In Cooperation with the World Bank, the Romanian National Agency for Mineral Resources, and Futures Group

Initial Sediment Transport Model of the Mining-Affected Aries River Basin, Romania

By Michael J. Friedel and Joshua I. Linard

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
Volume		
ounce, fluid (fl. oz)	0.02957	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic inch (in^3)	0.01639	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

SI to Inch/Pound

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
Volume		
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
Flow rate		
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Initial Sediment Transport Model of the Mining-Affected Aries River Basin, Romania

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Abstract

The Romanian government is interested in understanding the effects of existing and future mining activities on long-term dispersal, storage, and remobilization of sediment-associated metals. An initial Soil and Water Assessment Tool (SWAT) model was prepared using available data to evaluate hypothetical failure of the Valea Sesei tailings dam at the Rosia Poieni mine in the Aries River basin. Using the available data, the initial Aries River Basin SWAT model could not be manually calibrated to accurately reproduce monthly streamflow values observed at the Turda gage station. The poor simulation of the monthly streamflow is attributed to spatially limited soil and precipitation data, limited constraint information due to spatially and temporally limited streamflow measurements, and in ability to obtain optimal parameter values when using a manual calibration process. Suggestions to improve the Aries River basin sediment transport model include accounting for heterogeneity in model input, a two-tier nonlinear calibration strategy, and analysis of uncertainty in predictions.

Introduction

The basin degradation of fluvial systems by heavy metals can occur through natural weathering processes (Macklin, 1992), but more commonly degradation occurs from anthropogenic processes in response to base- and precious-metal mining operations. Some commonly associated mining-related processes that lead to elevated metal concentrations in basin-fluvial systems include acid-mine drainage (Gray, 1998), release of waste slurries containing solute and particulate metals (Salomons, 1995), erosion of contaminated impoundments and floodplains (Dennis and others, 2003), and failure of mine tailings dams (Grimalt and others, 1999; Macklin and others, 2003). Often the timing and interrelation among these processes lead to a catastrophic degradation of basin-fluvial systems. One recent example was the tailings dam failure at the Baia Borsa mine, 2000, which resulted in releasing acid water and about 20,000 tons of polluted sediment into the

Danube River of the Tisa basin, Romania. For this and other reasons, the Romanian government is interested in understanding the effects of existing and future mining activities on long-term dispersal, storage, and remobilization of sediment-associated metals. To achieve an outcome that could be applied in other mining-affected basins of Romania, the objective in this study is to develop and calibrate an initial model for quantifying the effects of sediment transport following a hypothetical tailings dam failure at the Valea Sesei tailings dam, Rosia Poieni mine (fig. 1).

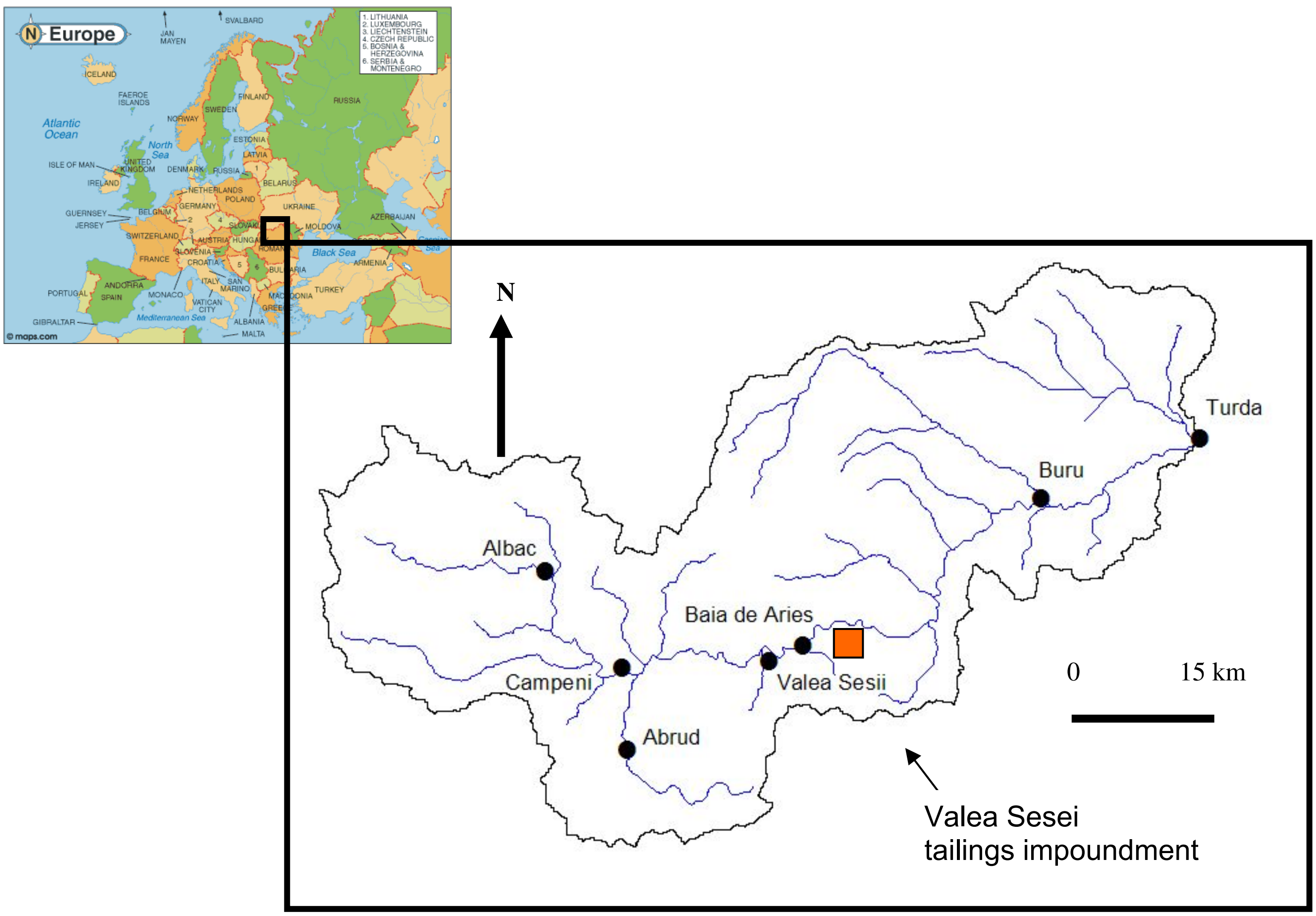

Figure 1. Aries River basin (about 2,500 km^2) with streamflow station locations and approximate location of the Valea Sesei tailings impoundment, Rosia Poieni mine.

Description of the Study Area

The Aries River is a major tributary to the River Mures that drains eastward along the northern edge of the Metaliferi Mountains, in northwestern Romania (fig. 1). The Metaliferi Mountains form the southern part of the larger Apuseni Mountain region, situated in the northwestern Carpathians. The River Aries (drainage area of 2,540 km^2) is a gravel-bed river with mountain headwaters rising to 1,160 m above sea level. The channel gradient is steepest upstream of Campeni, where the channel has also been dammed to create a reservoir. Near Baia de Aries, the streamflow discharge ranges from 5 to 63 m^3s^{-1}, with an average of 24 m^3s^{-1} (Forray and Hallbauer, 2000). With the exception of the Abrud and Iara Rivers, tributaries are relatively small, high-gradient streams with discharges of 0.01–2 m^3s^{-1}. The River Abrud (drainage area 274 km^2), the largest tributary to the Aries River, joins the main stem downstream of Campeni (fig. 1). The Abrud is a gravel-bed river that drains the southeastern and eastern flank of the Bucium, Rosia Poieni, and Rosia Montana ore deposits.

