SWAT

2014 Conference
Pernambuco, Brazil

Conference Proceedings

Texas Water Resources Institute Technical Report – TR-472

JULY 30 - AUGUST 1, 2014 – ARMAÇÃO HOTEL, PORTO DE GALINHAS, BRAZIL

Texas Water Resources Institute
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Soil & Water Assessment Tool | SWAT

The Soil and Water Assessment Tool (SWAT) is a public domain model jointly developed by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, part of The Texas A&M University System.

SWAT is a small watershed to river basin-scale model to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds.

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Foreword

The organizers of the 2014 International SWAT Conference want to express their thanks to the organizations and individuals involved and their preparation and dedication to coordinate a successful conference. We would also like to thank the Scientific Committee for their support in preparing the conference agenda and allowing for scientists and researchers around the globe to participate and exchange their scientific knowledge at this conference.

A special thank you to Pernambuco Federal University and Pernambuco Federal Rural University along with Suzana Maria Gico Lima Montenegro, Josiclêda Galvíncio, Josimar Gurgel Fernandes, and Danielle de Almeida Bressiani for their countless hours and efforts to host the SWAT Community. On behalf of the SWAT Community, we extend our sincere gratitude to you and your university for the kind invitation and welcoming hospitality.

The following Conference Proceedings contains papers covering a variety of topics including but not limited to large scale applications; climate change applications; model development; database and GIS application and development; environmental applications; hydrology; best management practices (BMPs); sensitivity, calibration and uncertainty; pesticide, bacteria, metals and pharmaceuticals; sediment, nutrients, and carbon, urban processes and management; and more.

The Conference Organizers hope you enjoyed the conference and continue to view these SWAT gatherings as a positive opportunity for our international research community to share the latest innovations developed for the Soil and Water Assessment Tool.

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The SWAT Literature Database: Overview of Database Structure and Key SWAT Literature Trends

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Abstract

The SWAT Literature Database for Peer-Reviewed Journal Articles can be accessed directly at https://www.card.iastate.edu/swat_articles/ or via a weblink at the SWAT model homepage (http://swat.tamu.edu/). The origins of the database can be traced to the "Comprehensive review of SWAT model paper" (also accessible via a weblink on the SWAT model homepage) that was published in Transactions ASABE in 2007. At that time, over 260 SWAT-related articles were documented in the peer-reviewed literature. By the time of the 2014 International SWAT Conference, 1,700 SWAT-related peer-reviewed papers were entered in the database. The majority of papers included in the database have been written in English although citation data has also been included for some papers written in other languages (e.g., Chinese, Farsi, German, Portuguese and Spanish). In addition, most of the papers included in the database describe some type of specific application of the standard SWAT model. However, other types of papers are also included which describe key predecessor or related models (i.e., ALMANAC, APEX, EPIC, GLEAMS, ROTO, SWRRB), applications of modified SWAT models including the SWIM model, or other types of pertinent analyses such as review studies that include discussion of SWAT. A general overview of the structure of the database is presented here including the types of papers included, search options, and other details. Key trends in the SWAT literature will are also described based on the literature that has been included in the database up until the time of that the conference was held in July 2014.

Keywords: SWAT model, modified SWAT models, literature database, peer-reviewed literature, citations, SWAT literature trends

Introduction

The original version of the Soil and Water Assessment Tool (SWAT) watershed-scale ecohydrological model (Arnold et al., 1992; Arnold et al., 1998; Williams et al., 2008) represented an interface of the Simulator for Water Resources in Rural Basins (SWRRB) water quality model (Williams et al., 1985) with the Routing of Outputs to the Outlet (ROTO) model (Arnold et al., 1995), and included components from other models plus new components to support comprehensive watershed- and river basin-scale water resource studies. Continued development of the SWAT code has continued virtually unabated since that time, resulting in releases of several major new versions during the past two decades (Arnold et al., 1998; Arnold and Fohrer, 2005; Gassman et al., 2007; Williams et al., 2008; Neitsch et al., 2011; Tuppad et al., 2011; Arnold et al. 2010b; 2011; 2012a; 2012b) as well as numerous minor subversions.

