The K2-RHEM-AGWA Suite of Modeling Tools–2023

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Abstract

The USDA-Agricultural Research Service's development of KINEROS and subsequently KINEROS2, dates back to the 1960s. Like any detailed, distributed watershed modeling tool, the K2 suite of tools require considerable time to delineate watersheds, discretize them into modeling elements and parameterize them. These requirements motivated the development of the Automated Geospatial Watershed Assessment (AGWA) tool (see: www.tucson.ars.ag.gov/agwa). AGWA is a GIS interface jointly developed by the USDA-Agricultural Research Service, the University of Arizona, the U.S. Environmental Protection Agency (EPA) and the University of Wyoming. AGWA automates the data synthesis, execution, and visualization of simulation results of a suite of hydrologic and erosion models (RHEM, KINEROS2, and SWAT) using nationally available data or user-provided input. The objectives of this paper are to: 1) Provide background on K2 and AGWA; 2) Provide an overview of the main features of K2 and AGWA tools; 3) Describe the development and expansion of snow modeling in detail; and 4) Discuss plans for future model improvements.

Introduction

The KINEROS2 (K2) and AGWA suite of modeling tools have been discussed in prior Joint Federal Interagency and SEDHYD conference papers (Goodrich et al. 2010; 2015; 2019). Therefore, abbreviated information on the background and development of K2 and AGWA will be presented herein. Greater emphasis will be given to describing the snow accumulation and melt routines incorporated into K2 and AGWA and a new version of RHEM.

KINEROS2 - KINematic Runoff and EROSion Model

The USDA-Agricultural Research Service's development of KINEROS and subsequently KINEROS2, dates back to the 1960s. KINEROS was formally released in 1990 (Woolhiser et al. 1990; Smith et al. 1995). The model simulates runoff, erosion, and sediment transport. The kinematic equations used for flow routing are coupled interactively with the Smith-Parlange infiltration equation. KINEROS and K2 represent a watershed as a collection of overland flow elements (planar, curvilinear, contracting, expanding) contributing to channels, as depicted in Figure 1. Representation of the watershed in this form enables solution of the flow-routing partial differential equations in one dimension, substantially reducing simulation time. KINEROS2, released in 2002 (Goodrich et al. 2002) includes an updated overall computational structure and additional model element types compared to KINEROS.

In addition to the overland flow and trapezoidal channel model element depicted in Figure 1, KINEROS2 includes the following additional model elements:

- Compound trapezoidal channel: Includes an overbank channel section with the capability of having different infiltration and roughness characteristics;
- Irregular channel cross-section: As might be derived from a ground survey or extracted from LIDAR-derived topography;
- Ponds/Detention Structures: Arbitrary shape, controlled outlet – discharge as a *f*(stage)
- Culverts/Pipes: Circular with free surface flow
- Injection: Hydrographs and sedigraphs injected from outside the modeled system or from a point discharge (e.g., pipe, drain)
- Diversion: Divert water and sediment from a single upstream element to as many as ten downstream elements;
- Adder: Summing the outflow from more than two upstream elements; and
- Continuous simulation with evapotranspiration.

A relatively thorough overview of the theoretical background of K2, including several applications, is presented by Semmens et al. (2008). Goodrich et al. (2012) provided further details on K2 and discussed model limitations, expectations, strategies, and approaches for K2 calibration and validation. K2 is public domain software that is distributed freely, along with associated model documentation and example input files (www.tucson.ars.ag.gov/kineros), tutorials. Additional versions of K2 have been developed for specialized applications. They include the KINEROS2-Opus2 (K2-O2) continuous model that can simulate biogeochemical nutrient cycling and plant growth under various types of management. The documentation and user manual for K2-O2 are available at https://www.tucson.ars.ag.gov/k2o2/doku.php. A flash flood forecasting version of K2 for a rapidly responding basin that ingests National Weather Service (NWS) Digital Hybrid Reflectivity (DHR) or Digital Precipitation Rate (DPR) radar products has also been developed (Unkrich et al. 2010). It has undergone testing by the NWS on 50+ watersheds in over a dozen NWS Weather Forecasting Offices (Schaffner et al., 2014; 2016; 2017) and is operational in 10+ watersheds in the southwest. Guber et al. (2010) used K2 as the runoff and routing tool to simulate the transport of indicators for organisms and manure-borne pathogens by coupling K2 to the Simulator of Transport With Infiltration and Runoff (STWIR - https://www.ars.usda.gov/northeast-area/beltsville-md-barc/beltsville-agricultural-research-center/emfsl/docs/environmental-transport/stwir/).

