classification, see Brinson (1993).

BACKGROUND: Wetland delineation is the process or procedure by which an area is determined to be a wetland or non-wetland (Environmental Laboratory 1987). Wetland delineations in the majority of cases are based on the presence of readily observable field indicators of hydrophytic vegetation, hydric soils, and wetland hydrology (USACE 2005). The 1987 Manual (Part IV, Section F, Atypical Situations) and associated Regional Supplements (Chapter 5) recognize that wetland delineations on some sites may be difficult because of human disturbance or natural events that may have altered or destroyed wetland indicators. In addition, some naturally occurring wetland types may lack indicators or may have indicators present only at certain times of year or during certain years in a multi-year cycle. Wetland delineations in these atypical and problem situations increasingly involve the use of direct hydrologic monitoring to confirm the presence of wetlands in cases where soils or vegetation have been significantly disturbed or are naturally problematic or where the hydrology of the site has been altered recently such that soil and vegetation indicators may give a misleading impression of the site's current wetland status.

APPLICATION OF HYDROLOGIC MODELS TO WETLAND CLASSES: The application of hydrologic models germane to a specific wetland class is, in part, the subject of this report. The first step in hydrologic modeling of wetlands is an accurate classification system. Wetland classification facilitates hydrologic modeling by identifying key model parameters characteristic of specific wetland classes which, in turn, reduces the variability that must be considered in model parameterization and the selection of an appropriate model.

Several classification systems have been published predominantly for stream ecosystems (Davis 1899; Matthes 1956; Lane 1957; Culbertson et al. 1967; Thornbury 1969; Khan 1971; Rosgen 1994). Classification systems developed by Cowardin et al. (1979 [reprinted 1992]) and Brinson (1993) are probably the most broadly accepted and used for wetland classification. Brinson's HGM classification was used in this report because its formative elements are directly related to wetland hydrology: geomorphic setting, predominant water source, and hydrodynamics. The geomorphic setting is the topographic location of the wetland within the surrounding landscape (Figure 2). Predominant water sources (hydrologic inputs) can include (1) direct precipitation, (2) surface water runoff (from upland sources), (3) surface water flow (from overbank flood events), and (4) groundwater discharge (usually through wetland sediments). Hydrodynamics refers to the mechanism of water delivery and the capacity of water to do work (move or carry sediment). It has both directional (e.g., one

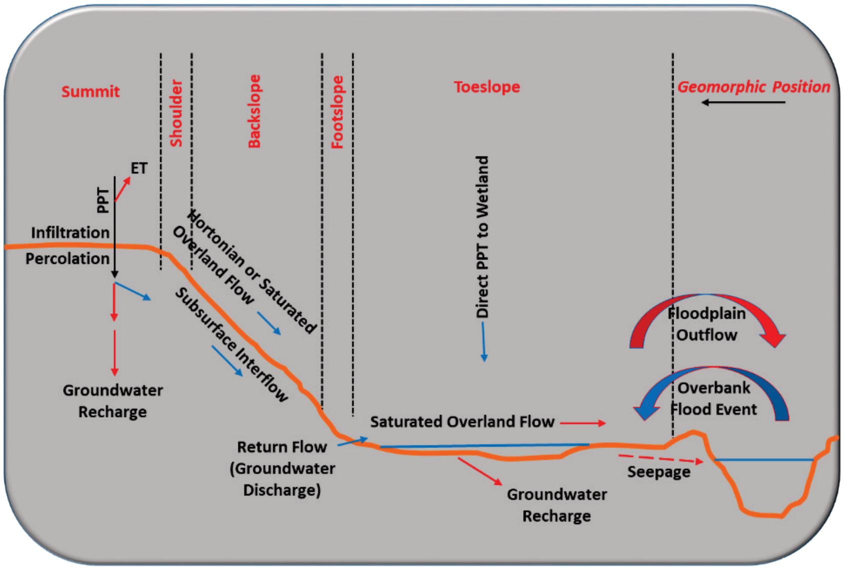
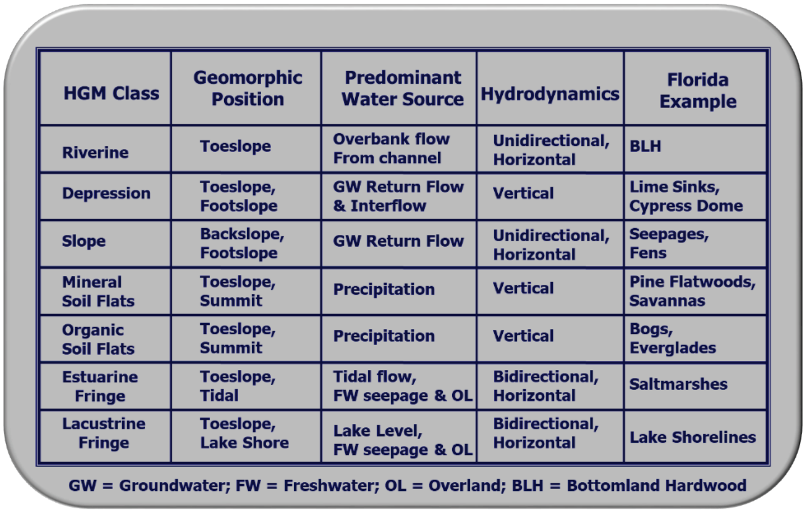


