Hydrologic models applied to the Brazilian Cerrado

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The InVEST models should be cited as: Tallis, H.T., Ricketts, T., Guerry, A.D.,Wood, S.A., Sharp, R., Nelson, E., Ennaanay, D.,Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., and Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M. (2013). InVEST 2.5.5 User's Guide. The Natural Capital Project, Stanford.

The latest versions of the InVEST models are available here:
http://www.naturalcapitalproject.org/models/models.html

Model summary

Increases in the amount of nutrients and sediments reaching aquatic systems can deteriorate terrestrial surface water quality and cause changes in species composition, losses in biodiversity and decreases in the provision of ecosystem services like clean drinking water, recreation, etc. (Allan, 2004; Carpenter et al, 1998). Changes in landcover/land use (LULC) can significantly impact surface water quality by regulating the amounts of nutrients and sediment reaching waterways (Allan 2004). For this reason, in our modeling efforts we focus on the impact of LULC on the regulation of nitrogen, phosphorus, and sediment in surface water as these inorganic elements generally have the largest impacts on aquatic ecosystem health (Allan, 2004; Keeler et al, 2012).

For biophysical modeling of surface water quality in our study area in southeastern Brazil, we implement a modified version of the InVEST nutrient export and retention models and sediment loss and retention models (Tallis et al. 2013).[1] Despite its limitations, InVEST presents a generally useful tool for rapid assessments and visualization of the general patterns and changes in the hydrological ecosystem services due to changes in the land cover/land use (Vigerstol & Aukema, 2011). It provides formulations that can be easily adapted to a specific context and is relatively less data intensive than other models like SWAT (Vigerstol & Aukema, 2011). Unlike other models like VIC, it is suitable for analysis at intermediate scales (from 30m to 10km

[1] Our modifications replaced intermediate model variables (that InVEST estimates from model parameters) with final values from the literature. We describe our version of the model, noting the equations used in the published models in footnotes. Note also that we used an older version of the InVEST models (v2.5.5 from 2013) than is currently available, as the newer versions were not available at the onset of our research.

geospatial data resolution), with the actual resolution determined by the resolution of the input data (Vigerstol & Aukema, 2011).

The InVEST models rely on spatially explicit data, with the study area being represented as a grid of identically sized cells (pixels) that may differ in their attributes like slope, landcover, soil type, precipitation, among other variables. The InVEST nutrient model depends on an annual water yield sub-model as an input to determine the amount of sediment or nutrient exported from a given pixel. Given that the nutrient and sediment models are structurally similar, we present the general form of these models, and then subsequently provide details for each component. A summary and a detailed description of the values used to parameterize these models for our study area can be found at the following The Nature Conservancy website: http://www.conservationgateway.org/ConservationPractices/EcosystemServices/tnc_dow_collaboration/brazil/Pages/default.aspx.

In the water quality models, each pixel i is assigned an export quantity, e_i, as a function of its current land use/land cover (LULC)[2], k_i, and several other features of the pixel, denoted by θ_i:

$$e_i = E(k_i, \theta_i)$$

This quantity represents the mass of the nutrients or sediments generated on pixel i that then exit as surface flow. Each pixel is also assigned a downhill target based on the steepest descent path in the elevation map (DEM). The pixel's local export is combined with any flow into the pixel from uphill and passed on to the next downhill pixel. In our analysis, a pixel is based on a 90m resolution.

Each pixel is also assigned a capture fraction, c_i, which depends solely on LULC type, k_i. The capture fraction specifies what proportion of nutrients or sediments entering pixel i from uphill sources is retained by the pixel. Thus, the fraction of uphill loading that continues to the next pixel downhill is $1-c_i$. For a particular pixel i, the total amount of nutrients or sediments leaving the pixel, x_i, is:

$$x_i = (1 - c_i)I_i + e_i$$

where I_i is the summed input from uphill sources (note that there may be more than one uphill pixel flowing into pixel i). Given e_i, c_i, and a flow direction for each pixel, the model routes nitrogen, phosphorus, or sediment downhill, measuring both how much of each ultimately reaches streams/water bodies and the export and retention on each pixel.