The Automated Geospatial Watershed Assessment (AGWA) Tool

AGWA (Miller et al., 2007) was developed to support the parameterization, execution, and visualization of simulation results of K2 and the Soil Water Assessment Tool (SWAT; Arnold and Fohrer, 2005) using GIS tools and geospatial data. AGWA was developed jointly by the USDA-ARS Southwest Watershed Research Center, the U.S. EPA Landscape Ecology Branch, the University of Arizona, and the University of Wyoming. The development of AGWA was undertaken with the following objectives: 1) that it provides simple, direct, transparent, and repeatable parameterization routines through an automated, intuitive interface; 2) that it is applicable to ungauged watersheds at multiple scales; 3) that it evaluates the impacts of management and be useful for scenario development; and 4) that it uses free and commonly available GIS data layers. Like K2, AGWA is public domain software available from the AGWA website (Miller et al. 2007; https://www.tucson.ars.ag.gov/agwa). AGWA is currently available as AGWA 1.5 for ArcView 3.x, AGWA 2.x for ArcGIS 9.x, and AGWA 3.X for ArcGIS 10.x. The AGWA website also contains documentation, supporting references, tutorials, training videos and a Google Groups support forum (https://groups.google.com/g/agwa-support). Support for K2 and AGWA is typically accomplished via the Google Group, e-mail, or phone.

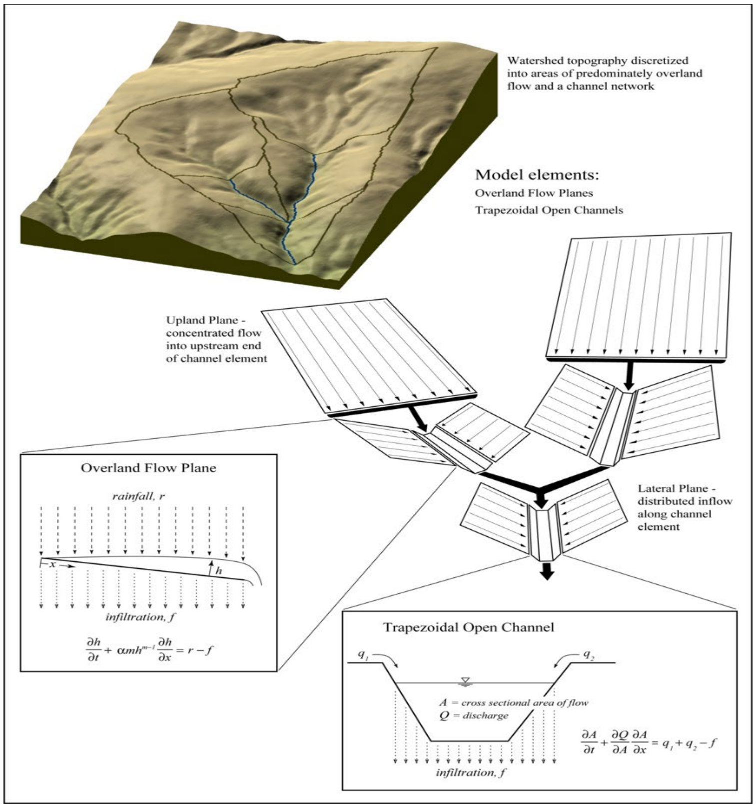

Figure 1. Abstraction of watershed discretized into KINEROS2 model elements (Goodrich et al., 2012).

To derive watershed model parameters with AGWA, descriptive geospatial data layers over the watershed of interest are required. These include raster-based digital elevation model (DEM) data, polygon soil data, and raster-based land cover/land use data. Soil data that are supported include NRCS SSURGO, gSSURGO, STATSGO, and FAO data. Land cover and land use data that AGWA supports include NLCD, NALC, GAP and LANDFIRE. Precipitation data is required to drive the model and can be input in several different formats.

The primary steps for conducting watershed modeling and analysis with AGWA are depicted in Figure 2 and include the following:

- Selection of a watershed outlet and delineation of the contributing watershed area
- Model selection and watershed discretization into model elements
- Watershed model element parameterization
- Precipitation input
- Model execution
- Change Analysis
- Results visualization.

AGWA intuitively guides the user through these steps. In addition to analyzing a single watershed, AGWA has an area of interest tool for multi-watershed analysis. During the delineation step AGWA will automatically fill the DEM if necessary and compute associated flow direction and flow accumulation rasters.

There are several options for *discretizing* the watershed into spatially distributed model elements. At this stage, the user selects whether K2 or SWAT will be used, as the two models conceptualize stream-contributing areas differently. Commonly used is the contributing source area (CSA) threshold. At this threshold, the head of a first-order channel is established. The CSA can be input as an area or a percentage of the total drainage of the watershed being analyzed. The second option is selecting a maximum hillslope flow length before stream initiation, and the third is using a pre-existing stream network. Using a pre-existing stream network does not guarantee the discretized streams will exactly match input streams, however using the hydro-enforced elevation rasters and streamlines in NHDPlus HR (https://www.usgs.gov/national-hydrography/nhdplus-high-resolution) for the delineation and discretization inputs ensures optimal agreement. A fourth case uses a point theme to define channel initiation points. In the third and fourth case, the upstream points of the existing stream network and the initiation points are snapped to the stream network defined by DEM flow accumulation.