Methods

The physically based numerical model known as the Soil and Water Assessment Tool (SWAT); (Neitsch, Arnold, Kindrey, and others, 2002; Neitsch, Arnold, and Srinivasan 2002; Arnold and others, 2002) was selected to simulate long-term dispersal, storage, and transport of sediment-associated metals following hypothetical failure of the Valea Sessi tailings dam. SWAT is a free computer program developed to predict the impact of land management practices on water, sediment, and chemical yields in large, complex basins having varying soils, land use, and management conditions over long time periods. The benefits of using the physically-based SWAT model are that the relative long-term effects of alternate input data (i.e., alternate model scenarios), such as management practices, climate, vegetation, and others, on water and sediment quality can be quantified. Before SWAT can be used to perform Aries River basin simulations, the following three modeling steps must be completed in order: construction, calibration, and validation. While not mandatory, many investigators are now performing the additional step of predictive analysis to evaluate the uncertainty in key surface-water predictions (Friedel, 2006).

Model Construction

An initial SWAT model was constructed during the first project year to represent hydrological processes in the Aries River basin. As is true with all models, the quality and degree of usefulness is based on the quality of information available. Because SWAT is a physically-based model, the types of information included topography, gage (precipitation and streamflow) station locations, climate (precipitation and temperature), land use, soil properties, and land management practices. Preprocessing of the information was done using programs such as Excel, Access, and Basins 3.1 (USEPA, 2001). The SWAT modeling software is included as part of the U.S. Environmental Protection Agency's preprocessing software called BASINS (USEPA, 2001). The BASINS acronym is for Better Assessment Science Integrating point and Non-point Sources software.

In addition, two Environmental Science Research Institute (ESRI) geographical information systems (GIS) programs, ArcView 3.x and Spatial Analyst (ESRI, 2006), were used.

Topography

SWAT requires three primary spatial data sets: a digital elevation model (DEM), a land-use grid, and a grid of soil map units. Each of these data sets required reprojection into an appropriate coordinate system. A 90-m-resolution DEM (Land_cover2000_Albers.dbf) was purchased from Romanian counterparts for use in subdividing the Aries River basin (fig. 2). This DEM compared favorably to one downloaded from a USGS site (seamlessusgs.gov) hosting global data obtained during U.S. shuttle flights. Each tributary basin was delineated from a point in the Aries basin that is co-located with seven stream gage sites (fig. 3). The Aries River basin then was subdivided into 38 sub-basins (fig. 3) of similar sizes (table 1), consistent with recommendations by Jha and others (2004). Following the determination of sub-basins, the BASINS program created a flow accumulation grid and a flow direction grid based on the physical characteristics of each sub-basin.

Land Use and Soils

The spatial representation of 15 land-use categories (fig. 4) was based on a 30-m grid (LanduseSoilRepSwat.txt), of which the largest lumped categories included forest (evergreen and mixed), 45.7%; pasture, 19.9%; range (grasses), 15.8%; and agricultural (generic and row crops) 13.8% (table 2). The map-unit grid (Soils_ST70_Project.dbf) corresponding to the Romanian Soil Geographic database characterized 30 soil types (table 3) at a 30-m resolution (fig. 5). At the time of model construction, however, there was no soil property information available from the government or other sources. For this reason, the Aries River basin was assumed to be characterized by a single soil layer with homogeneous soil properties. That is, the same set of initial soil properties were used for each soil type (characterized by percentages of 7.5% clay, 6.6% silt, and 86% sand, and a soil water capacity of 0.13, a permeability of 21, and dimensionless universal soil loss coefficient of, 17) (Usersoil.dbf).

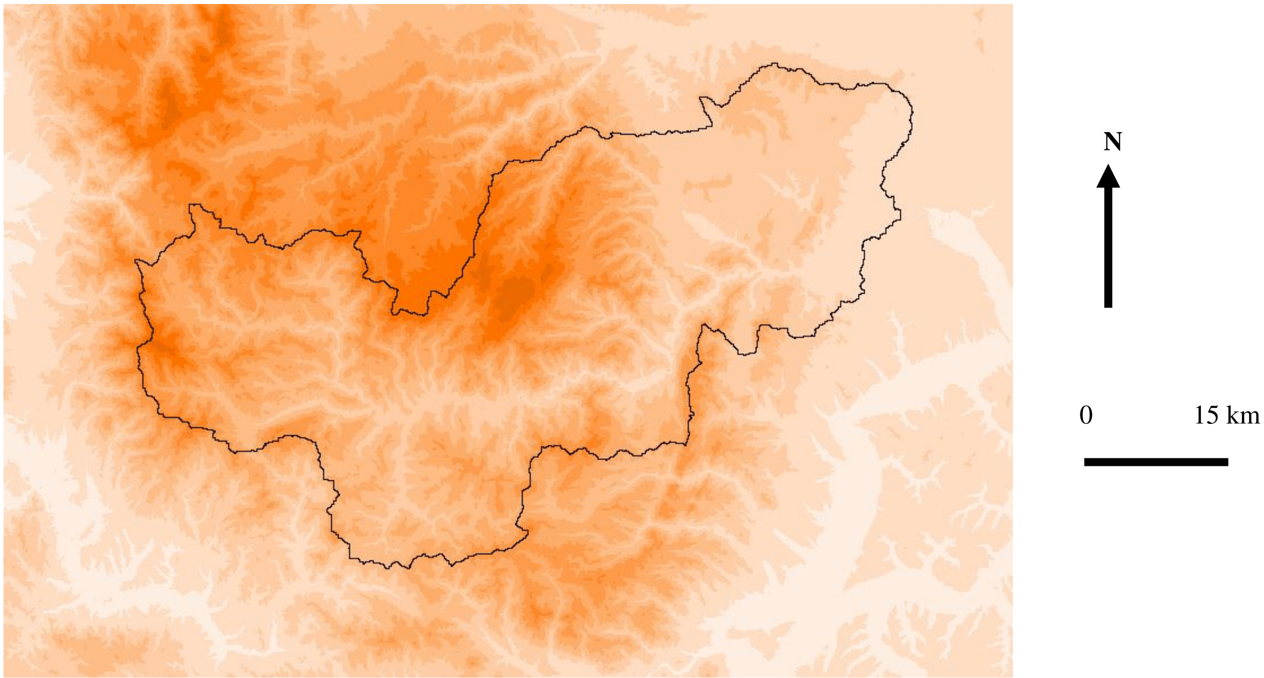

Figure 2. Digital elevation model data (90 m) used in SWAT model construction. Aries River basin outline on digital elevation model data. Darker color represents greater elevation.