Figure 2. Hillslope catena across a backslope and valley flat depicting geomorphic position and flow vectors.

direction) and magnitude (e.g., velocity) components. As an example, fringe wetlands (shoreline of lakes and tidal influenced) are characterized with bi-directional flow. In contrast, floodplain wetlands associated with riverine systems are generally unidirectional flow unless the overbank event floods and recedes through a common side channel or similar back swamp feature. Generally, riverine floodplain wetlands, which are driven predominantly by overbank flood events, are dynamically high energy systems. Saltwater fringe wetlands (e.g., saltmarshes) can be highly energetic systems especially in coastal ecosystems where lunar-driven, tidal amplitude, and associated velocities are high. These fringe wetland are capable of processing and transforming nutrients and exporting large amounts of labile organic carbon. For a detailed treatise of wetland classification, see *A Hydrogeomorphic Classification for Wetlands* (Brinson 1993).

Wetland hydrologic models with broad applications should be robust enough to simulate the hydrology of various wetland classes (Figure 3). For example, the hydrodynamics of depressions is considered “vertical” as evidenced by the prevalence of precipitation and groundwater exchange with lateral movement of water making a minor contribution. Consequently, a hydrologic model is needed that provides an accurate depiction of rainfall and groundwater interactions. In contrast, slope wetlands exhibit unidirectional horizontal flow as its major hydrologic component. Consequently, a hydrologic model that accounts for hillslope processes is required (i.e., subsurface inflow, saturated overland flow, and return flow parameters). Saltwater fringe wetlands, which exhibit bidirectional flow, are characterized by regular tidal cycles that vary with lunar phases. Consequently, a hydrologic model that incorporates the variation of tidal amplitude in response to tidal cycles is preferred.



HGM Class	Geomorphic Position	Predominant Water Source	Hydrodynamics	Florida Example
Riverine	Toeslope	Overbank flow From channel	Unidirectional, Horizontal	BLH
Depression	Toeslope, Footslope	GW Return Flow & Interflow	Vertical	Lime Sinks, Cypress Dome
Slope	Backslope, Footslope	GW Return Flow	Unidirectional, Horizontal	Seepages, Fens
Mineral Soil Flats	Toeslope, Summit	Precipitation	Vertical	Pine Flatwoods, Savannas
Organic Soil Flats	Toeslope, Summit	Precipitation	Vertical	Bogs, Everglades
Estuarine Fringe	Toeslope, Tidal	Tidal flow, FW seepage & OL	Bidirectional, Horizontal	Saltmarshes
Lacustrine Fringe	Toeslope, Lake Shore	Lake Level, FW seepage & OL	Bidirectional, Horizontal	Lake Shorelines

GW = Groundwater; FW = Freshwater; OL = Overland; BLH = Bottomland Hardwood

Figure 3. Wetland types with core HGM classification components using Florida wetland ecosystems.

WETLAND WATER BALANCE: Prior to hydrologic model use, a practitioner should identify the wetland hydrologic inputs (inlets) and outputs (outlets) and develop a conceptual water budget (e.g., Wetbud described below). A conceptual water budget facilitates the selection of a hydrologic model suitable for the wetland class encountered (Figure 4). The components (inflows and outflows) of a water budget form the basis of wetland hydrologic model development.