In the *parameterization* step, the model element polygons are intersected with soil polygons and the land use/land cover raster. AGWA contains look-up tables (editable) that relate the land cover, soils, and topographic properties to necessary hydrologic parameters for each model element. These tables were developed based on prior studies (Woolhiser et al. 1990; Rawls et al. 1982, etc.), experimental data, and expert opinion. It should be stressed that model parameters derived from the look-up tables and channel geometry regressions should only be viewed as initial estimates. An interface is provided to provide multipliers to a subset of the more sensitive parameters that are applied uniformly across all model elements to facilitate simple manual calibration. As AGWA generates input files for K2 and SWAT it is relatively straightforward to link to external parameter estimation software.

To drive either K2 or SWAT, *precipitation inputs* must be defined. As SWAT is a continuous model, daily rainfall from one or more rain gauges is required. Daily precipitation and temperature files can also be generated from a nearby, user-selected weather station (weather stations are included in AGWA for the U.S.). With more than one gauge, AGWA will create Thiessen polygons intersecting with watershed elements to create area-weighted precipitation inputs. The current release version of K2 is also continuous (see below for more detail). For the event-based version, the user can input observed or user-defined hyetographs, design storms, or raster-based precipitation surfaces representing return period-durations depths. For NOAA design storms, intensity distributions defined by NRCS regional types can be selected.

Model execution also encompasses model simulation file creation. Simulation creation entails the selection of the files created in the previous steps. For example, between creation and execution the user may select parameter multipliers for K2. By separating creation and execution, the user can edit input files, apply the adjustments noted above, and rerun the simulation without repeating the prior processing steps in AGWA.

Change analysis is facilitated in AGWA by storing simulation results for all the model elements in flat files associated with the simulation. AGWA can difference results from multiple simulations and saves the outcome in terms of absolute change or percent change for a variety of model outputs for each model element. This capability is especially useful for scenario analysis, where the user can explore the hydrologic impacts of land cover change resulting from development or wildfires, changes in storm inputs, or the addition of ponds or constructed channel features.

Visualization maps of simulation results can be ported back into the GIS environment for selected output variables and for differences of output variables (absolute or percent change) between two simulations. A variety of outputs can be displayed for any upland or channel model element, including major water balance components and fluxes (e.g., peak runoff rate, runoff volume, sediment yield, etc.) This function enables the user to visualize the spatial variability of model results and readily identify problem areas where conservation or mitigation efforts might be focused (e.g. application of post-fire mulch to reduce erosion). For K2 simulations, hydrographs and sedigraphs can also be displayed.