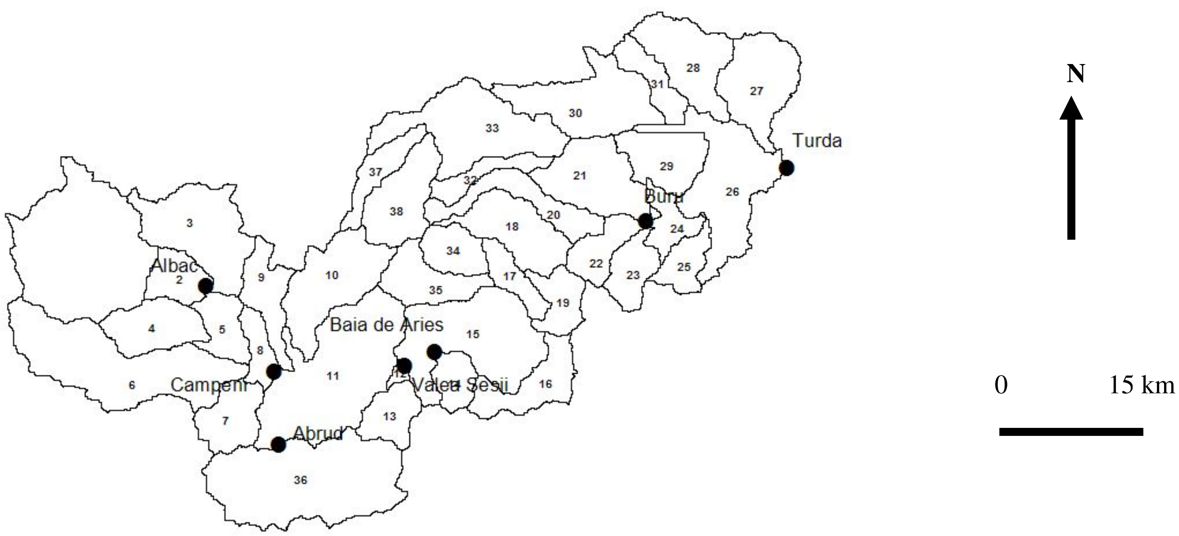

Figure 3. Aries River sub-basins used in SWAT model construction. Sub-basins were derived so that gage stations coincided with outlets. Sub-basins are outlined in black and numbered; other features include streamflow gage stations (dots), rain gage stations (squares), and temperature gage station (triangles).

Because land use and soils vary in the Aries River basin, multiple hydrologic response units (HRUs) were created in each sub-basin (for a total of 227). Because lumping of soil and land-use features may result in losing important hydrologic features, multiple HRUs within a sub-basin were defined if a land use category occupied more than 20% of the sub-basin area and a soil class consisted of at least 10% of the sub-basin area. No more than seven HRUs were created in any sub-basin, and each HRU had a unique parameter set (described in ruLanduseSoilRepSwat.txt).

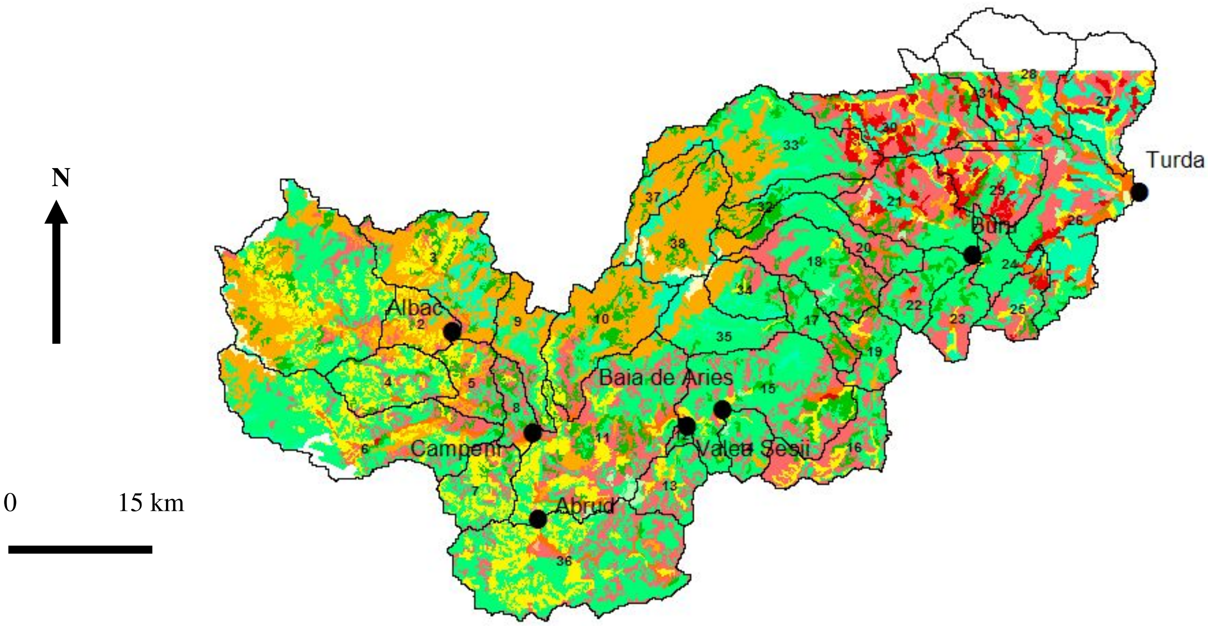

Figure 4. Land use within the Aries River sub-basins. Colors represent different land use regions.

Table 1. Aries River sub-basin spatial characteristics used in SWAT model construction.

[ha, hectares; m, meters; %, percent]

SUBBASIN	AREA ha	LENGTH m	SLOPE %	ELEVATION m
1	19875	24031	27.9	945
2	3319	11450	28.4	926
3	9879	20705	29.0	818
4	5380	15031	26.3	1044
5	3455	13689	31.8	740
6	16024	36463	29.7	880
7	4450	13491	20.9	690
8	2345	9955	25.9	695
9	4329	20277	32.4	983
10	8891	22310	26.3	1200
11	17392	32856	26.9	723
12	426	4717	33.9	593
13	3457	9055	30.5	737
14	2602	9806	34.1	999
15	13182	27072	31.4	889
16	5154	19482	23.6	829
17	2708	13029	34.8	725
18	6774	21442	31.6	1138
19	3336	11942	32.2	422
20	5193	27627	27.2	632
21	7907	17428	17.1	457
22	3547	14866	36.9	766
23	3419	12800	28.2	515
24	2739	11278	21.1	557
25	2855	14379	14.4	612
26	11685	22148	10.1	487
27	7656	17243	9.7	378
28	7360	18368	10.5	602
29	5356	11398	12.6	605
30	9774	24566	11.8	567
31	3135	17830	12.5	702
32	2631	17740	28.9	1060
33	11760	30508	30.1	1134
34	3391	10497	32.7	835
35	4895	16380	31.1	1142
36	18010	25834	24.6	705
37	3228	17804	27.8	1487
38	6505	17428	27.0	1265

Table 2. Aries River sub-basin land use characteristics used in the SWAT model construction.