Initial use and development of SWAT was primarily conducted by U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) and Texas A&M University scientists co-located at laboratories in Temple, Texas. Broader use of SWAT by other scientists, governmental agency personnel and additional users started gradually during the later 1990s, began to expand more rapidly in the first few years of the 21st century (Arnold and Fohrer, 2005; Gassman et al., 2007) and has greatly increased during the past decade. Gassman et al. (2007) documented over 260 SWAT-related studies in the peer-reviewed English journal article literature when they published their study in 2007. By the time of the 2014 International SWAT Conference, 1,700 SWAT-relevant studies were included in the SWAT Literature Database for Peer-Reviewed Journal Articles, which can be accessed directly at CARD (2014) via a weblink at the SWAT model homepage (SWAT, 2014a).

The majority of studies included in the SWAT Literature Database have been written in English although some are written in other languages; e.g., Chinese, Korean, Portuguese, Spanish, Farsi and German. In addition, most of the studies included in the database describe some type of specific application of the standard SWAT model. However, other types of studies have been entered in the database including: (1) applications of modified SWAT models, (2) review studies focused either on SWAT or comparisons of SWAT with other models, (3) studies that describe data and/or component development directly relevant to SWAT users, and (4) a limited set of studies which describe key predecessor or related models; i.e., ROTO, SWRRB, the Environmental Policy Impact Climate (EPIC) model (Williams et al., 2008), the Groundwater Loading Effects of Agricultural Management Systems Groundwater Loading (GLEAMS) model (Leonard et al., 1987), the Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 2008) or the ALMANAC Boreal Forest (ALMANACBF) variant (MacDonald et al., 2008), and the Agricultural Policy/Environmental eXtender (APEX) model (Williams et al., 2008; Gassman et al., 2010).

The objectives of this research are: (1) briefly describe the origins of the SWAT Literature Database, (2) describe the structure of the database including the types of papers that are included, how the papers are categorized, search options and other details, and (3) present some key trends in the SWAT literature including the range and types of journals entered in the database and some of the key application trends, based on the 1,700 papers entered in the database by late July, 2014 (just prior to the 2014 International SWAT Conference).

Database Origins

The original tracking of SWAT literature was in the form of a reference list that was created by Dr. Manuel Reyes (Personal communication. 2005. North Carolina A&T Univ., Greensboro, North Carolina) approximately a decade ago and maintained at that time on the SWAT website. The literature list evolved into a SWAT literature review paper that was presented at the 2005 SWAT International Conference held in Zurich, Switzerland (Gassman et al., 2005). The SWAT literature review paper provided the foundation for a more extensive review paper covering SWAT peer-reviewed journal article literature through approximately mid-2007 (Gassman et al., 2007). The subjective classification of 263 peer-reviewed SWAT journal articles identified in the literature at that time is shown in Table 1. This was intended to present a quick overview of the SWAT literature reviewed in Gassman et al. (2007) by categorizing the articles in one of three broad categories (hydrologic only, hydrologic & pollutant, and pollutant only) and one of the eight primary categories. The three broad categories revealed that the literature was virtually evenly split at that time between studies that reported only hydrologic results versus studies that reported both hydrological outputs and one or more pollutant indicators, while a small number of studies reported just pollutant indicators (recognizing that "pollutant only" studies were obviously based on underlying hydrological simulations but the authors chose not to report hydrological output as part of their results). The primary application categories reflect dominant trends in the types of studies that were reported in the SWAT literature at that time.

Table 1. Original categorization of SWAT peer-reviewed journal article literature in 2007[a].