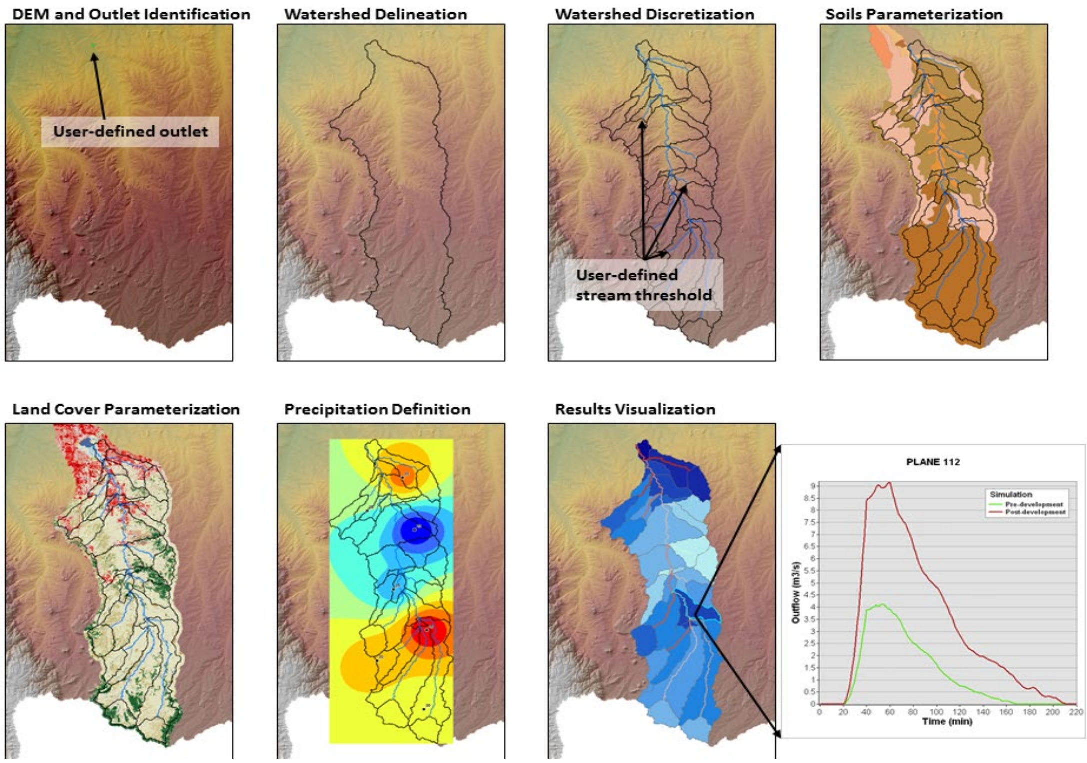

Figure 2. Primary steps in a watershed assessment using AGWA. Watershed delineation and subdivision into model elements using a DEM. Model elements are parameterized with soils, topography, and land cover layers. Precipitation drives the model, and spatially distributed results for each model element are imported and visualized in the GIS. Hydrographs and sedigraphs for any model element selected can also be displayed (Goodrich et al. 2015).

Specialized Tools Within AGWA: A number of tools within AGWA have been developed for various users to enable scenario analysis. These tools include:

- Land Cover Modification Tool
- Multi-Point and Multi-Watershed Tool
- Riparian Buffer Tool
- Post-Fire Assessment Tool (Guertin et al., 2019)
- Urban Tool (add-in to ArcMap; Korgaonkar et al., 2018)
- Channel Diversion – Artificial Wetlands Tool
- Military Disturbance Tool (Levick et al., 2019)
- Storage/Pond Characterization Toolbox (Guertin et al., 2019)
- Inundation Tool
- Facilitator Export Tool.

These tools are described in more detail in a prior paper from the 2019 SEDHYD conference (Goodrich et al., 2019)

Updates to RHEM – Release of Version 2.4

The Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al., 2011) was developed from experimental data collected explicitly on rangeland sites across the Western U.S. Runoff generation and erosion on the hillslope are modeled in response to hydrological inputs and hydraulic parameters that are adjusted based on intrinsic soil properties and land surface conditions. RHEM divides the hillslope into (1) splash and sheet detachment areas and (2) concentrated flow areas. Accurate partitioning of hillslope erosion into splash and sheet and concentrated-flow-dominated processes has a significant implication on rangeland erosion modeling, especially following disturbances. Several studies have demonstrated a considerable increase in concentrated flow erosion when shrub-dominated rangelands are disturbed by fire or woody species encroachment compared to undisturbed conditions (e.g Al-Hamdan et al., 2012; Pierson et al., 2013a, 2013b; Williams et al., 2016). Concentrated flow plays two interactive functions in generating soil erosion. First, it can act as a transport agent for sediments detached by rain splash and sheet flow. Second, it can become a soil detachment agent and sediment source. Hydraulics of concentrated flow plays a critical factor in both functions.

Historically, rangeland model parameterization of concentrated flow processes are based on studies conducted to describe concentrated flow hydraulics on croplands (e.g., Nearing et al., 1997). More recently efforts accelerated to develop physically-based overland flow erosion models that are specifically parameterized for rangelands (Nearing et al., 2011; Al-Hamdan et al., 2015). The current version of RHEM (v.2.4) uses the following equation developed by Al-Hamdan et al. (2012) to predict the concentrated flow width (w):

$$w = \frac{2.46Q^{0.39}}{S^{0.4}} \quad (1)$$

RHEM includes the dynamic erodibility concept based on the stream power to estimate concentrated flow erosion. The new approach has improved erosion estimates for concentrated flow erosion with an acceptable error range (Al-Hamdan et al., 2015). The model has integrated an equation developed by Al-Hamdan et al. (2012) to calculate K_ω for a broad range of undisturbed rangeland sites in which concentrated are active, but sediment availability is low (e.g., extensive bare ground, but limited loose sediments, long eroded sites, etc.). The model also has the capability to use equations developed by Al-Hamdan et al. (2012) for predicting maximum erodibility for a wide range of disturbed rangeland sites. This is needed in the case of abrupt disturbance (e.g., post-fire, instantly available sediment pulse) where concentrated flow is actively eroding and soil is not limited, with steep slope gradients (>20%) for soils with high silt content and exposed loose soil (Al-Hamdan et al., 2012).

Using data from rainfall simulator experiments conducted on rangelands with a wide range of characteristics, Al-Hamdan et al. (2013) showed that the formation of continuous concentrated flow paths at the plot scale positively correlates with flow discharge per unit width, slope, and ground cover. Using the same data set, they developed a logistic equation to estimate the probability of overland flow becoming concentrated on rangeland:

$$P = \frac{exp(-6.397+8.335S+3.252bare+3440q)}{1+exp(-6.397+8.335S+3.252bare+3440q)} \quad (2)$$

Where S is the slope (m m^{-1}), bare is a fraction of bare soil to total area (m^2 m^{-2}), and q is flow discharge per unit width (m^2 s^{-1}). Concentrated flow paths in RHEM are spaced in 1 m increments perpendicular to the hillslope angle. This means that concentrated flow paths are constantly formed, and the distance between each flow path is 1 m. Therefore, the interpretation of P becomes the probability that overland flow will be significantly highly erosive concentrated flow (Al-Hamdan et al., 2017).