Wetland water balance or budget generally refers to the relationship between input and output of water within a wetland area. The hydraulic and hydrologic processes of wetlands are directly related to the predominant water source or sources and the hydrodynamics of the flow of water into, within and out of the wetland. Furthermore, there is a direct correspondence between the hydrologic dynamism and wetland functions and processes (Brinson et al. 1995). The change in wetland hydrology or storage (ΔS) can be described by inputs and outputs generally over a specified time period (Figure 4 and Equation 1).

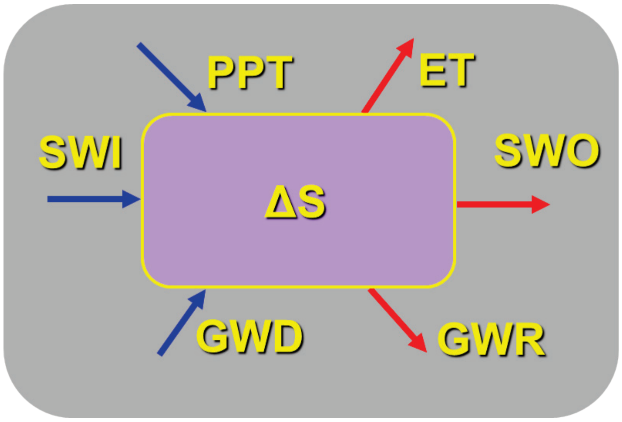


Figure 4. Wetland water balance depicting inputs (in blue) and outputs (in red).

$$\Delta S = \sum Inputs - \sum Outputs \tag{1}$$

$$\sum Inputs = PPT + SWI + GWD \tag{2}$$

$$\sum Outputs = ET + SWO + GWR \tag{3}$$

Wetland inputs may include precipitation (PPT), surface water inflow (SWI), and groundwater discharge (GWD) (Equation 2). PPT can enter wetlands either directly (rainfall or snowfall) or indirectly by overland flow or SWI or return flow from hillslope hydrologic processes or aquifer discharge (GWD). Herein, GWD is treated as any water sources that originate from the below the ground surface (i.e., the sum of return flow and aquifer discharge). Outputs may include evapotranspiration (ET), surface water outflow (SWO), and groundwater recharge (GWR) (Equation 3). ET is the sum of transpiration mediated by vegetation and evaporation off surfaces. ET is highest during daylight hours when plants transpire. In riverine systems, SWO can include direct surface water from the wetland/floodplain complex to the stream channel during stream stage recession. SWO can also include groundwater seepage through the soil matrix (generally the levee) to the stream channel (Figure 2).

GENERAL MODEL TYPES: There are two major types of models that are based on their ability to predict outcomes: mathematically deterministic models and probabilistic (stochastic) models. As the name implies, deterministic models are fixed and decisive such as y = f(x) where y can be predicted *completely* from x (i.e., y is a direct function of x). In reality, y cannot always be determined completely from x. Consequently, a probabilistic model is more appropriate. A pure probabilistic model predicts Y at random from a probability distribution of p(y) in the form Y ~ p(y). Models can be both deterministic and probabilistic. For example, a regression model, which can be represented in the form Y ~ p(y/x), states that for a given x, Y is predicted from a probability distribution. It is deterministic in that the value of x might be known. However, y is not predicted *precisely*. This fact is evidenced by the 95% confidence or prediction intervals that enclose the regression plot.

Depending on the application, one-, two- or three-dimensional models (1D, 2D, and 3D, respectively) should be selected (Table 1). The 1D models are steady or unsteady state approaches based only on channel cross-sections (depth averaged) and unidirectional flow. The 2D models are grid or mesh based, which extend 1D models across the floodplain or valley and can include braided or anastomosed channels, river meanders, and depositional bars with some depth-varied velocity. The 3D models are 2D models that include a structured or unstructured grid or mesh with a provision to flow around structures and vary velocity by depth.

Hydrologic models pertinent to wetlands should address horizontal (unidirectional and bidirectional hydrodynamics) and vertical flow (Figure 2). Horizontal flow includes surface water flow inflow and outflow (Figure 4). Unidirectional flow is surface water flow generally in one direction such as overbank flood events, overland flow, or down-valley flow. The energetics of unidirectional flow varies with slope or gradient across the wetland system. Bidirectional surface water flow occurs along lake shorelines or in response to lunar tidal cycles (e.g., salt marshes). Bidirectional hydrodynamics on lake shorelines can be generated by fluctuations in water level and by wind (secchi). Regular tides, especially semi-diurnal tides, dominate the energetics of salt marshes. Vertical flow refers to ground water exchange as depicted in Figure 4.

