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A GIS-BASED VULNERABILITY ASSESSMENT TOOL FOR SURFACE WATER AND GROUNDWATER

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ABSTRACT: Water resources and infrastructure - dams, aquifers, streams, and reservoirs - represent "critical infrastructure and key resources" as defined by the National Infrastructure Protection Plan (NIPP) of 2009. The importance of these key resources and assets provides the motivation to develop methods for assessing their vulnerability to natural or anthropogenic threats. Improved methods using GIS-based tools capable of assessing the vulnerability of these key water resources to unintentional and/or intentional harm and the resultant consequences of that harm can be a critical contribution to the management and protection of water resources and infrastructure. With this goal, an ArcGIS-based tool, the Water Resources Vulnerability Assessment Tool (WRVAT), has been developed in response to the need to inventory and assess the vulnerability of water resource systems, including dams. Vulnerability assessments conducted using the WRVAT consider intrinsic characteristics of the system, both accidental and intentional extrinsic threats to the system, and the consequences of system compromise. This work identifies existing threats and provides a methodology for more readily identifying hazards to water resources and infrastructure by determining the critical intrinsic characteristics and external threats affecting these resources and infrastructure.
KEY TERMS: GIS; vulnerability assessment; surface water; groundwater

INTRODUCTION

Water resources, including shallow aquifers, streams, dams and reservoirs, represent "key resources" and "key assets" as defined in the U.S. Department of Homeland Security's National Infrastructure Protection Plan of 2006. The ability to protect these resources and assets is critical to national security, public health and safety, and economic vitality. WRVAT was developed to conduct comprehensive vulnerability assessments of groundwater, surface water, and dam resources. The WRVAT approach breaks vulnerability into three categories: intrinsic or inherent vulnerability, threats or extrinsic vulnerability, and consequences.

WRVAT automates the development and manipulation of model inputs, the evaluation of models, the comparison of model scenario outputs, and the development of metadata and an audit trail inside the ArcGIS framework. User-friendly graphical user interfaces (GUIs) drive the development of vulnerability models and input datasets. A file-system geodatabase is used to manage vulnerability assessment inputs and outputs and tracks all components of an analysis. WRVAT leverages the power of ArcGIS for management, analysis and visualization for all aspects of a vulnerability assessment.

WRVAT was applied to evaluate water resources throughout the state of Mississippi. Intrinsic Vulnerability was calculated for all surface water bodies in the state. The water table aquifer throughout the State of Mississippi was evaluated, using the WRVAT to identify the most vulnerable areas of the aquifer based on intrinsic properties of the ground surface and the unsaturated zone. Additionally the WRVAT was used to determine the overall vulnerability of the outcrop and subcrop extents of the Sparta aquifer. WRVAT was used also to evaluate the intrinsic vulnerability of Mississippi's entire database of over 3,700 dams in less than 20 minutes. This paper discusses the WRVAT surface water and groundwater methodology and describes a surface water vulnerability assessment conducted for sub-basins within the Little Tallahatchie River hydrologic basin.

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VULNERABILITY ASSESSMENT METHODOLGY

The WRVAT defines a surface water system as consisting of surface water bodies: lakes, reservoirs, rivers, major streams, and perennial streams. The groundwater system includes: the unsaturated zone, the saturated geologic units that overlie an aquifer, if any, and an aquifer. The vulnerability of the groundwater can be determined for any constituent in the system (i.e., the unsaturated zone, the units overlying an aquifer, and/or an aquifer). The vulnerability of surface water and groundwater consists of three components: the intrinsic vulnerability, the extrinsic vulnerability, and consequences. The total vulnerability of surface water or groundwater, *V*, is calculated as:

$$V = SI\sum_{n=1}^{N}\left[P_nE_n\left(\sum_{m=1}^{M}C_{n,m}R_m\right)\right]$$ Equation 1.

where *SI* is the intrinsic vulnerability of the water resource, the product P_nE_n represents the extrinsic vulnerability of the water resource, the product $C_{n,m}R_m$ represents the consequences once the water has been contaminated, and N and M are the total number of extrinsic factors and receptors, respectively, being considered. These parameters are discussed in more detail in the following paragraphs.