[ha, hectares; m, meters; %, percent]

Land Use Aries River Basin	SWAT Parameter	Area Ha	Area Acres	Basin %
Agricultural Land-Generic	AGRL	6117	15115	2.41
Agricultural Land-Row Crops	AGRR	28996	71651	11.4
Forest-Evergreen	FRSE	36545	90304	14.4
Forest-Mixed	FRST	79516	196489	31.3
Industrial	UIDU	269	665	0.11
Institutional	UINS	1006	2486	0.40
Orchard	ORCD	504	1246	0.20
Pasture	PAST	50577	124979	19.9
Range-Brush	RNGB	17505	43256	6.89
Range-Grasses	RNGE	22728	56163	8.95
Residential-Low Density	URLD	90.8	224.8	0.04
Residential-Med/Low Density	URML	7992	19750	3.15
Water	WATR	582	1439	0.23
Wetlands-Mixed	WETL	1508	3727	0.59
Wetlands-Non-Forested	WETN	88.9	217.2	0.03

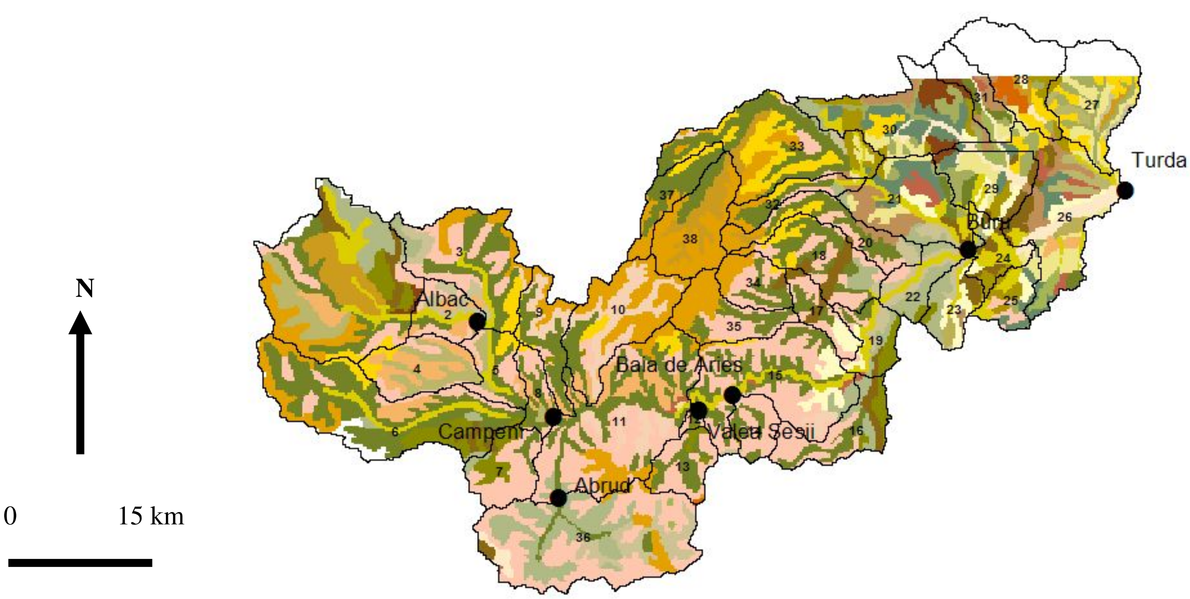

Figure 5. Surficial soil types within the Aries River sub-basins. Colors represent different soil types.

Table 3. Aries River sub-basin soil type characteristics used in model construction.

[ha, hectares; m, meters; %, percent]

#	Soil Type	Area ha	Area acres	Basin %	#	Soil Type	Area ha	Area acres	Basin %
1	ra025	47256	116772	18.6	31	ra058	1660	4102	0.65
2	ra030	45099	111441	17.8	32	ra003	1557	3848	0.61
3	ra054	21255	52523	8.37	33	ra017	1324	3271	0.52
4	ra031	14610	36102	5.75	34	ra067	1264	3124	0.5
5	ra033	8567	21169	3.37	35	ra044	1156	2857	0.46
6	ra023	8181	20217	3.22	36	ra051	1172	2895	0.46
7	ra036	7259	17937	2.86	37	ra039	985.2	2434	0.39
8	ra019	6076	15014	2.39	38	ra011	771.2	1906	0.3
9	ra037	5739	14183	2.26	39	ra063	701.4	1733	0.28
10	ra043	5155	12737	2.03	40	ra021	668.2	1651	0.26
11	ra034	4719	11660	1.86	41	ra066	659.8	1631	0.26
12	ra008	4599	11366	1.81	42	ra018	587.7	1452	0.23
13	ra046	4512	11150	1.78	43	ra047	596.1	1473	0.23
14	ra035	4441	10974	1.75	44	ra059	554.4	1369	0.22
15	ra055	4407	10889	1.73	45	ra006	540.1	1335	0.21
16	ra002	4298	10620	1.69	46	ra049	492.6	1217	0.19
17	ra040	4097	10124	1.61	47	ra041	422.5	1044	0.17
18	ra048	3995	9872	1.57	48	ra050	443.0	1095	0.17
19	ra045	3913	9668	1.54	49	ra005	385.8	953.3	0.15
20	ra042	3642	8999	1.43	50	ra007	329.8	814.9	0.13
21	ra024	3353	8286	1.32	51	ra001	310.9	768.3	0.12
22	ra061	3004	7423	1.18	52	ra012	282.1	696.7	0.11
23	ra065	2659	6571	1.05	53	ra057	268.7	664.1	0.11
24	ra028	2636	6512	1.04	54	ra064	206.2	509.4	0.08
25	ra038	2590	6400	1.02	55	ra060	183.4	453.3	0.07
26	ra020	2455	6065	0.97	56	ra026	99.76	246.2	0.04
27	ra010	2168	5356	0.85	57	ra027	63.99	158.1	0.03
28	ra029	1978	4888	0.78	58	ra032	21.06	52.06	0.01
29	ra052	1841	4549	0.72	59	ra062	21.87	54.04	0.01
30	ra056	1792	4427	0.71	60	ra022	2.298	5.679	0

Climate and Streamflow

Climate and streamflow measurements taken in the Aries River basin were obtained from six national hydrometeorological stations—Abrud, Albac, Baia de Aries, Buru, Campeni, and Turda—and a seventh at Valea Sesei operated by the Rosia Poieni mine. All of these data were presented as paper records with no indication of quality control or quality assurance. To be able to use and evaluate these data, all paper records were converted to digital format. A cursory review was performed on all of the data to identify time gaps in the record, as well as measurement outliers. Because SWAT requires a continuous record of both daily precipitation (rain and snow) and temperatures (minimum and maximum) over the period of model calibration and simulation, the most obvious and immediate concerns were associated with differing periods of record and differing types of measurements (precipitation, temperature, radiation, and streamflow discharge) recorded (table 4).