RHEM v.2.4 is fully integrated into KINEROS2 and serves as the hydrology-erosion-sediment transport engine for overland flow hillslope model elements. RHEM v.2.4 is also available as a stand alone web service at https://dss.tucson.ars.ag.gov/rhem/. Documentation, training and tutorials, and related publications are also available at this website.

Development and Expansion of K2-RHEM-Snow

K2-RHEM-Snow, or simply RHEM-Snow, is designed to be run with the standard set of forcing inputs produced by the CLIGEN weather generator (daily inputs of precipitation, maximum and minimum temperature, dewpoint temperature, solar radiation, and wind speed). However, the model can also be run using other user-generated forcing datasets and an optionally incorporate long-wave radiation as well as precipitation inputs that are already partitioned between rainfall and snowfall. (though if not given, e.g. when using CLIGEN data, these quantities are generated internally in the model).

There is a single layer that encompasses most of the snowpack (except for a thin surface layer, which is used to compute energy fluxes to / from the atmosphere), as well as a shallow soil layer. Due to desired computational constraints of RHEM-Snow (daily forcing information from CLIGEN), the calculation of the snowpack energy balance is slightly simplified. It calculates all snowpack mass and energy balance terms, though the computation of energy balance is simplified (i.e., the snow surface temperature is an empirical function of air temperature, humidity, and net incoming radiation). The model also estimates changes in snow density, albedo, and canopy interception. In addition, there is a simple model for keeping track of the temperature / moisture in the top soil layer. RHEM-Snow, along with its documentation can also be downloaded at https://github.com/ARS-SWRC/RHEM-Snow, though the following sections also present a simplified version of the model formulations in RHEM-Snow.

1) Precipitation and Humidity

RHEM-snow can either incorporate already partitioned rainfall and snowfall, or it can separate the rainfall and snowfall based on air temperature. In that case, snowfall fraction is computed over a continus range of air temperatures, the lower limit of which is all snowfall and the upper limit of which is all rainfall. In addition to the rain-snow transition, there are standard expressions to compute vapor pressure, saturated vapor pressure, and, relative humidity.

2) Solar Radiation

Solar Radiation is given as a forcing input. However, RHEM-Snow also computes potential solar radiation for a particular location, including on inclined surfaces. This potential radiation is used for two purposes. First, if long-wave radiation is computed, the ratio given to potential flat-surface solar radiation is used to estimate a cloud fraction, which affects the computation of incoming long-wave radiation (see 'Long-wave Radiation' section below). Second, if solar radiation is adjusted for slope and aspect influences, given solar radiation values are multiplied by a solar forcing index computed for the inclined surface, where

$$SFI = {}^{R_s}/_{R_0} \qquad (3)$$

R_s is the potential solar radiation on the inclined surface and R_0 is the flat surface potential solar radiation. The potential solar radiation (both $R_0$and R_s) are computed using a computer code developed by Dr. Felix Hebeler, Dept. of Geography, University of Zurich, slightly modified to accept the slope-aspect conventions in RHEM-Snow, and to output daily solar radiation values. The code follows the approach of Kumar et al. 1997 (note that specific equations related to the algorithm can be found in that reference). It calculates clear sky radiation corrected for the incident angle (self-shading) plus diffuse and reflected radiation. There is also a user-adjustable parameter that applies a simple multiplier to the solar radiation (after any adjustments are made for slope and aspect) so the final downward solar radiation is computed as:

$$R_{sd} = R_{obs} \times SFI \times f_r \qquad (4)$$

where R_{obs} is the observed solar radiation, SFI, is the solar forcing index (from 1) and f_r is the user-defined multiplier.

3) Long-wave Radiation
If not given as a forcing input, incoming long-wave radiation is computed using the Stefan-Boltzmann equation:

$$R_{ld} = \varepsilon_a \sigma \mathrm{T}_a^{\ 4} \qquad (5)$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\, {}^{W}/_{m^2 K}$), T_a is the air temperature (in Kelvin), and ε_a is the effective emisivity from the sky. Emissivity is calculated as:

$$\varepsilon_a = CF + (1 - CF) \times \varepsilon_{acls} \qquad (6)$$

where CF is the cloud fraction, and ε_{acls} is the clear sky emisivity. Parameterization of clear sky emisivity follows Satterlund (1979):

$$\varepsilon_{acls} = 1.08\left[1 - exp\left(-\left(\frac{e_a}{100}\right)^{T_a/_{2016}}\right)\right] \qquad (7)$$

where e_a is the vapor pressure in Pa. Here, the cloud cover fraction is estimated from the Bristow and Campbell (1984) transmission factor;

$$CF = \left(1 - {}^{T_F}/_{a}\right) \qquad (8)$$

where the transmission factor, T_F, is calculated here as the ratio between observed and calculated clear sky solar radiation for the modeled location. a is a user-defined parameter.