Surface water intrinsic vulnerability is calculated as a measure of how long it takes a surface spill to travel overland to a surface water body. The surface water intrinsic vulnerability is based on characteristics of the land surface and the locations of water bodies. Groundwater intrinsic vulnerability is conceptualized as a measure of how long it takes for a contaminant spilled on the ground surface to migrate vertically to the groundwater constituent and then travel horizontally to exit points, which are defined as surface water bodies and wells for groundwater in phreatic aquifers and wells for groundwater in confined aquifers. The intrinsic vulnerability is determined based on intrinsic characteristics of the groundwater constituent and overlying units and on the mobility of the contaminant.

Extrinsic vulnerability is a function of the types and density of potential sources of water contamination. The product P_nE_n consists of the normalized density of extrinsic factor *n* (E_n) and the likelihood that extrinsic factor *n* will release contaminants through intentional or accidental means (P_n). The consequence is a measure of the environmental, health, and/or financial impact to a receptor resulting from contamination of a water resource. The product $C_{n,m}R_m$, which represents consequences, consists of the normalized density of receptor *m* (R_m) and the relative consequence if water used by receptor *m* is contaminated by a release from extrinsic factor *n* ($C_{n,m}$). The WRVAT method provides the ability to consider numerous extrinsic factors, or threats, and consequences thus the summations in the equation above.

Surface Water Intrinsic Vulnerability

The WRVAT calculates the intrinsic vulnerability of surface water based on the time scale for runoff, also known as overland flow. Assuming no limit on the unsaturated zone thickness and infinite storage in the unsaturated zone, the time for overland flow (t_o) can be given by:

$$t_o = \frac{t_m L_o}{L_o - K_s t_m}$$ Equation 2.

Where L_o is the length for overland flow, and K_s is the saturated hydraulic conductivity of the surface soil, and t_m is the time for overland flow ignoring infiltration into the unsaturated zone. The parameter t_m can be estimated using an equation for the time of concentration for surface water flow (Chin, 2000 based on Kerby, 1959):

$$t_m = 86.735\left(\frac{L_o n}{\sqrt{S}}\right)^{0.467}$$ Equation 3.

Where L_o is the length in meters for overland flow defined as the average down slope distance to the nearest surface water body, *S* is the effective slope of the ground surface, and *n* is the retardance or roughness coefficient defined as the average surface retardance value of the overland flow. The value selected for the retardance coefficient is based on the type of surface (Kerby,1959).

A time for overland flow is calculated for each grid cell in a study area grid. Overland flow is considered to begin at the center of the grid cell and end at the nearest down-slope surface water body. The ArcGIS geoprocessing tool *Flow Direction* is used by the WRVAT to calculate the direction of steepest descent for each grid. The geoprocessing tool *Flow Length* is then used by the WRVAT to calculate the length of overland flow along the path defined by the direction of steepest descent from the grid cell to the nearest water body. The nearest down-slope surface water body may be located within the grid cell in some cases but, for the majority of cases, the nearest down-slope surface water body will be located several grid cells away. For the latter case, calculation of the time for overland flow considers the average values for the saturated hydraulic conductivity, surface retardance, and length for the entire flow path over which overland flow occurs. This is done by averaging each of these parameters over all the grid cells that fall along the flow path. The intrinsic vulnerability is calculated as the log-normalized time for overland flow. The log values are used because the range in times for overland flow is large. The intrinsic vulnerability for surface water is calculated as:

$$SI_N = 1 - \left(\frac{\log(t_o) - \log(t_{min})}{\log(t_{max}) - \log(t_{min})} \right)$$ Equation 4.

Where S_{IN} is the surface water intrinsic vulnerability for the grid cell, t_o is the time of overland flow (from Equations 2 and 3) for the grid cell, t_{min} is the minimum time of overland flow for all grid cells in a user defined region of interest, and t_{max} is the maximum time of overland flow for all grid cells in a user defined region of interest.

Groundwater Intrinsic Vulnerability

The WRVAT calculates the intrinsic vulnerability of the groundwater constituent based on the effective residence time for a contaminant to travel vertically from the ground surface through each overlying unit to the groundwater constituent and then travel horizontally to an exit point. The WRVAT defines the residence time as an effective residence time, *t*, based on a modified Green-Ampt type model:

$$t = \frac{LR\phi}{KX}$$ Equation 5.

where *L* is the length of transport, *R* is the retardation factor, φ is the porosity, *K* is the hydraulic conductivity, and *X* is a modification factor. The modification factor for the unsaturated zone accounts for variability in infiltration and the modification factor for the overlying units accounts for spatial variability in lithology and/or thickness. No modification factor is included for aquifers. The calculations of residence times assume a constant water source and homogeneity in the vertical direction (e.g., constant vertical hydraulic conductivity, thickness, porosity, etc.). The retardation term is incorporated in the residence time in order to include the variability in contaminant mobility. Only aqueous-phase contaminants are considered by the WRVAT. The retardation term, *R*, is calculated as:

$$R = 1 + (K_d \rho_b / \phi)$$ Equation 6.