Whereas all of the hydrometeorological stations have continuous precipitation and streamflow measurements, the temperature measurements cover only 6 months from October to March. Because the recorded temperatures provided by the Romanians represented a daily average, they could not be used. To remedy this situation, the hourly temperature data recorded at the Baisaora station located northeast of Baia de Aries between sub-basins 20 and 32 (latitude: 46.5330^0 N, longitude: 23.3170^0 E, elevation 1,356 m) were retrieved using the National Oceanic and Atmospheric Administration (NOAA) web server at the National Climatic Data Center (NCDC) (go to discovery map at *http://gis.ncdc.noaa.gov/aimstools/gis.jsp*). The Baisaora data provided a continuous record of daily minimum and maximum temperatures (fig. 6) for input to the SWAT model (baisaora_C.dbf). Daily precipitation information (fig. 7) used in the initial SWAT model (baia_P.dbf) were taken from the Baia de Aries station located on the main stem of the Aries River (latitude: 46.3818^0 N, longitude: 23.2834^0 E, elevation: 483 m). A summary of selected SWAT files used in the model construction process is provided in table 5.

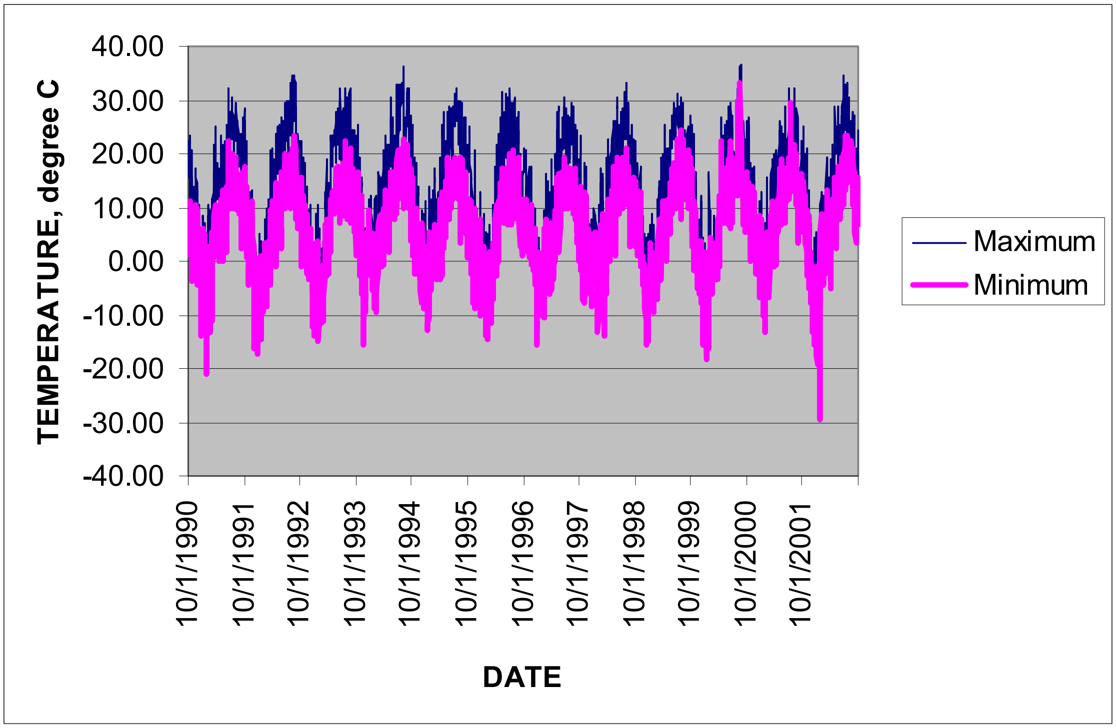

Figure 6. Temperature range at Baisora monitoring station from 10/1/1990 to 10/30/2001 (latitude: 46.5330^0 N, longitude: 23.3170^0 E, elevation: 1,356 m)

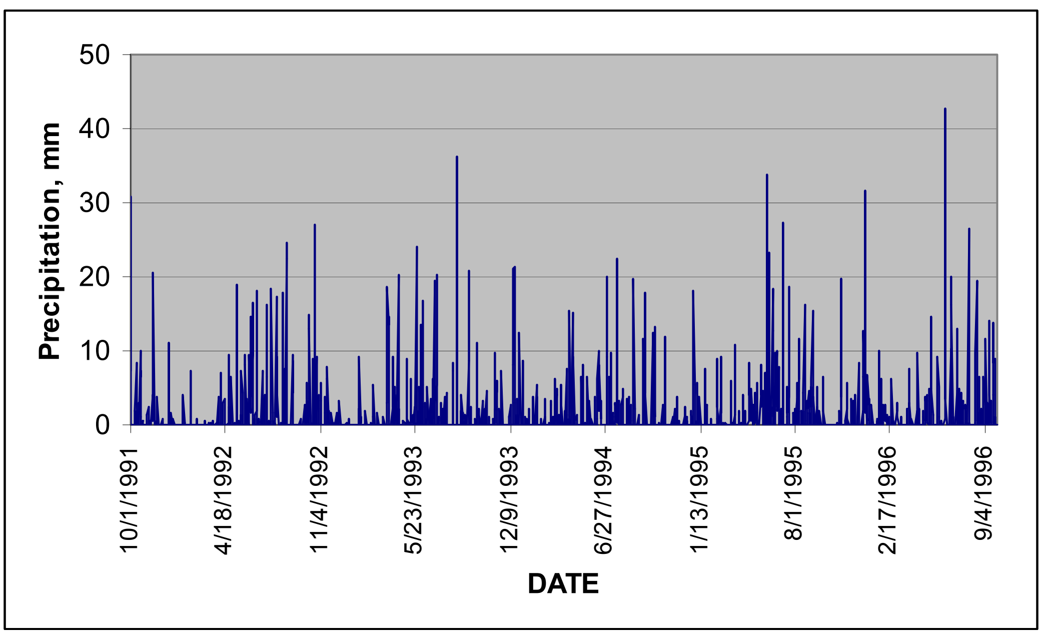

Figure 7. Daily precipitation recorded at the Baia de Aries monitoring station (latitude: 46.3818^0 N, longitude: 23.2834^0 E, elevation: 483 m). Period of record shown (10/1/1991 to 9/30/1996) is used in the SWAT calibration.

Model Calibration and Validation

To effectively use the SWAT model for the evaluation of long-term storage, mobilization, and transport of contaminated sediment, both the flow and transport model components require model calibration (optimal estimation of their respective parameter values) and validation (comparative SWAT simulation to streamflow observed over an alternate time period for measurements not used in calibration). The period from 10/1/1991 to 9/30/1996 was used for calibration, and the period from 10/1/1996 to 9/30/2001 was available for model validation. The first year of each simulation was not included in assessing the calibration because that year was needed as an initialization period to reduce the effect of the assumed initial condition specified for soil moisture.

The Aries River basin SWAT model calibration consisted of manually changing selected parameter values. For example, the magnitude of direct runoff in the model was controlled using the curve number parameter (CN) specific for each hydrologic response unit. In addition to adjusting the CN values, the hydraulic conductivities were increased, generally by an order of magnitude. After calibrating to the runoff peaks in each model, attempts were made to match simulated base flow to observed base flow by modifying values of parameter groups such as ground-water delay, infiltration, and soil capacity. Following these adjustments, the magnitude and temporal distribution of some streamflow peaks were similar to those of the observed discharge (fig. 8). The calibration progress following these changes to model parameter values was monitored by evaluating several statistical criteria such as a least-squares objective function that was updated following each simulation (flow_sep.xls).

Table 4. Summary of available climate and streamflow data for Aries River basin.