Model Selection Criteria. Hydrologic models can be extremely complex. With that complexity, complex and numerous parametric inputs are required that may not be accurate, and in some cases, not even available. In general, it is beneficial to select a model that is relatively simple but does not compromise accuracy or its ability to support regulatory decisions. When selecting or reviewing a model for appropriateness, several factors should be considered (Figure 5):

1. Has the model purpose been defined concisely, and is it appropriate for the regulatory decision?
2. Is the model capable of assessing various scenarios or alternatives supportive of the Section 404(b) (1) guidelines and the National Environmental Policy Act (1969) and the regulatory decision-making process?
3. Is the model capable of predicting (forecasting) future conditions with and without the regulated activity or compensatory mitigation action? Can it measure restoration progress and success?
4. Has the appropriate spatial scale for the model been identified? Scale issues include hydro-physiography/ecoregion, watershed position, hillslope position, and stream/wetland position?
5. Have the model boundaries (assessment area and watershed area) been clearly delineated (Figure 6)? Have existing conditions been adequately described?
6. Does the model account for watershed position that is important for hydrologic processes and functions such as desynchronization of stream flow, variation in stored alluvium, sediment transport and deposition, and flood hazard reduction downstream?

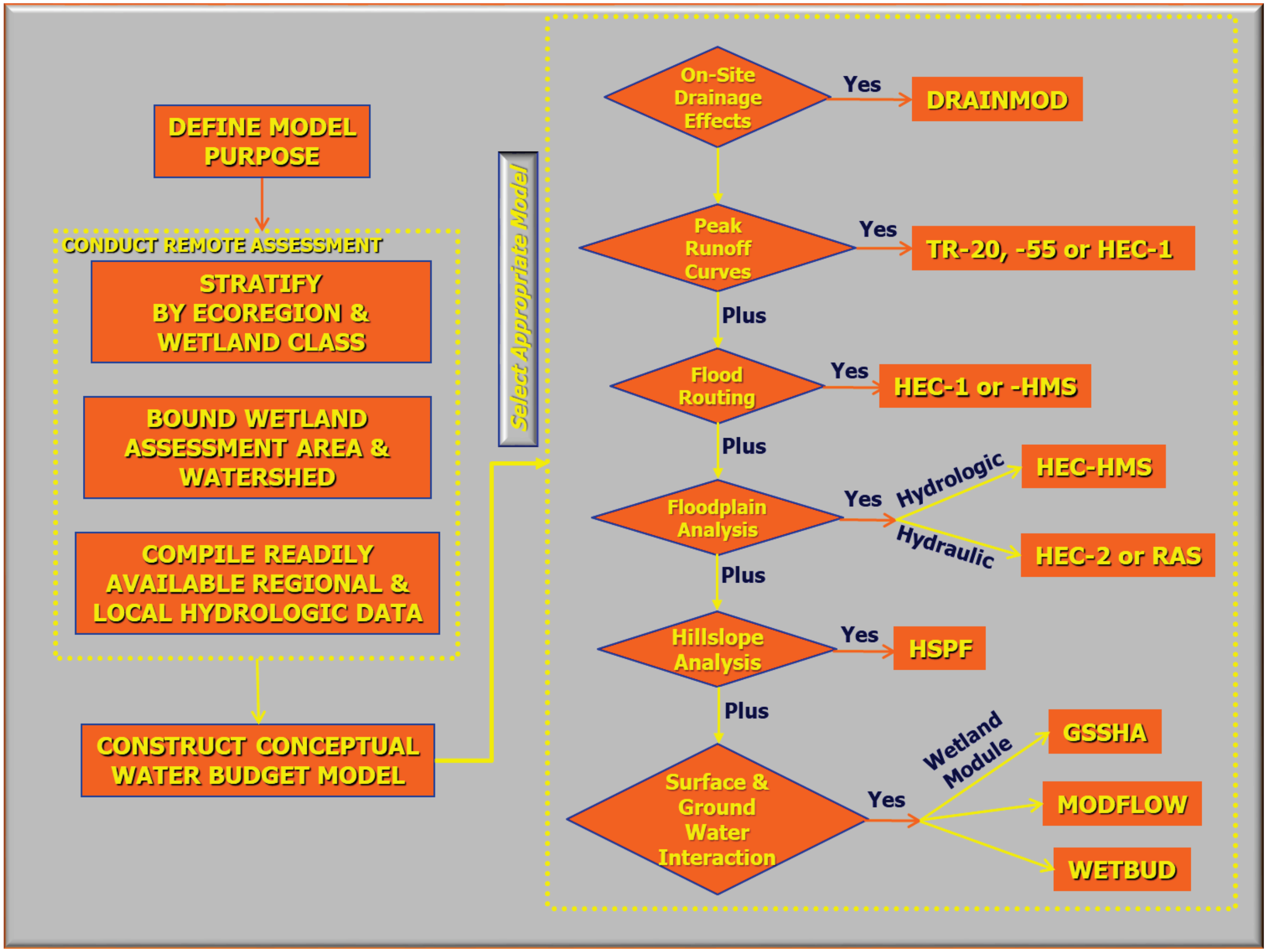