where K_d is the distribution coefficient, ρ_b is the bulk density, and φ is the porosity. For the unsaturated zone, Equation 5 is an effective vertical residence time where the length of transport is the thickness of the unsaturated zone, the hydraulic conductivity is the vertical unsaturated hydraulic conductivity for the unsaturated zone, and the modification factor accounts for variable infiltration due to topography and is referred to as the topographic factor. The topographic factor, *T*, is determined as:

$$T = \frac{1}{1 - 86.735 K_S \left(\frac{n}{\sqrt{S}} \right)^{0.467} L_o^{\ 0.533}}$$ Equation 7.

where L_o is the overland flow length in meters, *S* is the slope of the ground surface, *n* is the retardance or roughness coefficient, and K_s is the saturated hydraulic conductivity of the surface soil in meters per second.

For units that overlie an aquifer, Equation 5 is also an effective vertical residence time where the length of transport is the thickness of the overlying unit, the hydraulic conductivity is the vertical hydraulic conductivity of the overlying unit, and the modification factor accounts for spatial variability in the lithology and/or thickness of the overlying unit. A vertical residence time is calculated for each overlying unit and they are then summed to obtain the overall residence time for travel from the base of the unsaturated zone to the top of an aquifer. Equation 5 is also used to calculate the effective horizontal residence time in an aquifer. In this case, the length of transport is the effective horizontal distance to surrounding exit points (wells and surface water bodies) and the hydraulic conductivity is the effective horizontal hydraulic conductivity of the aquifer. The length in the aquifer is a representative length to all potential exit points (such as a well or stream) within some user-defined neighborhood region in the aquifer. The effective length, L_h, is calculated for each grid using:

$$L_h = \sqrt{\frac{A_N}{N_w}}$$ Equation 8.

where N_w is the weighted sum of all exit points within the user defined neighborhood and A_N is the area of the user defined neighborhood within which the exit points are considered. The weighting scheme uses a weighting kernel to assign weights to the exit points inversely proportional to their distance from the grid cell. For this scheme, more exit points yield smaller effective lengths and exit points located nearer to the grid cell yield smaller effective lengths.

The total effective residence time for an aquifer, t, is given by:

$$t = \sum_{i=1}^{n}\left(t_{v,i}^{uz} + t_{v,i}^{sat}\right) + t_{v,Aq}^{uz} + t_h$$ Equation 9.

where $t^{uz}_{v,i}$ is the vertical residence time through the unsaturated thickness of the i^{th} overlying unit, $t^{sat}_{v,i}$ is the vertical residence time through the saturated thickness of the i^{th} overlying unit, $t^{uz}_{v,Aq}$, is vertical residence time through the unsaturated thickness of an aquifer, t_h is the horizontal residence time in the aquifer, and n is the total number of overlying units. Note, that if a unit is fully unsaturated or saturated then the corresponding $t^{uz}_{v,i}$, ($t^{uz}_{v,Aq}$, for an aquifer) or $t^{sat}_{v,i}$, is zero. The range in the calculated effective residence times can be large primarily due to the large range in hydraulic conductivity values. The log of the effective residence times is used to assess the intrinsic vulnerability as described by Equation 4.

Surface Water and Groundwater Extrinsic Vulnerability and Consequences Assessments

The extrinsic vulnerability is expressed by the parameters P_n and E_n in Equation 1 where n is the extrinsic factor, P is the likelihood that extrinsic factor n will release contaminants, and E is the normalized density of extrinsic factor n. The value assigned to the likelihood is independent for each extrinsic factor. The normalized density of the extrinsic factors is calculated based on the point density, line density, or areal distribution of the factor within a user-specified area. Design of the extrinsic vulnerability for surface water and groundwater in the WRVAT provides significant flexibility in the number, type(s), and probabilities of extrinsic factors that allows users to easily customize applications for their specific needs. If a threat, or extrinsic factor n, can be represented in a GIS as a point, line, or polygon it can be used as an input parameter for an extrinsic vulnerability assessment.