Primary Application Category	Hydrologic Only	Hydrologic & Pollutant	Pollutant Only
Calibration and/or sensitivity analysis	15	20	2
Climate change impacts	22	8	--
GIS interface descriptions	3	3	2
Hydrologic assessments	42	--	--
Delineation or input data effects	21	15	--
Comparisons with other models/methods	5	7	1
Interfaces with other models	13	15	6
Pollutant assessments	--	57	6

[a]Source: Gassman et al. (2007)

The categorization of SWAT articles in Gassman et al. (2007) was a catalyst for an expanded on-line SWAT Literature Database, which was initially conceptualized by authors Gassman and Srinivasan in communications that occurred during 2007. Development of the first version of the on-line database began sometime later in 2008 and became accessible to the global internet community in early 2009. The current structure of the database reflects gradual evolution of the SWAT peer-reviewed journal article literature since that time as well as occasional enhancements or additions of database features. The categorization of SWAT articles in the current database was directly influenced by the classification scheme used in Table 1 although the number of categories has since expanded considerably as described below.

Overview of Database

The citation data included in the SWAT Literature Database is limited to "peer-reviewed journal articles", with recognition that the peer review process is much stronger and legitimate for some publishers/journals versus others. Some articles included in the database appear in journals maintained by publishers who have been identified as using questionable or unethical publishing practices (Beall, 2014). Also, thousands of SWAT-related articles or reports exist in the so-called grey literature that encompasses government reports, conference papers, etc. (Wikipedia, 2014) including hundreds of SWAT-related studies in SWAT conference proceedings alone (SWAT, 2104). SWAT articles published in the realm of such grey literature are excluded from the database although many may be of higher quality than some of the journal articles included in the database. Database users are encouraged to exercise discernment regarding the source of specific articles logged in the database and the usage of a given article in their own research.

Each entry included in the database includes specific citation information for the study (e.g., authors, title, journal, year published), language the study was published in, the watershed or region the study was performed for, abstract, and keywords. Calibration, validation, and/or other general information is also available for a limited set of articles included in the database. A Digital Object Identifier (DOI) and/or Uniform Resource Locator (URL) is also provided for the vast majority of articles. Only 25% of the abstracts were visible for the 1,700 papers considered for this study, due to the need to obtain permission from publishers to display the abstracts. But it is anticipated that more abstracts will become visible as additional permissions are obtained from specific publishers in the future. And users can easily access abstracts for most articles via the DOI or URL links. All abstracts are included in database searches as described below.

Each article is categorized in up to three categories: broad, primary or secondary (primary and secondary categorizations are described below). The distribution of the 1,700 articles per the 13 broad categories included in the database is shown in Table 2. The three original broad categories (Table 1) remain dominant, with a total of 1,553 articles classified as hydrologic only, hydrologic & pollutant, or pollutant only (Table 2). The other 10 categories included in Table 2 reflect the growing diverse types of studies that are relevant to the SWAT user community, including articles describing reviews of SWAT for specific types of applications, comparisons of SWAT with other models, or other types of review studies (62 total in the review/history category), as well as very specific types of applications that require a specific broad category (e.g., crop/plant growth and carbon cycling).

Thirteen different languages were represented in the database (Table 3) with the vast majority published in English (1,618 out of 1,700 articles, with three of those articles published in both Spanish and English). However, limited internet searches hint that considerably more peer-reviewed SWAT-related journal articles exist in some languages, especially Chinese and Korean. Virtually all of the non-English articles have English abstracts and keywords. However, accurate classification of non-English articles into the broad, primary and secondary categories is constrained by the limited amount of English information available only in the abstracts.

Table 4 presents the distribution of the 1,700 articles by specific models represented in the database. Nearly 1,500 articles describe some sort of application or review of the standard SWAT model (specific versions of SWAT are not identified in the database). These include a limited number of studies in which the authors use SWAT results from a previous study rather than reporting new SWAT analyses (e.g., Ide et al., 2014). Over 160 articles describe an

Table 2. Broad categorization of articles (out of 1,700) in SWAT Literature Database

Category	Total papers	Category	Total papers
hydrologic only	781	pre-SWAT or SWAT-related	10
hydrologic & pollutant	643	crop/plant growth	7
pollutant only	129	computational approaches	6
review/history	62	BMP review or conceptual approach	5
interface tool and/or other software	20	carbon cycling	3
conceptual approach	16	watershed descriptions	3
data or component development	15		