4) Net Radiation and Albedo
Net Radiation is computed as:

$$R_n = R_{sd}(1 - \alpha) + R_{ld} - R_{lu} \qquad (9)$$

where R_{sd} is the incoming solar radiation, R_{ld} is the incoming long-wave radiation, R_{lu} is the outgoing long-wave radiation, and α is the snow albedo.

R_{lu} is calculated using the Stephan-Boltzmann equation:

$$R_{lu} = \varepsilon_s \sigma \mathrm{T}_s^{\ 4} \qquad (10)$$

where ε_s is the snow emissivity (0.99), σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\, {}^{W}/_{m^2 K}$), and T_s is the snowpack temperature. Due to the computational constraints of the model, rather than iteratively solving the energy balance, surface snow temperature is estimated using an empirical equation based on air temperature, relative humidity and net incoming radiation, fitted to data from field sites in Arizona which has detailed measurements of radiation components and surface temperature.

5) Sensible and Latent heat
Sensible heat flux when the temperature is computed as:

$$Q_h = K_h \rho_a c_p (T_s - T_a) \qquad (11)$$

Here, c_p is the air-specific heat capacity ($1005\ \frac{J}{kg°K}$), K_h is the sensible heat conductance, ρ_a is the air density, T_a is the air temperature, and T_s is the snow temperature.

The variation of ρ_a, the air density with elevation, is estimated because air pressure is not given. ρ_a is calculated as:

$$\rho_a = \frac{P}{R_d T_a} \qquad (12)$$

Where pressure is estimated to be:

$$P = P_0 \times \exp\left(-\frac{gz}{R_d T_0}\right) \qquad (13)$$

Here, R_d, the specific gas constant for dry air is 287.058 $\frac{J}{kg°K}$, g, the acceleration due to gravity, is 9.81 $\frac{m}{s^2}$, and $T_0 = T_a + (L \times z)$, L is an estimated lapse rate (6.5 $\frac{°K}{km}$), P_0 is standard sea level pressure (101.325 kPa), and z is the elevation.

The latent heat flux is computed as:

$$Q_e = K_e \frac{0.622 \times h_v}{R_d \times T_a}(e_a - e_s(T_s)) \qquad (14)$$

where K_e is the latent heat conductance, $e_s(T_s)$ is the saturated vapor pressure at the snow surface, e_a is the air vapor pressure, R_d is the dry gas constant, h_v is the latent heat of sublimation (2834 kJ/kg).

6) Heat from Precipitation

Heat from precipitation considers heat from rainfall and snowfall separately (assuming that rainfall temperature is the maximum of air temperature and freezing temperature, and snowfall temperature is the minimum of air temperature and freezing temperature):

$$Q_p = P_s C_s \rho_w \min(T_a, 0) + P_r\left[h_f \rho_w + C_w \rho_w \max(T_a, 0)\right] \qquad (15)$$

P_s is the snow rate, P_r is the rain rate, C_s is the specific heat of ice (2.05 $\frac{kJ}{kg-K}$), C_w is the specific heat of water (4.181 $\frac{kJ}{kg-K}$), ρ_w is the density of water (1000 $\frac{kg}{m^3}$), and h_f is the latent heat of fusion (334 $\frac{kJ}{kg-K}$).

7) Ground Heat

Ground heat flux is given by:

$$Q_g = -k\frac{dT}{dz} \qquad (16)$$

k is the snow/soil thermal conductivity, dz is the distance between the damping depth, and the middle of the snowpack, and dT is the temperature difference between the damping depth, and the middle of the snowpack. At this point, snow/soil thermal conductivity, damping depth, and temperature at damping depth are user defined parameters.

8) Melt and Snowpack Mass and Energy Balance

RHEM-Snow computes potential melt energy based on energy contributions of other energy balance terms:

$$Q_m \times dt = -\max\left(0, cc + \left(Q_n + Q_h + Q_e + Q_p + Q_g\right) \times dt\right) \qquad (17)$$

Here, Q_n is the net radiation, Q_h is the sensible heat, Q_e is the latent heat, Q_p is the precip heat, Q_g is the ground heat, dt is the model timestep, and cc is the cold content.

Melt mass flux is computed as:

$$M = -\frac{Q_m \times dt}{\rho_w \times h_f} \qquad (18)$$

Melt is limited such that it cannot exceed SWE (note that the energy flux is also limited). RHEM-Snow does not account for the liquid holding capacity of water, so this melt is immediately removed from the snowpack. The resulting mass balance of the snowpack is:

$$\frac{dSWE}{dt} = P_s + P_r - E - M \qquad (19)$$

where P_s is snowfall (which includes both throughfall and unloaded snow, if under canopy), P_r is rainfall (which includes both rain and drip from the canopy), E is sublimation, and M is snowmelt.