Station	Location	Measurement type	Frequency	Period of record Begin	End	Number years	Filename
Abrud	Aries						
	River	Precipitation	daily	1993	2001	9	Abrud.xls
	Mainstem			2002		1,2 mos	Abrud.xls
		Streamflow	daily	2003	2004	2	Abrud.xls
		Temperature	daily	NONE	NONE	NONE	NONE
		Radiation	daily	NONE	NONE	NONE	NONE
Albac	Aries	Precipitation	daily	1989	2004	15	Albac.xls
	River	Streamflow	daily	1989	2004	15	Albac.xls
	Mainstem	Radiation	daily	1989,90,92,93,94		5	Albac.xls
		Temperature	daily	2000	2004	5	Albac.xls
		Solid flows	daily	1991,94,95-2004		11	Albac.xls
Buru	Aries	Precipitation	daily	1978	2004	26	Aries_buru.xls
	River	Streamflow	daily	1978	2004	26	Aries_buru.xls
	Mainstem	Termperature	daily	2000	2004	5	Aries_buru.xls
		Radiation	daily	1986	2004	19	Aries_buru.xls
		Solid flows	daily	NONE	NONE	NONE	NONE
Baia de Aries	Aries	Precipitation	daily	1950	1955	6	Baia de Aries.xls
	River	Streamflow	daily	1950	1955	6	Baia de Aries.xls
	Mainstem	Precipitation	daily	1978	2004	26	Baia de Aries.xls
		Streamflow	daily	1978	2004	26	Baia de Aries.xls
		Temperature	daily	2001	2004	3	Baia de Aries.xls
		Radiation	daily	NONE	NONE	NONE	NONE
		Solid flows	daily	NONE	NONE	NONE	NONE
Valea Sesei	Aries	Precipitation	daily	2001	2004	4	Valea Sesei.xls
	River	Streamflow	daily	2001	2004	4	Valea Sesei.xls
	Tributary	Temperature	daily	2002	2004	3	Valea Sesei.xls
		Radiation	daily	NONE	NONE	NONE	NONE
		Solid flows	daily	NONE	NONE	NONE	NONE
Turda	Aries	Precipitation	daily	2003	2004	2	Aries_turda.xls
	River	Streamflow	daily	2003	2004	2	Aries_turda.xls
	Basin	Temperature	daily	NONE	NONE	NONE	NONE
	Outlet	Radiation	daily	NONE	NONE	NONE	NONE
		Solid flows	daily	NONE	NONE	NONE	NONE
		Streamflow	monthly	1951	2004	54	turda.xls

Table 5. Summary of selected SWAT model files used in Aries River Basin simulations. These data are available on the accompanying CD.

Model	Aries River Basin
Folder	SWAT_model_files
File location	Path\filename.grd,shp,mxd,xls
Spatial Data	C:\BASINS\data\
DEM	romania\DEM\srtm_41_03\project_extr1.grd
Mask	romania\Watershed\aries\shapes\Waters8.shp
Streams	romania\Watershed\aries\shapes\riv9.shp
Sub-basins	romania\Watershed\aries\shapes\watsub12.shp
Gage stations	romania\streamflow\aries_gages_Project.shp
Land use location	romania\Features\Land_cover2000_Albers.shp
Soil type location	romania\Features\feature_soil3.grd
Arc .mxd file	romania\swat_check_090606.mxd
Soil parameters	Usersoil.dbf
Soil location	Soils_ST70_Project.dbf
Temporal Data	
Precipitation	romania\ baia_P.dbf
Solar radiation	romania\ romania_monthly_PCP_nSolrad.xls
Temperature	romania\ baisaora_C.dbf
Streamflow	romania\ *.dbf romania\ *.dbf
Coordinates and filenames	romania\Climate.dbf
Filenames used for weather data	romania\Precip.dbf
Summary Data	
Land use and soils	\text\LanduseSoilRepSwat.txt
Hydrologic response units	\text\HruLanduseSoilRepSwat.txt
Calibration Data	
Period of record	1991-1996 flow_sep.xls macro to update flow_sep.xls data/figs. following each simulation Cntl-S

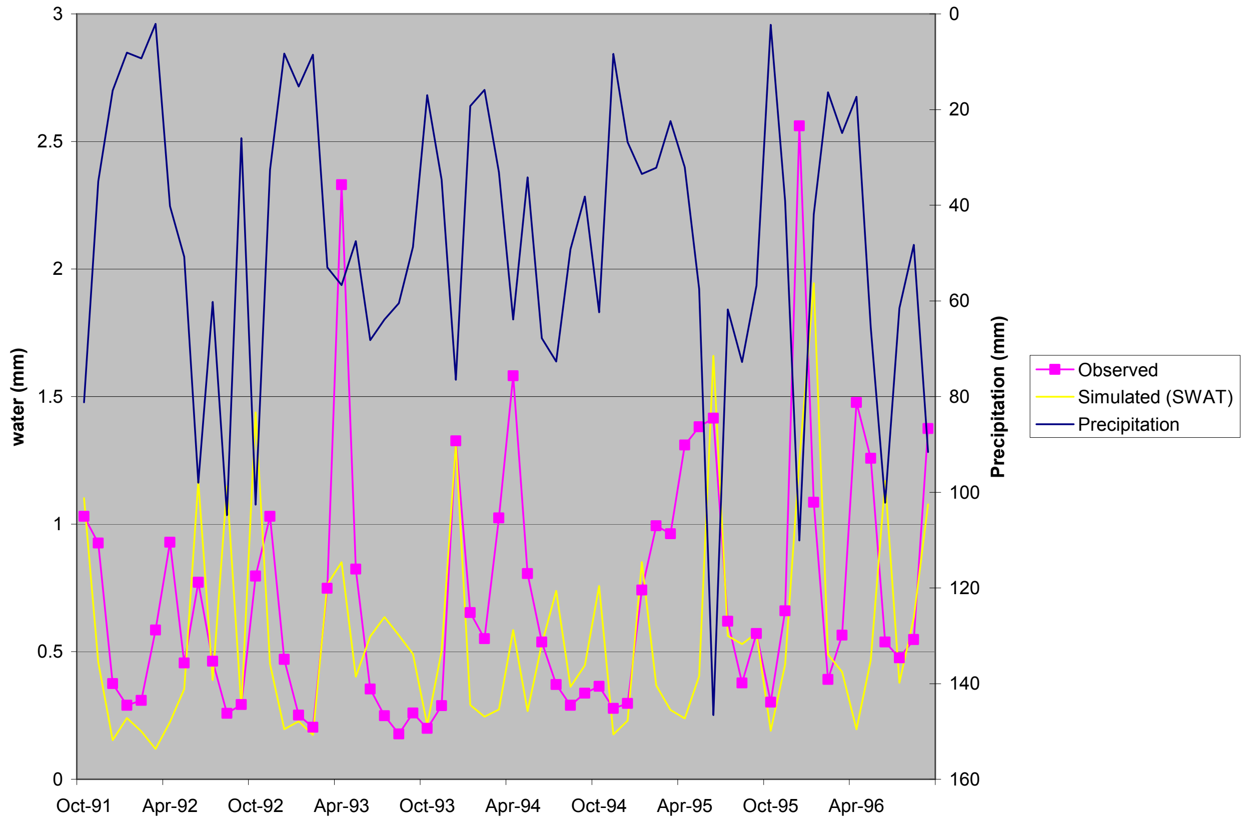

Figure 8. Observed versus simulated (SWAT) mean monthly streamflow discharge at Turda.