Table 3. Total articles by language (out of 1,700) in SWAT Literature Database[a]

Language	Total papers	Language	Total papers
English	1,614	Indonesian	4
Chinese	35	German	3
Portuguese	15	Spanish & English	3
Korean	8	Basque	1
Spanish	6	Polish	1
Farsi	4	Romanian	1
French	4	Vietnamese	1

Table 4. Total articles by specific model (out of 1,700) in SWAT Literature Database

Specific model or combinations of models	Total papers
SWAT	1,492
ESWAT	9
SWAT-G	14
SWIM	31
SWAT (modified)	80
SWAT (modified) & SWAT	27
Pre-SWAT or SWAT-related[a]	12
Pre-SWAT or SWAT-related[a] & SWAT	15
None	20

[a]Includes ALMANAC, ALMANACBF, APEX, EPIC, GLEAMS, SWRRB and/or ROTO

application or review involving a modified version of SWAT (Table 4) including modified models with unique names such as Soil and Water Integrated Model (SWIM; Krysanova et al., 1998), Extended SWAT (ESWAT; van Griensven and Bauwens, 2001), and SWAT-Germany (SWAT-G; Eckhardt et al., 2002). Many articles describe interfaces with other models such as the MODFLOW groundwater model (e.g., Menking et al., 2004; Kim et al., 2008) or comparisons with other models such as the Hydrological Simulation Program-Fortran (HSPF) water quality model (e.g., Van Liew et al., 2003; Saleh and Du, 2004). No attempt is made to track other models that appear in the SWAT literature that were not developed and/or maintained at the co-located USDA-ARS and Texas AgriLife laboratories in Temple, Texas (as described in Williams et al., 2008). However, multiple models are indicated in a database entry for interfaces or comparisons between two or more "Temple models" (e.g., APEX and SWAT).

Primary and Secondary Categories

The 43 categories listed in Table 5 (including a "none" category) reflect the evolution of both the specific category names as well as the number of categories used to classify the 1,700 articles into primary and secondary categories, relative to the original categories listed in Table 1. Primary classifications are included for virtually all articles in the database, with five exceptions classified as none (Table 5). Secondary classifications are also included for the majority of articles although over 200 articles were defined as none (Table 5). The combined totals of articles classified within a category (primary plus secondary articles within a given category) are ranked in Table 5. Six of the original categories (some now with revised names) listed in Table 1 are ranked in the top 10 of the total combined articles (e.g., hydrologic assessment, pollutant cycling/loss and transport, climate change), underscoring that the original categorizations remain relatively robust in capturing major trends across SWAT applications reported in the literature.

The categories listed in Table 5 reflects the increasing types of applications that SWAT is being applied to. For example, the original "Delineation or input data effects" category is now split into "input effects", "land use effects", "climate data effects", "HRU and/or subwatershed delineation effects", and "DEM effects" (Table 5). The generic input effects category is actually outdated; articles currently classified within that category will eventually be reclassified into one of the more specific category types such as land use effects or climate data effects. The "hydrologic assessment" category is a general category which covers many studies that focus on SWAT hydrologic testing, water balance and similar types of results (and practically speaking, the vast majority of the studies could be classified as a hydrologic assessment in some way). Several specific hydrologic-related categories are now included in the database such as "groundwater and/or soil water impacts", "snowmelt and/or glacier melt processes", and "evapotranspiration assessment." The pollutant cycling/loss and transport category (Table 5) encompasses studies that report results of multiple pollutant outputs; e.g., nutrient cycling and transport (nitrogen and phosphorus), sediment loss and transport, pesticide fate and transport, and/or pathogen fate and transport. However, studies that report output for just one of those pollutant loss categories are classified just in that specific category (at either a primary or secondary level); e.g., a study that describes nitrogen and/or phosphorus impacts for a stream system is classified as being in the nutrient cycling and transport category. Several of the other categories capture emerging trends in more recent literature including "crop growth/yield or plant parameters", "bioenergy crop evaluation", "land use change and climate change effects", "crop water productivity or lue/green water", "Green-Ampt application", "karst effects" and "modified curve number approach."