The consequence for surface water and groundwater is expressed by the parameters $C_{n,m}$ and R_m in Equation 1 where n is the extrinsic factor, m is the receptor, C is the consequence to receptor m from factor n, and R is the normalized density of receptor m. Receptors are defined as any user of surface water (e.g., humans, wildlife, industrial facility, etc.). Consequences are defined as impacts resulting from contamination of surface water or groundwarer. Example consequences include toxicity, clean up costs, and costs due to loss or replacement of water resources. The normalized density of the receptors is calculated based on the point density, line density, or areal distribution of the receptor within a user-specified area. Consequence assessments can be customized to incorporate any number of receptors and types of consequences. If receptors and consequences can be conceptualized as points, lines or polygons in GIS they may be used as inputs in consequence assessments.

EXAMPLE SURFACE WATER VULNERABILITY ASSESSMENT

A complete surface water vulnerability assessment (intrinsic, extrinsic, and consequence) was conducted for the Little Tallahatchie River hydrologic basin located in north-central Mississippi. In the 1930's a dam was constructed on the Little Tallahatchie River near the town of Sardis, Mississippi, creating Sardis Lake. Sardis Lake is nearly 100,000 acres within three Mississippi counties. Though there are some municipalities in the basin, the large majority of land is agricultural or forested.

Intrinsic Vulnerability

The length for overland flow, or L_o (Equation 2), and effective slope of the ground surface, or S (Equation 3) were derived from a 28.7 m digital elevation model (DEM) downloaded from the United States Geological Survey (USGS, 2007). Locations of reservoirs, lakes, and major rivers (e.g., Sardis Lake) were downloaded from the Mississippi Department of Environmental Quality (MDEQ) website (MDEQ, 2008). The Derive Water Bodies tool in WRVAT was used to derive the locations of lower order streams from the DEM. Although the locations of perennial and intermittent streams are available on the MDEQ website, they were not used in the analysis for the following reasons. The intrinsic vulnerability, calculated as the time for overland flow, is a function of the flow path to the nearest surface water body. Those flow paths were determined using the DEM. As the size of streams decreases, so does the depression in the topography caused by those streams. The small valleys, containing small streams, in the DEM may be inconsistent with the perennial and intermittent stream coverages available online leading to problems calculating the flow path. In order to maintain consistency between the overland flow paths calculated from the DEM and the locations of small streams, the DEM was used to determine the locations of lower order streams.

The *Derive Water Bodies* tool outputs the flow direction for each grid cell in the DEM in addition to a water bodies layer. The flow direction for each grid cell represents the direction of steepest descent and is assumed to govern the direction water flows from one grid cell to another. ArcGIS assigns a number from 1 to 255 for these directions which are as follows: 1 -east, 2 - southeast, 4 - south, 8 - southwest, 16 - west, 32 - northwest, 64 - north, 128 -northeast, and 255 as no flow.

Using the *Calculate Flow Length and Slope* tool, the flow length of the overland path was calculated from the center of each grid cell to the nearest surface water body along the path of steepest descent. The slope across the path of steepest descent was calculated as the difference between the elevation of the starting point (center of grid cell) and the elevation of the point where the flow path meets the water body.

The saturated hydraulic conductivity of the surface soil, or K_s, is derived from SSURGO digital soil survey data, downloaded from the National Cooperative Soil Survey's Soil Survey Geographic Database (USDA, 2008), was used to assign saturated hydraulic conductivity values to the surface soil. These data, in the form of an Access database and shapefile, consist of soil map units for the entire state of Mississippi. Each soil map unit is made up of two or more soil components, for which physical properties, including saturated hydraulic conductivity, are available with depth. The number of soil components per soil map unit varies from two to 21. For each soil component, the saturated hydraulic conductivity is given for several depths in the soil. For this analysis, the saturated hydraulic conductivity of the soil map unit was taken as the average of the representative saturated hydraulic conductivity for the uppermost depth of the soil components making up the soil map unit. These average saturated hydraulic conductivities were assigned to the polygons representing the soil map units. The polygon file was then converted to a raster file. For this conversion, the saturated hydraulic conductivity assigned to each grid cell in the raster was the value from the polygon file at the location of the middle of the grid cell.

The roughness coefficient is a function of the land coverage type. Kerby (1959) provides roughness coefficients for six broad land surface types. The land coverage for the state of Mississippi can be obtained from the 2001 national land cover dataset provided by the U.S. Geological Survey. Using the general values provided by Kerby (1959) and scientific judgment, a roughness coefficient was estimated for each land coverage type in Mississippi. The *Derive Roughness Coefficient* tool in WRVAT was used to map the roughness coefficients to the NLCD, resulting in the roughness coefficient raster for the state of Mississippi.