Results

The initial Aries River basin SWAT model could not be manually calibrated to accurately reproduce monthly streamflow discharge values observed at Turda (fig. 8). Whereas the least-squares objective function values (defined as the sum of squared differences between observed and simulated streamflow discharge) dropped with consecutive parameter value modifications, indicating a progressively better profile match, the final statistical criteria showed that the estimated parameter values were of poor quality. For example, one of the traditional statistical criteria used to determine the success of the model calibration process is a Nash-Sutcliffe-score (Nash and Sutcliffe, 1970) equal to or greater than 0.5. Following this model calibration process, the Nash-Sutcliffe score improved from a negative value to about 0.1. For this reason, no attempt was made to validate the streamflow discharge, to calibrate soil erosion and transport parameters, or to conduct predictive analysis (Friedel, 2005; 2006).

The inability to estimate reasonable model parameter values during the manual calibration process is attributed to the limited and poor data quality. Specifically, the climate and soils data used to represent basin processes were treated as spatially homogeneous, despite the fact that there were 67 soil types mapped. In addition, the correlation coefficient between precipitation recorded at two stations with different elevations (Baisaora, 1,134 m, and Baia de Aries, 543 m) was weak (0.2), also indicating heterogeneous spatial processes (fig. 9) not accounted for in the model.

Another likely factor contributing to the poor match between observed and simulated streamflow discharge is the comparatively limited streamflow information available to calibrate the model when using only the Turda discharge record. Note how the correlation coefficients decrease when comparing the complete period of record (table 6) to the 2004 water year (table 7). This decrease shows temporal heterogeneity and the importance of calibration using multiple stations and longer periods of record. In addition, the intermediate correlations between gage stations not including Valea Sesei and Turda probably reflect similar precipitation but differences in local surface-water withdrawals for public consumption. The poor correlation of Valea Sesei discharge with other gage sites can be attributed to the controlled source outlet of mine discharge from the tailings pond. The decreased correlation between gage records upstream with Turda is uncertain. The poor correlation between streamflow records at Turda with the other gage stations underscores the importance of using multiple gage sites for calibration of our model parameters. To reach the ultimate goal of understanding long-term storage, mobilization, and transport of contaminated sediment following failure of a mine tailings dam, additional model refinements and calibration should be undertaken. The following section provides suggested improvements in order of their importance.

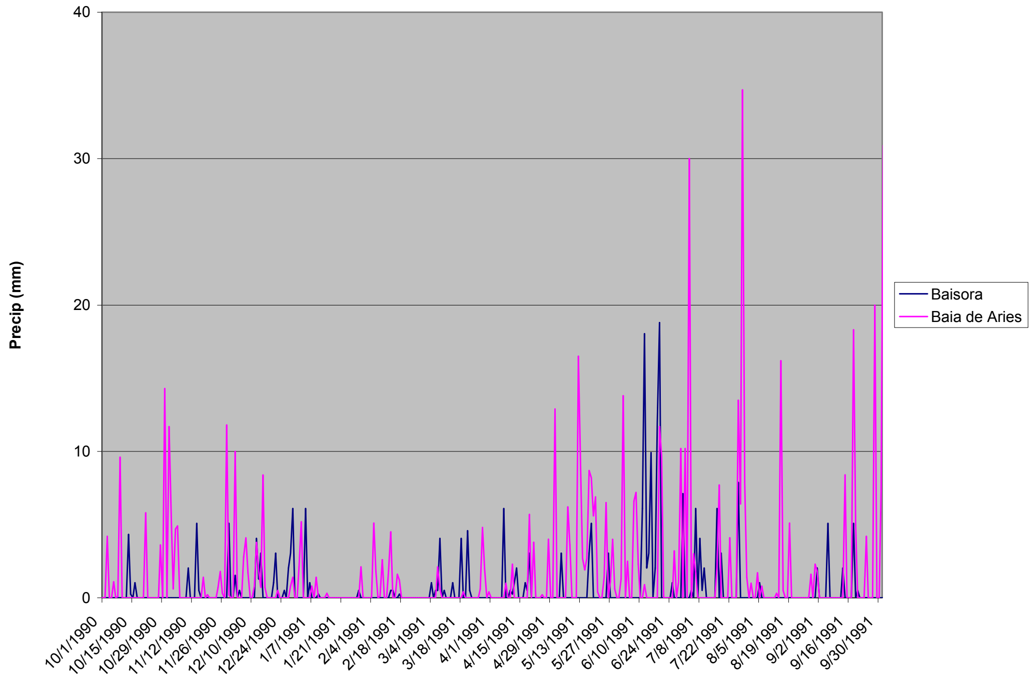

Figure 9. Comparison of precipitation at monitoring stations at Baisaora (latitude: 46.5330^0 N, longitude: 23.3170^0 E, elevation: 1356 m) and Baia de Aries (latitude: 46.3818^0 N, longitude: 23.2834^0 E, elevation: 483 m) from 10/1/1990 to 10/30/1991. The correlation coefficient over complete record was poor (0.2), showing spatial heterogeneity.

Table 6. Correlation matrix for streamflow between gage stations (in order downstream from headwaters) over their total period record in the Aries River basin. High correlation coefficients are bolded, showing a strong relation between stations.

	Albac	*Abrud*	*Baia de Aries*	*Buru*	*Turda*
Albac	1.00				
Abrud	**0.79**	1.00			
Baia de Aries	**0.92**	**0.89**	1.00		
Buru	**0.88**	**0.89**	**0.96**	1.00	
Turda	0.30	0.25	0.31	0.32	1.00

Table 7. Correlation matrix for median streamflow discharge between gage stations in Aries River basin, 2004. Intermediate correlation coefficients are bolded (there were no high correlation coefficients), showing a relation between stations.

	Location	Mainstem	Mainstem	Tributary	Mainstem	Mainstem	Tributary
Location	*Station*	*Albac*	*Abrud*	*V. Sesei*	*Baia de Aries*	*Buru*	*Turda*
Mainstem	*Albac*	1					
Mainstem	*Abrud*	0.43	1				
Mainstem	*V. Sesei*	**0.55**	0.42	1			
Mainstem	*Baia de Aries*	**0.55**	0.23	0.29	1		
Tributary	*Buru*	0.22	0.44	0.28	**0.62**	1	
Tributary	*Turda*	0.00	-0.26	0.09	0.25	-0.23	1

Suggestions for Model Improvement

Model input

Spatial precipitation and temperature

Presently, the climate information over the calibration period of record is represented by a temperature/time series and precipitation/time series from two different locations and elevations. Because spatial climate information has a first-order influence on model uncertainty, introducing spatial precipitation and temperature time series would improve the parameter estimation process, resulting in a better match between observed and simulated streamflow. One suggestion is to derive time series using the downscaled climate approach described by Hay and others (2003), and Clark and Hay (2005). In this approach, climate data from the NOAA website for about 35 Romanian meteorological stations (fig. 10), representing various elevations across the Aries River Basin, would be used to statistically derive spatial and temporal precipitation and temperature data sets for each model sub-basin. Because these data sets would represent climate information at the centroid of each model sub-basin, these time series could be used in the Aries River basin SWAT model for improved model calibration, simulation, and predictive analysis.