Figure 5. Model selection criteria. Hydrologic Engineering Center – Flood Hydrography (HEC-1); Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS); Hydrologic Engineering Center - River Analysis System (HEC-RAS); Hydrologic Simulation Program – Fortran (HSPF); Modular Finite-Difference Groundwater Flow Model (MODFLOW); Gridded Surface Subsurface Hydrologic Analysis (GSSHA);wetland budget (WETBUD).

Figure 6. Illustration of bounding the wetland assessment area and the contributing watershed (from Pruitt 2004).

7. Were hillslope hydrology sources included such as subsurface interflow, saturated overland flow, and return flow?
8. Is the model capable of assessing structural and non-structural features in the stream channel and wetland (e.g., channel stability (degradation versus aggradation), berms and levees, bridges and culverts)?
9. Can the model provide useful hydrologic information applicable to wetland functions and facilitate validation of those functions?
10. Can the model be used for performance standards and success criteria?
11. Is the model sensitive to seasonal variability, periods of drought and precipitation excess?
12. Level of Effort (LOE): What are the parametric input requirements? Are hydrologic data readily available? Are field measurements required? The LOE in Table 2 for each model was determined based on the following benchmarks: (1) number and data requirements for model inputs, (2) data availability, and (3) intensity of field data measurements. The LOE score was graded from 1 (low) to 3 (high) depending on the three criteria.