Annual water yield sub-model

The annual water yield model represents a sum of both surface and subsurface flows. Most importantly, the water yield data layer is used in the nutrient models to compute a topographic index, which aims to distinguish between zones of higher and lower yields. It is not a traditional rainfall-runoff water quality model since it computes an annual average nutrient export.[3] In

[2] E() here denotes a generic function
[3] For more details, please refer to the InVEST 2.5.5 User's guide and see the last section in this document.

particular, the water yield sub-model estimates the annual net water surplus in each pixel as the difference between precipitation and evapotranspiration, according to:

$$w_i = \left(1 - \frac{AET_i}{P_i}\right) P_i$$

where w_i is net runoff, AET_i is actual evapotranspiration, and P_i is annual precipitation. Our estimates of P_i are based on annual data from weather stations in the region, while the evapotranspiration fraction AET_i/P_i for LULC is calculated in the model as:

$$\frac{AET_i}{P_i} = \frac{1+\omega_i R_i}{1+\omega_i R_i + \frac{1}{R_i}}$$

The exceptions to the use of this equation are the developed land cover classes (i.e., urban areas and infrastructure) and water bodies, which are directly assigned an *AET* value based on empirical studies. In the AET_i/P_i fraction, ω_i is a modified dimensionless ratio of plant accessible water storage to expected precipitation during the year as defined by Zhang et al. (2001). Using a previous published study on the empirical modeling of hydrological catchments (Zhang et al. 2001), we assign a value of 2 to ω for natural cover classes and eucalyptus plantations and 0.5 for pasture and croplands.[4] R_i is the dimensionless Budyko Dryness index on pixel *i* for LULC *j*, and is defined as the ratio of potential evapotranspiration to precipitation (Budyko 1974) and is given by:

$$R_i = \frac{ETk_i}{P_i}$$

where ETk_i is potential evapotranspiration.

Thus, except for the developed and water classes, the final water yield per pixel is determined as:

$$w_i = \left(1 - \frac{1+\omega_i R_i}{1+\omega_i R_i + \frac{1}{R_i}}\right) P_i$$

This final value provides the volume of water flowing from each pixel downhill to a stream, reservoir or other water body.

[4] In the original InVEST model, ω, is calculated through a series of equations. First, the available water content (AWC) in the soil is calculated using $AWC = (FC - Wilt) \cdot \min(d_s, d_r)$, where *FC* is field capacity for the local soil type, *Wilt* is wilting point for current LULC, d_s is soil depth, and d_r is root depth. *ETk* is calculated as *k***Eto*, where *Eto* is reference evapotranspiration, and *k* is a specific land cover/land use class constant. Then, given *AWC* and the Zhang seasonality constant, *Z*, omega is calculated as: $\omega_i = Z\frac{AWC_i}{P_i}$. Updated versions of the InVEST model (Version 3.0 available here: http://ncp-dev.stanford.edu/~dataportal/invest-releases/documentation/current_release/) use the parameters suggested by Donohue et al (2012), which provides different empirical expressions for the value of the parameter. The new versions of the InVEST model were not available at the start of our modeling work.

Nutrient model

In the nutrient model (which we applied for nitrogen (N) and phosphorus (P)) the water yield is routed downhill to generate a relative runoff index for each pixel. Pixels downhill experience a relatively greater amount of surface flow, increasing the amount of nutrients they export. Similarly, uphill pixels experience less flow and thus export less. The relative runoff index is calculated following the below equations.

First, each pixel is assigned a runoff index:

$$\lambda_i = \log\left(\sum_{u \in U_i} w_u\right)$$

where w_u is the water yield in each of the U uphill pixels that flows into i. The landscape average cumulative surface flow is determined based on:

$$\bar{\lambda} = \text{mean}(\lambda_i)$$

Then each pixel is assigned its relative runoff index, according to:

$$RRI_i = \frac{\lambda_i}{\bar{\lambda}}$$

Finally, we calculate each pixel's export mass based on the loading coefficient for the corresponding LULC class, L_{ki}, and RRI_i:

$$e_i = E(k_i, RRI_i) = RRI_i \cdot L_{ki}$$

Note that L_{ki} typically varies according to the type of nutrient (N or P).

Sediment loss model

The sediment loss model calculates the amount of soil exported from a pixel based on the universal soil loss equation (USLE) (Wischmeier and Smith, 1978):

$$e_i = R \cdot K_i \cdot LS_i \cdot C_i \cdot P_i$$

Here, R is the rainfall erosivity, a measure of the amount of kinetic energy in regional rainfall, K_i is soil erodibility, LS_i is a function of pixel i's slope, and C_i and P_i correspond to the LULC and any applied management factors. K_i, C_i and P_i are based directly on empirical literature for each of the local LULC categories, while R and LS_i are calculated using model equations parameterized with values from our study area.