Spatial soil parameters

Because there was no soil information available during the initial model construction phase, the initial model calibration uses 67 basin soil types (fig. 5), but all have the same parameter values (homogeneous). After this initial model was prepared, new soil parameter information was provided to the team. Consequently, an obvious suggestion is to update the soil model parameters using values from this published soil information to account for spatial variation (heterogeneity) across the Aries River basin. Whereas introducing soil heterogeneity into the model will undoubtedly improve the estimated parameter values, the manual model calibration process will take longer.

Point sources and sinks

Another suggestion to improve the model is to find and introduce information on the location and magnitude of streamflow withdrawal and return flows within the basin.

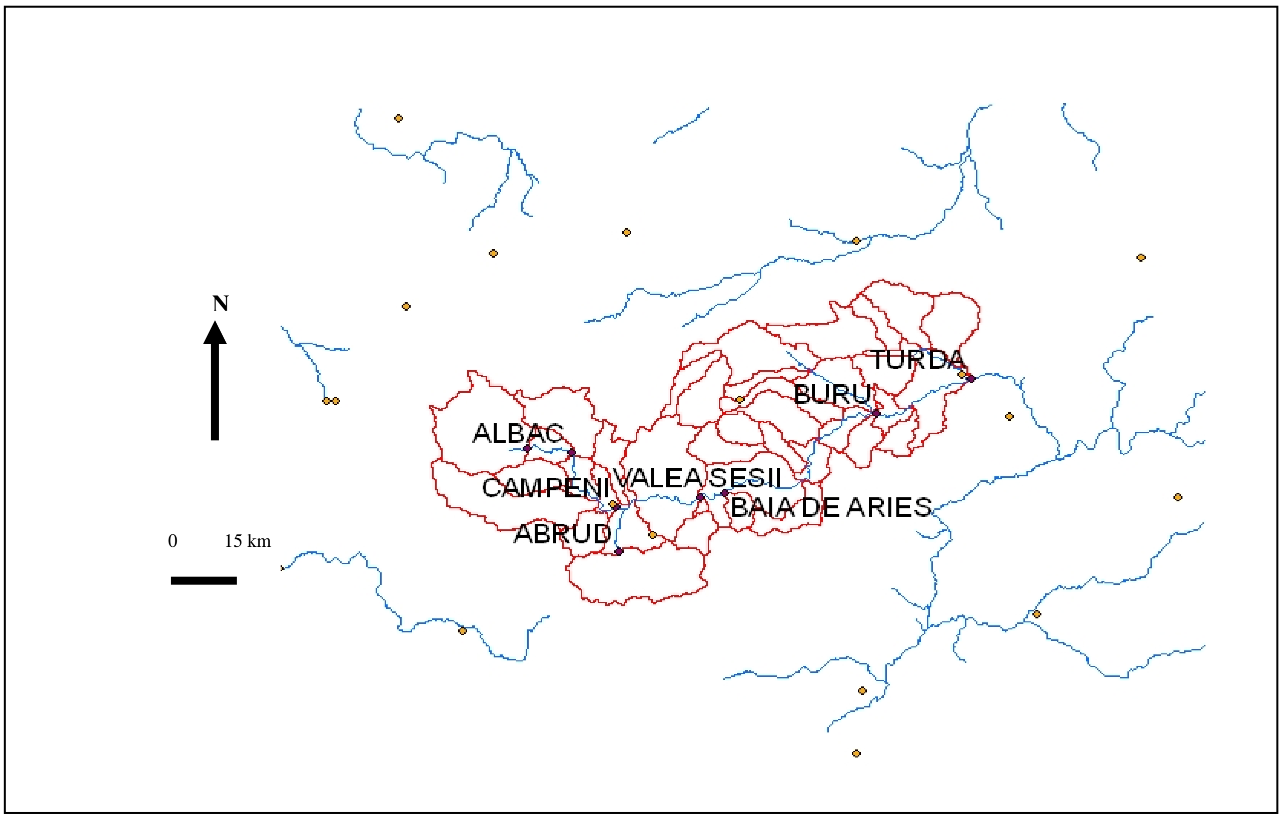

Figure 10. Stations (triangles) for which NOAA has climate data available for estimating sub-basin time series using a downscaled approach. Blue lines represent streams in surrounding basins.

Model calibration

Streamflow

Given the level of implied heterogeneity discussed in the model input and the lack of correlation between streamflow gage stations, a two-tiered calibration strategy is suggested. First, the calibration of parameter values should be based on the long-period (1951-2003) monthly median streamflow at Turda. Second, these estimated parameter values should be used as the initial parameter values for calibration using daily streamflow discharge values over various periods at the seven primary gage stations (Albac, Abrud, Campeni, Valea Sesei, Baia de Aries, Buru, and Turda).

Validation

For the models to be accepted as reasonable representations of hydrologic processes in the Aries River basin, the simulated hydrographs should be similar to the observed hydrographs and the estimated mass balances should be consistent with the long-term means noted previously. The Nash-Sutcliffe scores for the calibration and validation periods should be greater than 0.5.

Sensitivity Analysis and Nonlinear Regression

The introduction of heterogeneity into the SWAT model will increase the number of soil parameters by more than an order of magnitude. For example, instead of one set of 10 primary soil parameters there will be 67 sets, giving 670 soil parameter values that may require calibration. This number of parameters is an intractable problem for manual calibration. One suggestion is to apply a nonlinear regression algorithm, such as described by Doherty (2004), to calibrate the model parameter values. One advantage of using nonlinear regression to calibrate the model is the ability for a direct evaluation of parameter sensitivities and for eigenvector analysis (Friedel, 2005). In using this approach, the insensitive parameters can be identified and removed from the calibration process, thereby reducing model uncertainty. Another advantage is the possibility of simultaneously calibrating all parameter values in a one-tiered approach, using all of the streamflow measurements.

Predictive analysis

When model calibration is conducted mathematically, the process leads to the estimation of an optimal set of parameter values that will be non-unique (Friedel, 2006). For this reason, the simulation for water or sediment transport will represent one of an infinite number of possible outcomes; therefore, computing the minimum and maximum limits of nonlinear uncertainty for a prediction is suggested. The ability to place limits on the prediction uncertainty is inherently stronger than simply testing the model validity using a traditional split-sample approach (Friedel, 2005).

Summary and Conclusions

The initial Aries River Basin SWAT model could not be manually calibrated to accurately reproduce monthly streamflow discharge values observed at the Turda gage station. The inability to estimate reasonable model parameter values during the manual calibration process is attributed to three issues. First, the available soils and precipitation data at the time of this study was spatially limited and of poor quality. Second, the streamflow information content used to calibrate the model was limited to the Turda discharge record. Third, the manual calibration process is time consuming and can not arrive at an optimal set of parameter values. Given the level of implied heterogeneity discussed in model input and the lack of correlation between streamflow gage stations, a two-tiered calibration strategy is suggested for model improvement.

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