Table 5. Total number of articles classified by specific primary and secondary categories, and the combined total of the primary and secondary categories, in the SWAT Literature Database[a]

Rank	Primary/secondary application category	Primary[b]	Secondary[b]	Total[b]
1	hydrologic assessment	150	530	679
2	calibration, sensitivity, and/or uncertainty analysis	186	118	304
3	pollutant cycling/loss and transport	77	169	246
4	None	5	227	232
5	climate change	177	44	221
6	nutrient cycling and transport	53	125	177
7	model comparison	120	44	163
8	sediment loss and transport	57	103	160
9	model interface	130	21	151
10	BMP evaluation	88	40	128
11	input effects	86	40	126
12	land use effects	82	14	95
13	impoundment and/or wetland effects	39	28	67
14	crop growth/yield or plant parameters	27	34	61
15	economic assessment	18	27	45
16	GIS interface, GIS utility, or other type of interface/utility	39	4	43
17	groundwater and/or soil water impacts	27	15	42
18	climate data effects	32	2	34
19	snowmelt and/or glacier melt processes	19	11	30
20	BMP evaluation (genetic algorithm or similar optimization)	25	3	28
21	irrigation impacts or irrigation BMP scenarios	16	12	28
22	pesticide fate and transport	18	9	27
23	bioenergy crop evaluation	20	6	26
24	critical source area assessment	15	10	25
25	land use change and climate change effects	22	1	23
26	data/component contribution to SWAT	18	3	21
27	pathogen fate and transport	15	6	21
28	evapotranspiration assessment	14	6	20
29	review / history	12	5	20
30	computational efficiency	8	6	14
31	crop water productivity or blue/green water	13	1	14
32	modified curve number approach	12	2	14
33	tile drainage effects	10	3	13
34	soil data resolution effects	11	0	11
35	flood impacts or conveyances	7	3	10
36	HUMUS application	1	9	10
37	HRU and/or subwatershed delineation effects	8	1	9
38	in stream processes	7	2	9
39	karst effects	2	7	9
40	Green-Ampt application	4	3	7
41	urban stormwater and/or BMP evaluation	5	1	6
42	baseflow analysis techniques	2	2	4
43	DEM effects	4	0	4

[a]Total articles = 1,700, just prior to the 2014 International SWAT Conference in late July.
[b]Total occurrences for each primary and secondary category, as well as the total occurrences for the combined primary and secondary categories.

Note that classification of SWAT articles into categories listed in Table 5 is an inherently subjective process and that some articles could be easily classified into three or more categories. It is also important for users to remember that the number of primary and secondary categories is not static and will likely change in the future. In addition, it is possible that some articles that are already classified in specific primary and secondary categories could be reclassified in the future depending on what new categories are added. For example, two additional categories actually already existed by the time of the 2014 International SWAT Conference that had not yet been utilized for classifying articles in the database; i.e., "point sources" and "pollutant indices." It is anticipated that some articles already categorized in the database will be re-categorized into these two new categories in future (as well as other articles that are entered in the database in the future). Finally, it is important to note that the names of some categories currently listed in Table 5 may change in the future, if such changes can provide a better overall description of the subset of articles that are classified within that given category. I

In general, it is best to view the broad, primary and secondary categories as screening tools that can provide initial useful summaries of SWAT studies published on a particular topic. Additional search options are provided within the database that overcome the limitations of the three basic categories as described in more detail below.

Database Search Options

Search capabilities include several previously described options: (1) journal title, (2) model, (3) broad, primary, or secondary category, (4) language, or (5) year. Searches can also be performed on any word or phrase of interest and article abstracts are included in these searches (even if the abstract is not visible). Some examples of specific search results are presented in Table 6. Users should be careful in selecting and interpreting search terms; e.g., note the example in Table 6 in which a search on "India" results in including articles about SWAT applications in "Indiana."