The energy balance is:

$$\frac{dcc}{dt} = Q_n + Q_h + Q_e + Q_g + Q_m \qquad (20)$$

Where cold content is limited so that in a given timestep, the bulk snowpack temperature cannot be colder than the snow surface temperature. Note that if there is an imbalance, then excess heat is added to the sensible heating term.

9) Canopy Interception

Canopy interception is calculated from:

$$I_t = I_{t-1} + 0.7(I_{max} - I_{t-1})\left(1 - \exp\left({}^{S}/_{I_{max}}\right)\right) - u - e - d \quad (21)$$

where I_t is the intercepted snow for the current timestep, I_{t-1} is the intercepted snow for the previous timestep, S is the snowfall, I_{max} is the maximum interception capacity, u is the snow unloading rate, e is the canopy sublimation rate, and d is the melt-drip rate. The maximum interception capacity is given by (Hedstrom and Pomeroy 1998):

$$I_{max} = 4.4LAI \quad (22)$$

where LAI is the total leaf area index (that includes stems, leaves, and branches). The term for new snow interception ($0.7(I_{max} - I_{t-1})\left(1 - \exp\left({}^{S}/_{I_{max}}\right)\right)$) is based on formulations from Liston and Elder, 2006.

10) Snow Density

Snow density in RHEM-Snow is given by:

$$\rho_t = \max\left[\rho_i, \min\left[\rho_{max}, (1-f)\times\rho_{t-1} + f\times\rho_i + d_s + d_s + d_l\right]\right] \qquad (23)$$

Here, ρ_t is the snow density for the current timestep, ρ_{t-1} is the snow density for the previous timestep, ρ_i is a user-definable parameter representing the density of new snowfall, ρ_{max} is the maximum allowable snow density, f is the fraction of pack that is contributed by new snowfall ($f = \frac{d_n}{d_t}$, where d_n is the new snow depth, and d_t is the total snow depth (including new snowfall). d_s is the densification due to overburden.

11) Near Surface Hydrology Model

After the rainfall and snowmelt are combined, it is infiltrated into the soil. Infiltration runoff is computed as

$$R_i = NWI \times F_m \times (\max(0, SM - SM_{\mathrm{i,min}})/(SM_{\mathrm{i,max}} - SM_{\mathrm{i,min}}) \quad (24)$$

where NWI is the net water input, F_m is the maximum possible fraction of infiltration excess runoff (e.g. at saturated conditions), SM is the soil moisture content, $SM_{\mathrm{i,max}}$ is the soil moisture at which infiltration excess runoff is maximized.

Next, evapotranspiration is computed as:

$$ET = PET \times \min(1, \max(0, SM - WP)/(CMC - WP) \quad (25)$$

where CMC and WP are, respectively, critical moisture content and wilting point. PET is a function of daily incoming solar radiation and air temperature, as in Martel et al., 2017:

$$PET = R_s/(\rho \times L_f) \times (T_m + 5)/100 \quad (26)$$

where R_s is the extraterrestrial radiation in MJ/m^2/day, ρ is the density of water (1000 kg/m^3), L_f is the latent heat flux (2.26 MJ/kg), and T_m is the daily mean temperature.

Percolation out of the topsoil layer is computed as:

$$D = k \times \left(\frac{SM - SM_{res}}{SM_{sat} - SM_{res}}\right)^{2b+3} \quad (27)$$

where k is the saturated hydraulic conductivity, SM is the soil moisture, SM_{sat} is the saturated soil moisture, SM_{res} is the residual soil moisture, and b is the pore size distribution index.

Below the topsoil layer are two conceptual layers representing 1) the rest of the vadose zone, and 2) the phreatic zone, which enables estimation of baseflow originating from the deep soil layers.

12) Coupling with K2

RHEM-Snow output (rainfall + snowmelt) is fully integrated with K2. RHEM-Snow contains subroutines to disaggregate both rainfall and snowmelt inputs (currently, K2 is driven with 5 minute disaggregated output). The disaggregation of rainfall inputs uses the same method that is currently used to disaggregate rainfall inputs that is currently used in RHEM (using a double exponential function), and snowmelt is disaggregated to mimic a daily distribution that peaks in the afternoon, similar to Webb et al., 2017. K2 simulations occur on days snowfall and/or rainfall to produce estimates of overland flow and runoff. Compared to RHEM (without snow), RHEM-Snow, when coupled with K2, tends to produce slightly reduced runoff, though for individual events, runoff can be enhanced (in the case of rain-on-snow events where significant snowmelt occurs along with rainfall), or diminished (in the case of snowfall that was formerly considered as rainfall, or for rain-on-snow events where the snowpack absorbs or partially absorbs the rainfall without melting).

AGWA: Transition to Esri ArcGIS Pro

The current release of ArcMap, version 10.8.2 released on December 09, 2021, will be the final release of ArcMap and will be retired on March 01, 2026 (https://support.esri.com/en/arcmap-esri-plan, accessed 12/13/2022). The migration of AGWA continues, and it is now moving to ArcGIS Pro, the latest ESRI desktop GIS software, which is designed to replace ArcMap.