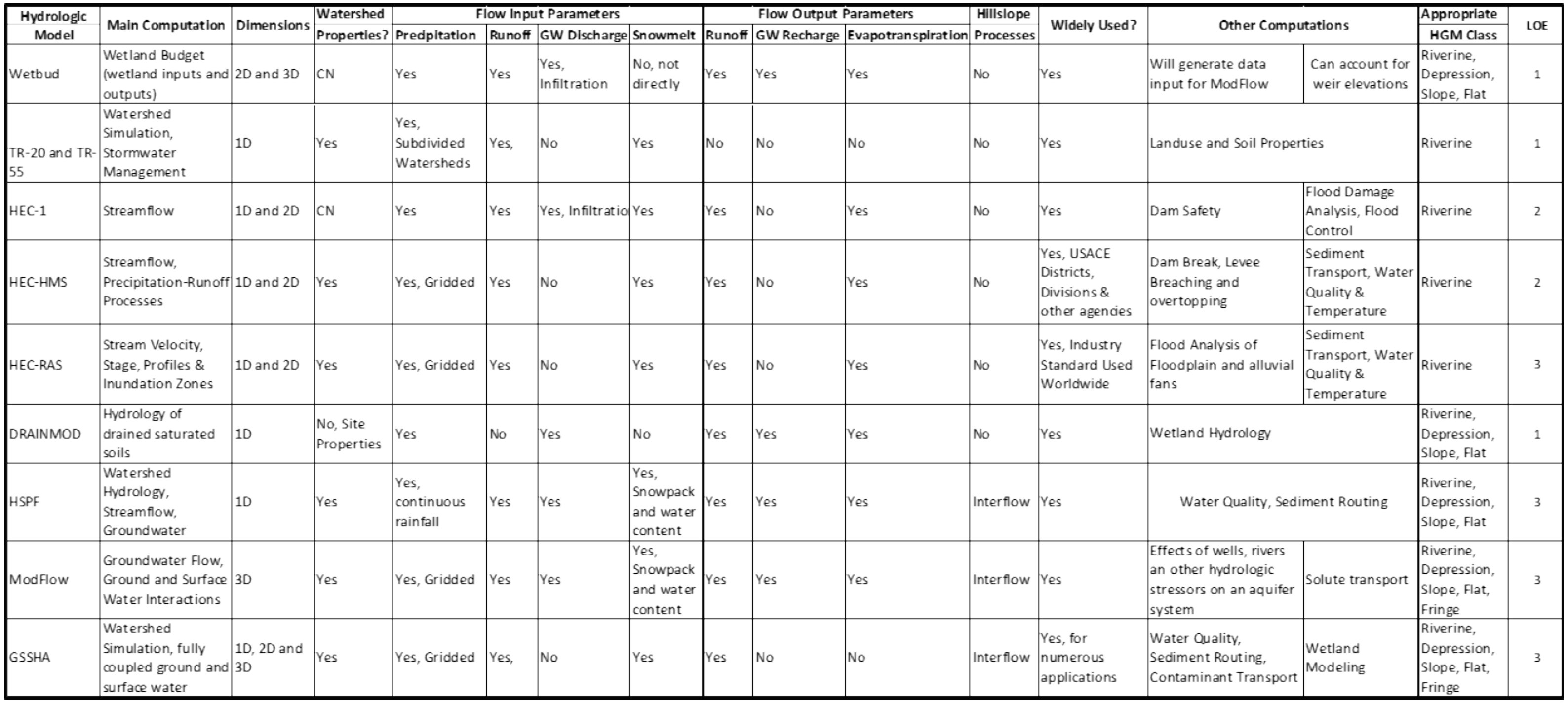
COMPARISON OF HYDROLOGIC MODELS: For comparison, the following models were selected based on their degree of efficacy in simulating and predicting wetland hydrology: Wetbud, TR-20 and TR-55, HEC-1, HEC-HMS, HEC-RAS, DRAINMOD, HSPF, MODFLOW and GSSHA (Table 2).

Wetbud. Wetbud (wetland budget), as the name implies, is a wetland budget program capable of utilizing hydrologic inputs as described above in the section on Wetland Water Balance. The model uses precipation, temperature, wind speed, dew point, and solar data to estimate evapotranspiration (Agioutantis et al. 2016). Parameters are included for water input and output time series data. Wetbud is applicable to both wetland restoration design and existing wetland hydrologic assessments. It makes available two versions: 2D and 3D formulations.

The model can be downloaded here: *http://www.landrehab.org/wetbud/*

TR-20 and TR-55 Methods. Developed by the Natural Resource Conservation Service (NRCS) in response to the need for stormwater management, the National Engineering Handbook described these methods. Technical release numbers 20 and 55 coincide with TR-20 and TR-55, respectively.

Table 2. Comparison of selected hydrologic models with pertinence to HGM wetland classes. CN = runoff curve number; GW = ground water; LOE = level of effort: The LOE score was graded from 1 (low) to 3 (high) based on three criteria: (1) number and data requirements for model inputs, (2) data availability, and (3) Intensity of field data measurements.