Table 6. Example search results of 1,700 articles using general database search tool

Type of search	Example search term (total articles returned in search result)
country names	China (228[a]); India (126; 54 are "Indiana"); Iran (39); South Korea (49)
crop/plant names	rice (54); corn (71); miscanthus (13); forest (185); wheat (39)
conservation practices	cover crop (13); terrace (23); filter strip (39) stone bund (2)
climatic terms	climate change (307); precipitation (302); temperature (204); rain (612)
author last name	Arnold (147); Srinivasan (109); Wang (78[b]); Smith (16[b]); Chaubey (28)
calibration terms	auto-calibration (16); auto calibration (2); automatic calibration (23)
pollutant terms	sediment (497); nitrogen (252); phosphorus (235); pesticide (63)
impoundment terms	paddy (26); rice paddy (7); impoundment (71); wetland (78); pond (144)

[a]Two of the articles do not actually describe an application of SWAT in China; further sorting using standard database language tool results in 195 English, 31Chinese and 2 German articles.
[b]Multiple authors represented by totals of these two searches.

Nested searches or sorting can also be performed of initial sorting or search results. For example, sorting by language of the 228 articles returned from searching for "China" results in the breakdown by language described in footnote "a" in Table 6. In a second example, sorting on "nutrient cycling and transport" within the Primary Application Category yields 53 articles; sub-searches performed on those 53 articles using the terms "nitrogen" and "phosphorus" results in 28 and 25 articles, respectively. In general, caution should be used in performing nested searches at this time (more testing is needed to confirm such searches always generate sensible results).

Other Database functions

Database users have the option of uploading citation data for a peer-reviewed SWAT-related journal article; some users have taken advantage of this option. Guidance is provided in the uploading form as to how users should structure the citation data they are uploading to the database. Users also have the option to contact database staff via a weblink at the top of the database. This option has rarely been used but users are encouraged to use it more, especially if they encountered typos or other problems regarding a specific citation included in the database.

Citations for each new article are automatically generated and added to two different reference lists ordered either alphabetically or by the specific model(s) featured in the paper (see Table 4 and related discussion above). The format of the references is roughly equivalent to what is required for manuscripts submitted to *Transactions of the ASABE*. The reference list ordered by specific models is structured such that subheadings are provided by each term that shows up in the Model category (including "none") which includes every unique modified SWAT model name recorded in the database. These model name subcategories are ordered alphabetically.

A Readme document (either this specific paper or a variant of it) is provided in a weblink at the top of the database to provide guidance for users regarding the database structure, search options, etc. There is also a weblink that allows access to overview or lead-off articles for SWAT special issues published in several different journals, which are either posted on or accessible via a sublink on the SWAT model website.

Conclusions

The SWAT Literature Database is a resource available to the global SWAT user community and other interested users, that supports access to much of the SWAT peer-reviewed journal article literature that spans nearly 400 different journals (per the 1,700 articles discussed here). The database predominantly features applications of the standard SWAT model but also includes articles describing applications of modified SWAT models, review articles that include discussion of SWAT and/or modified SWAT models, and a limited number of articles describing pre- or related-SWAT models. Updating of articles in the database occurs regularly; readers will note that the number of articles in the database now exceed the 1,700 articles reported here. In addition, additions or changes to existing broad, primary and secondary categories occasionally occur and can be expected in the future. It is desired that continual updating of the database will continue long-term although this cannot be guaranteed.

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The SWAT model and a web-based information system to assess the water balance of Sardinia (Italy)

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Abstract

Thanks mostly to the achievements of Information and Communication Technologies (ICT) and the advances of computer simulation, water monitoring and assessment systems are evolving from a simple, local-scale approach toward complex spatially explicit regional applications. With support of the Sardinian Regional Water Authorities, the aim it to develop a web-based catchment observation and assessment system for the management of water resources in Sardinia. Such a system, based on the Soil and Water Assessment Tool (SWAT), compute the water resource availability for the island and monitor state indicators of the environment and their changes.