AGWA for ArcGIS Pro uses Python and leverages ArcPy to create AGWA as a toolbox for ArcGIS Pro. Written as a Python Toolbox, the latest version of AGWA has many advantages and improvements over prior releases. Written as a Python toolbox:

- AGWA is easily shared and accessed in ArcGIS Pro
- Users can extend and customize AGWA to fit their needs
- AGWA does not need to be recompiled for each release of ArcGIS Pro
- Users will already be familiar with the UI/UX as the tool interface implements tools and toolboxes the same as ArcToolbox
- AGWA can be scripted and run outside of ArcGIS Pro
- Inside of ArcGIS Pro, AGWA can be accessed from the Catalog pane, the Python window, ModelBuilder, and called from another script

- Because ArcGIS Pro is multithreaded, the user interface remains responsive, dynamic, and usable while AGWA tools are executing.

Additionally, AGWA for ArcGIS Pro is designed as the foundation for a migration to an online version of AGWA, dubbed dotAGWA. Like the desktop version, the online version relies heavily on geoprocessing. However, geoprocessing is unavailable in the ArcGIS Enterprise SDK (https://developers.arcgis.com/enterprise-sdk/guide/net/design-philosophy-for-arcgis-enterprise-sdk-net/, accessed 4/4/2023), which eliminates that particular migration path for Internet-connected extensions and functionality built using the ArcObjects SDK (e.g. AGWA 3.x). The ground-up rewrite as a Python toolbox is the natural choice and solution to geoprocessing for both the desktop and online versions of AGWA, allowing the publishing of geoprocessing services from the desktop tools to support the online version.

The AGWA website has various step-by-step tutorials highlighting different functionality available in the tool. Currently, there are 14 tutorials and the requisite data to run them available on the AGWA website, with plans to add more as new features and tools are released. In addition, YouTube video tutorials are available at: https://www.youtube.com/channel/UCNsUT54S36evimKEfmY2CrQ?.

Future Plans and Model Development

Extending the KINEROS2 event model to a continuous model requires supplying the initial soil moisture condition before each event and carrying over deposited, unconsolidated sediment between events. The soil moisture condition is simulated by a finite-difference solution to the one-dimensional Richards equation describing water movement in the soil, along with plant evapotranspiration and soil evaporation. These components were adapted from the Opus2 model (Smith, 1992). To maintain a reasonable execution speed, the soil water model can operate on longer time steps than the routing model and represents the average condition across the model element. During rainfall/runoff, the time step is user-defined (default is 60 minutes). When the surface is dry, the time step extends to a daily interval. To couple the routing and soil water models, infiltration computed by the infiltration model during routing is spatially averaged and accumulated over the longer time step. This infiltrated volume is then applied at a constant rate to the soil water model over the same time step. When rainfall or inflow is detected on a previously dry element, the initial soil moisture condition is computed from the upper 300 mm of the soil water profile.

Daily values of min/max temperature and radiation are used to estimate the daily potential evapotranspiration (PET) using the Penman-Monteith equation (Ritchie, 1972). PET is partitioned into plant ET, soil surface evaporation and evaporation of water intercepted by the plant canopy. For sub-daily time steps, it is assumed that PET varies sinusoidally between dawn and dusk. ET can be estimated for multiple plant species, given the areal coverage, leaf area index and root depth of each plant species. In the soil model, plant water use is distributed by depth according to the soil water potential seen by the roots at each level. There is continuous accounting of the water available in the root zone, which is compared with the water demand of the plant and with the estimated wilting point potential, to limit plant water uptake in response to stress.

The flash flood forecasting (FFF) version of KINEROS2 is currently a standalone tool. This version utilizes input from NOAA National Weather Service radar products. Weighting coefficients relating the radar grid to the K2 model elements are now computed via an external GIS operation. Incorporating the FFF version of K2 into AGWA will require a few additions: 1) distributing the FFF version of K2 with AGWA; 2) distributing the polar-centric radar grids for all available radars in the US; and 3) adding and automating the GIS functionality that intersects the radar grid and watershed discretization to derive the weighting coefficients that associate radar grids cells to K2 model elements.

New design storm temporal distributions. As part NOAA ATLAS 14 efforts to publish digitally accessible point precipitation frequency efforts, NOAA has also derived temporal storm distributions for extreme rainfall for design storm durations for different spatial regions (https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume1.pdf; At present 11 volumes, accessed 4/4/2023). The Natural Resources Conservation Service currently provides 27 new regions with GIS polygons where they apply. These regions and new temporal storm distribution have been incorporated into AGWA. As the new regions and distributions are developed and released by NOAA, they will be incorporated into AGWA.

The K2-RHEM snow validation will continue at sites with high-quality data. In addition, efforts will go toward improving and validating the rain-on-snow functionality. This will include further investigation of erosion and erodibility for rain on snow events when the soil is frozen/unfrozen and has different levels of soil moisture.

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