Hydrologic	Main Computation	Dimensions	Watershed	Flow Input Parameters				Flow Output Parameters			Hillslope	Widely Used?	Other Computations		Appropriate	LOE
Model			Properties?	Precipitation	Runoff	GW Discharge	Snowmelt	Runoff	GW Recharge	Evapotranspiration	Processes				HGM Class	
Wetbud	Wetland Budget (wetland inputs and outputs)	2D and 3D	CN	Yes	Yes	Yes, Infiltration	No, not directly	Yes	Yes	Yes	No	Yes	Will generate data input for ModFlow	Can account for weir elevations	Riverine, Depression, Slope, Flat	1
TR-20 and TR-55	Watershed Simulation, Stormwater Management	1D	Yes	Yes, Subdivided Watersheds	Yes,	No	Yes	No	No	No	No	Yes	Landuse and Soil Properties		Riverine	1
HEC-1	Streamflow	1D and 2D	CN	Yes	Yes	Yes, Infiltratio	Yes	Yes	No	Yes	No	Yes	Dam Safety	Flood Damage Analysis, Flood Control	Riverine	2
HEC-HMS	Streamflow, Precipitation-Runoff Processes	1D and 2D	Yes	Yes, Gridded	Yes	No	Yes	Yes	No	Yes	No	Yes, USACE Districts, Divisions & other agencies	Dam Break, Levee Breaching and overtopping	Sediment Transport, Water Quality & Temperature	Riverine	2
HEC-RAS	Stream Velocity, Stage, Profiles & Inundation Zones	1D and 2D	Yes	Yes, Gridded	Yes	No	Yes	Yes	No	Yes	No	Yes, Industry Standard Used Worldwide	Flood Analysis of Floodplain and alluvial fans	Sediment Transport, Water Quality & Temperature	Riverine	3
DRAINMOD	Hydrology of drained saturated soils	1D	No, Site Properties	Yes	No	Yes	No	Yes	Yes	Yes	No	Yes	Wetland Hydrology		Riverine, Depression, Slope, Flat	1
HSPF	Watershed Hydrology, Streamflow, Groundwater	1D	Yes	Yes, continuous rainfall	Yes	Yes	Yes, Snowpack and water content	Yes	Yes	Yes	Interflow	Yes	Water Quality, Sediment Routing		Riverine, Depression, Slope, Flat	3
ModFlow	Groundwater Flow, Ground and Surface Water Interactions	3D	Yes	Yes, Gridded	Yes	Yes	Yes, Snowpack and water content	Yes	Yes	Yes	Interflow	Yes	Effects of wells, rivers an other hydrologic stressors on an aquifer system	Solute transport	Riverine, Depression, Slope, Flat, Fringe	3
GSSHA	Watershed Simulation, fully coupled ground and surface water	1D, 2D and 3D	Yes	Yes, Gridded	Yes,	No	Yes	Yes	No	No	Interflow	Yes, for numerous applications	Water Quality, Sediment Routing, Contaminant Transport	Wetland Modeling	Riverine, Depression, Slope, Flat, Fringe	3

Due to their ease of use, they have been used broadly by engineers, hydrologists, and regulators. The methods have been used for watershed assessments and planning, flood insurance and flood hazard studies, reservoir design, and stream restoration projects. The methods were based on a single-event rainfall-runoff models (Fennessey et al. 2001). The methods use run-off curve numbers (CN) to estimate peak runoff rates. TR-55, which was used prior to the availability of fast computers, is a simpler, manual version of TR-20.

TR-20 and TR-55 generally require that the assessed watershed be subdivided into sub-watersheds of similar characteristics based on the identification of control points or model nodes located at a structure, diversion point, confluence of tributaries, or a flood-gauge location. CNs are defined by land use or cover types and soil mapped units to compute surface runoff from each sub-watershed.

The models can be downloaded here:

TR-20 - Hydrology Model – US Department of Agriculture (USDA)
http://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/WinTR20/WinTR-20_Setup_Version3.20.exe

TR-55 - NRCS - USDA
https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/hydrology/?cid=stelprdb1042925

Hydrologic Engineering Center – Flood Hydrography (HEC-1). HEC-1, which simulates precipitation-runoff processes, is capable of channel and reservoir routing and diversions. It is limited to a single event analysis, and backwater conditions are not provided. Model output is a computation of streamflow hydrographs at specified locations.

Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS). HEC-HMS, which simulates precipitation-runoff processes, is the most commonly used hydrologic model and has additional capabilities over its predecessor, HEC-1. For hydraulic modeling, HEC-HMS is used for the simulation of floods for impact assessment studies. It can also forecast streamflow, estimate depth-area reduction, and offer erosion and sediment transport and water quality components. HEC-HMS and HEC-RAS models have been integrated at a regional scale.

Hydrologic Engineering Center - River Analysis System (HEC-RAS). HEC-RAS, which is an updated version of HEC-2, is a hydraulic model capable of computing stream flow and water surface profiles including overbank flooding and flow through structures. It is also used for floodplain management for flood insurance. The main components of the model are the utilization of channel (and valley) cross-sections and Manning's values, which determine its accuracy. HEC-GeoRAS is an extension of ArcGIS and provides visual representation of stream flow and inundation zones.