SWAT is employed to assess the water cycle of the island taking into consideration natural and/or man-made changes to the system. The Sardinian SWAT set up is composed of 108 catchments, subdivided in 1209 subbasins, each characterized by a rich variety of soil, land cover and geo-morphological regions. The model has been calibrated and validated versus stream flow data of various monitoring gages scattered within the island.

Results of the application of the model are exposed within a modern web-based information system, that exploits a Spatial Data Infrastructure (SDI), complex server side technologies and client side applications. One important effort is to improve and promote a innovative environmental management system particularly targeting observational (e.g. agricultural droughts and water quality measurements) gaps for the water domain.

In this work, we describe the implementation of the SWAT model for the Sardinian case study and how the web information system has been further developed to meet end-user's needs.

Keywords: SWAT, GIS, Web Information System, water budget, hydrology, Sardinia, Swat Cup,

Introduction

Sardinia is one of the largest islands in Europe, and after Sicily is the second in the Mediterranean sea, with a total area of approximately 24090 square kilometers. It is located in the west of the Mediterranean sea, to the west of the Italian peninsula and to the south of Corsica. Rivers are fast flowing and discharge small water volumes in winter, that are reduced to trickles in the summer. There are numerous artificial lakes used for irrigation purposes mainly and for electricity that have profoundly altered the hydrological natural system of the island. The weather is typical Mediterranean with mild temperatures all year around. The hot/dry season goes from May to September, with a dominant north-westerly wind. Economical activities, such as agriculture and farming draw on tradition and culture of this territory. Sardinian specific features make its environment and ecosystems extremely valuable and vulnerable to human pressure and climate change. In such a complex system, economical growth needs to be pursued taking into account issues related to water resources management/exploitation.

Observed warming over several decades has been linked to changes in the large-scale water cycle. Observed data on environmental states as well as climate projections provide evidence that water and natural resources are strongly vulnerable to climate change. The Intergovernmental Panel on Climate Change predicts a further rise in air temperature from about 1.4°C to 5.8°C by the end of the century and changes in precipitation patterns. Threats comprise droughts and flooding, desertification and degradation of productive soils, to cite some issues. Although there is scientific consensus that climate-induced changes are in place and will amplify in the future, there is a lack of knowledge mostly at the local scale on the quantification of these changes. The motivation of the work undertaken stems from two fundamental considerations. The first is the fact that several gaps of knowledge exist in terms of observations and research needs related to the water cycle in the Sardinian region. Current information about the hydrology of the island is inadequate. Observational data and data access are prerequisites for adaptive management, yet many observational networks are collapsing. The second is related to the ever varying climatic conditions and their effects and thus to the need of developing adequate measures and policies to protect water resources.

The development of a set of different scenarios of probable environmental changes through numerical simulations of the complex climate system is a powerful method to estimate the possible chain of reactions resulting from a change in a certain forcing factor. This objective is achieved by building a data-driven infrastructure that feeds models and scenarios and whose results are exposed on a web-based Information and Forecasting System to explore the past, present and future hydrologic scenarios for Sardinia.

The Sardinia SWAT model set-up

Input data has been provided by various sources, such as the Sardinia's Government, the Regional Agency for water protection (ARPAS), Ente Autonomo Flumendosa (EAF), and the University of Cagliari. Stream and watershed delineation has been based on a 10x10 meter resolution DEM (Digital Elevation Model) and has been driven using a minimum draining area of 1000 hectares. The virtual river network which is calculated by ArcGIS SWAT (Francisco et al, 2006) preprocessor has been conditioned (using the "burn-in" option) to limit discrepancies with the official data. To this end, we made use of a detailed river network, provided by the Sardinia's Government.