Extrinsic Vulnerability

Extrinsic vulnerability is defined as the likelihood that surface water will be contaminated by threats external to the surface water. Two inputs are required for the analysis of extrinsic vulnerability. The first input is the likelihood that the extrinsic factor will release contaminant and, once released, the contaminant will reach the surface water. The second input is the spatial locations of the extrinsic factors. Development of the likelihood values assumes any contaminant released from the extrinsic factors will cause contamination of surface water. The likelihood can be unique for each extrinsic factor. Once the likelihoods for all extrinsic factors are input into the surface water module, they are normalized to values between 0 and 1. Extrinsic factors included in this model were: roads, surface impoundments, discharge elimination sites, toxic inventory sites and croplands. Densities of these factors in sub-basins of the Little Tallahatchie River basin were calculated and considered in the overall surface water vulnerability assessment for the basin.

Consequence Assessment

In the assessment of total vulnerability, the surface water module in the WRVAT includes the impacts from contamination of surface water by the extrinsic factors on specific receptors. This impact is referred to as the consequence. Two inputs are required for the assessment of consequence. The first input is the ranking of the impact on the receptor resulting from contamination by the extrinsic factor. The second input is the spatial distribution of the receptors. Once all consequence rankings are input into the surface water module, they are normalized to values between 0 and 1. Normalized consequence ranking values of 0 indicate that there is no consequence to the receptor if surface water is contaminated by the extrinsic factor and values of 1 indicate the maximum consequence to the receptor if surface water is contaminated by the extrinsic factor. The receptors considered by the analysis of the Little Tallahatchie River hydrologic basin were cities and small towns, recreational facilities with a surface water body, wildlife management areas, and state parks.

Results

The total vulnerability of surface water in the Little Tallahatchie River hydrologic basin was determined using the *Surface Water Vulnerability* tool in WRVAT which takes the calculated coverages for intrinsic, extrinsic, and consequences and weights each according to user-specified factors and aggregates them to arrive at a total vulnerability ranking. Since the total vulnerability is a product, if either the density of extrinsic factors or the density of receptors is zero, the total vulnerability will be zero even though the intrinsic vulnerability is non-zero. This reflects the fact that areas with no extrinsic factors, which are the sources of contamination, are not vulnerable. In addition, areas with no receptors, or users of surface water, are also not vulnerable because contamination of surface water in those areas would have no environmental consequence.

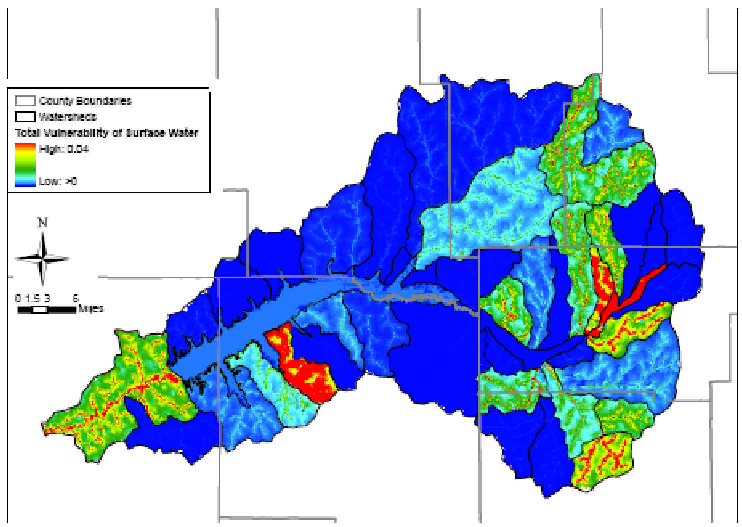

Figure 1. Total Vulnerability of Surface Water in the Little Tallahatchie River Basin

The total vulnerability of surface water in the Little Tallahatchie River hydrologic basin is shown in Figure 1. Note that these results are applicable only for the extrinsic factors and associated likelihoods and receptors and associated consequence rankings selected for this analysis. Selection of different extrinsic factors, receptors, likelihood values, and/or consequence rankings would yield different results. The intrinsic vulnerability is very similar for all sub-basins within the Little Tallahatchie River hydrologic basin. Therefore, the difference in total vulnerability between sub-basins is mainly a function of the densities of and likelihoods for extrinsic factors and the densities of and consequence rankings for receptors throughout the hydrologic basin.

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