HEC models can be downloaded from the USACE, Hydrologic Engineering Center:
https://www.hec.usace.army.mil

DRAINMOD. DRAINMOD is a process-based, distributed, field-scale model developed to describe the hydrology of poorly drained and artificially drained soils (Skaggs et al. 2012). It has been used widely to assess the effects of drainage systems on wetlands. However, it can also be used to describe the hydrology of wetlands that are undrained. Model parameters include weather data, soil properties, seepage dynamics, and drainage system properties.

DRAINMOD can be downloaded here:
https://www.bae.ncsu.edu/agricultural-water-management/drainmod/

Hydrologic Simulation Program – Fortran (HSPF). HSPF simulates for extended periods of time the hydrologic, and associated water quality, processes on pervious and impervious land surfaces and in streams and well-mixed impoundments (Bicknell et al. 1997). HSPF is capable of computing streamflow from continuous rainfall. HSPF simulates interception of soil moisture, surface runoff, interflow, baseflow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand, temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton.

HSPS can be downloaded here:
https://www.epa.gov/ceam/hydrological-simulation-program-fortran-hspf

Modular Finite-Difference Groundwater Flow Model (MODFLOW). MODFLOW, which is the most widely used groundwater model in the world, is capable of multi-dimensional simulations (USGS Fact Sheet, FS-121-97). It is capable of modeling exchange between surface and ground water systems including rivers, ephemeral streams, and reservoirs. It has been used extensively on the effects of groundwater withdrawals on water tables.

MODFLOW can be downloaded here:
https://www.usgs.gov/software/modflow-6-usgs-modular-hydrologic-model

Gridded Surface Subsurface Hydrologic Analysis (GSSHA). The principal purpose of the GSSHA is to model important watershed processes. GSSHA can be used as an episodic or continuous model where soil surface moisture, groundwater levels, stream interactions, and constituent fate are continuously simulated. The fully coupled groundwater-to-surface water interaction allows GSSHA to model basins in both arid and humid environments. The model is capable of computing flows, stream depths, and soil moisture and can account for hillslope processes (e.g., subsurface interflow and return flow). GSSHA is highly useable on Department of Defense installations to predict impacts of training operations. GSSHA 2.0 includes a new capability to model wetlands using two parts: conceptual and physical components.

GSSHA can be downloaded here:
https://www.gsshawiki.com/GSSHA_Download

CONCLUSIONS: In general, the kinetics of wetlands act to slow down the flow of water whether surface or subsurface flow, which supports a full suite of wetland functions including temporary and long-term water storage, biogeochemical cycling, nutrient removal and transformation, and expression of unique plant and animal habitat suited to wetland ecosystems.

Hydrologic models help define the problem and identify opportunities, elucidate the relationship between physicochemical and biological functions of an aquatic ecosystem, provide analytical tools to enhance data annotation and synthesis, enable comparisons between and across ecosystem types and physiography, accommodate communication in regards to hydrologic processes and functions across scientific disciplines, and describe important wetland values to the public.

All the hydrologic models evaluated have the capability of simulating wetland one-dimensionally at a minimum (Table 2). Wetbud, HEC-1, HEC-HMS, HEC-RAS, MODFLOW and GSSHA have 2D capabilities. Wetbud and GSSHA have advanced modules capable of 3D applications. In addition, GSSHA has a module specific to wetland hydrology simulation. With the exception of DRAINMOD, the models evaluated offer watershed-scale properties. The HEC models have been used extensively to simulate dam breaks, levee breaching and flood damage. In addition, HEC-HMS and HEC-RAS are capable of routing sediment and assessing water quality including temperature. ModFlow has been used to simulate the effects of groundwater withdrawal on surface and ground water hydrology. HSPF can simulate well-mixed rivers, reservoirs and 1D water bodies. However, it can be integrated with other models to solve more complex hydrologic and water quality applications.

With the exception of DRAINMOD, the hydrologic models evaluated have the capability to simulate overbank flood events in riverine settings. However, only four of the models, Wetbud, HSPF, MODFLOW, and GSSHA, provide for groundwater flow (e.g., recharge, interflow, and return flow), which is an important water source in headwater slope wetlands (Figure 2). GSSHA has been revised to include a routine for wetland modeling. MODFLOW is probably the best model for use when groundwater withdrawal is an issue. The HEC models are capable of computing stream flow and flood frequency.

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