Rainfall erosivity is estimated as a function of $I30$, the maximum intensity of a 30-minute rainfall (cm/hr), following:

$$R = (210 + 80\log_{10}(I30)) \cdot I30$$

The slope factor, LS, is calculated as:

$$LS_i = 1.6 \cdot \left(\frac{cellsize \cdot \#cells}{22.13}\right)^n \left(\frac{\sin(0.01745 \cdot slope_i)}{0.09}\right)^{1.4}$$

where n is a function of $slope_i$, and represents the distance traveled by a drop of water given its initial energy.[5] Cell size is defined as 90m, as the resolution our analysis is 90x90m and the USLE uses the unit contributing area, which is the contributing area divided by the side length of the receiving cell. Finally, pixel i's soil export, e_i, is calculated as the product of each of these factors as specified in the USLE above.

Transport to a stream

Nutrients and sediments exported from a given pixel are routed to the next pixel downhill. The flow direction is determined by the path of steepest descent in the digital elevation map (DEM). Flow paths route pixel-to-pixel until they encounter a pixel that is part of the stream network.

As nutrients and exports are transported across the landscape, a portion is retained on each pixel crossed. This capture fraction, c_i above, is determined by the LULC class of the intervening pixel. The escaping fraction ($1-c_i$) continues on, combined with the local export from pixel i, e_i, to the next pixel downhill, where the process of capture and export is repeated.

Interpretation of the model outputs

The InVEST models generate output in terms of the total average annual amounts (in kilograms) of sediment, nitrogen, and phosphorus reaching the waterways in our study area for a given landscape (scenario). The models allow us to calculate the amounts of the three elements for given points of interest like the water extraction points for the towns and households that rely on surface water.

Assumptions behind the models[6]

- The water yield model assumes that all water available for evapotranspiration is based on rainfall in the area or, in the case of irrigated crops, comes from within the study area. It does not incorporate cases when the water is derived from outside the watershed or from groundwater.
- The models do not account for heterogeneity within a LULC class or soil type. This includes heterogeneity in the vegetation composition or differences in the soil characteristics within a soil type.
- The models assume steady-state conditions and do not consider transitional dynamics and inter-period linkages. This implies that changes in sediment and nutrients loadings into

[5] The value of n is conditional on the slope in the pixel:

$$n = \begin{cases} 0.5, if\ slope \geq 5\% \\ 0.4, if\ 3.5\% < slope < 5\% \\ 0.3, if\ 1\% < slope \leq 3.5\% \\ 0.2, if\ slope \leq 1\% \end{cases}$$

[6] These assumptions are based on Vigerstol & Aukema (2011) and the InVEST user manual available here: http://ncp-dev.stanford.edu/~dataportal/invest-releases/documentation/current_release/waterpurification.html

waterways in one year do not carry over into the next year. It assumes away any effects of LULC on groundwater.

- The models do not account for chemical and biological interactions beyond filtration by terrestrial vegetation and may not capture well processes in dry areas with flash floods, areas that are dependent on groundwater, or areas whose hydrology is determined by rainfall intensity.
- The models do not consider point-source pollution.
- The models are based on a continuous downward flow path trajectory of water, nutrients, and sediments and assume away tile drainage and changes in the flow due to extensive ditching practices. However, ditches and canals are not common in our study area.
- The water yield model assumes away complex processes that redistribute water over space and time and represents water partitioning by a single parameter that varies by LULC, but not within a LULC class.
- The Universal Soil Loss Equation, on which the sediment model is based, assumes no erosion from gullies, landslides, or streambank processes. Instead, it focuses on erosion from sheet wash (rill or inter-rill erosion).

Limitations of the models

A limitation of the InVEST models is their inability to model daily, seasonal and sub-seasonal variability in the model outputs (Vigerstol & Aukema, 2011; Tallis et al, 2013). Instead, they provide average annual values of the amounts of nutrients and sediment reaching the waterways. They also focus on surface and shallow subsurface water and do not incorporate groundwater processes and impacts. The models also do not account for any water resource infrastructure that redistributes the water flow (Vigerstol & Aukema, 2011)

InVEST is based on models derived at the watershed and sub-watershed scales (Tallis et al, 2013). Therefore, the model outputs may not be accurate at smaller scales. For this reason, the use of pixel-level maps of the marginal contributions of each pixel to inform decision-making has been discouraged (Tallis et al, 2013).

While InVEST is based on biophysical relationships that have been widely accepted by hydrologists, it makes some simplifications in the models, which introduces uncertainties (Vigerstol & Aukema, 2011). Even though local calibration data can be used to validate the models, such information is not readily or adequately available for many developing countries.

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