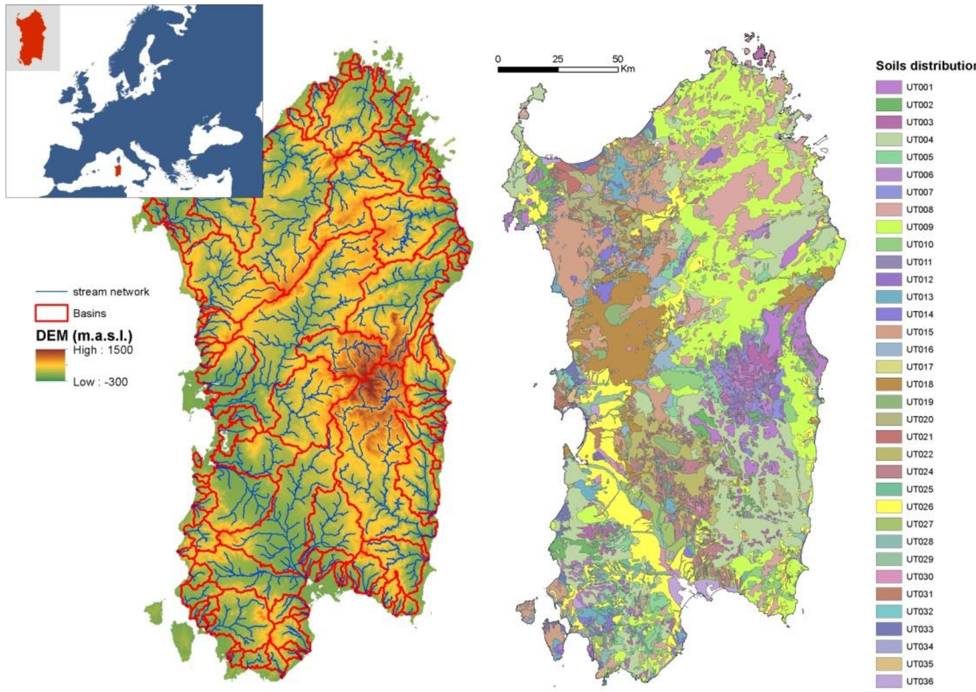


Figura 1. Delineation of Sardinian watershed through ArcSWAT watershed delineator on the right. On the left the soil map.

Main issues encountered concern the delineation of flat areas with low slopes where often the delineation system fail to recognize the watershed limit. Other issues in such areas are mainly due to the presence of many artificial channels that crossed several hydraulic borders and that some river's path was modified from their natural course. In order to overcome to such problems, several modifications to the river network and to the resulting watersheds were necessary. With this strategy good results both for the subbasins and rivers, validated also against satellite images, were obtained in the delineation process performed by the ArcSWAT pre-processor. The Sardinian SWAT set-up produced 1209 subbasins that can be grouped in 108 main watersheds (Fig.1).

Soil and Land Use

Hydrological Response Units (HRUs), representing areas within the subbasin with a unique combination of land cover, soil type and management practice, were defined for each subbasin with 10% thresholds. Land use parameterization for Sardinia were derived by literature values and associated to a land cover vector map (2008 derived from 2006 satellite data). This map is based on the CORINE Land Cover standard at the 5th level, which gives information on the status and the changes of the environment. The land cover is and consists in a geographical database describing vegetation and land use, through 76 classes grouped in a five levels nomenclature. The scale of the land use database is 1:25.000, with a minimum mapping unit of 0.5 hectars in urban areas and 0.75 hectars in extra-urban areas. Land cover classes have been associated to the USGS Land Use classes through a lookup table. Soil data has been produced on the basis of previous studies (Collu A., Lecca et. Al., 2003, Arangino, et al., 1986; Aru et al., 1991; Costantini et al., 1999; Montanarella, 1999; Righini et al., 2001). The main physical parameters were considered in the soil database, and they referred to 40 soil profiles found within the Sardinian region, according with FAO and US Taxonomy standards (Arangino et. al, 1986). In particular, the field soil survey regarded the assessment of the different layers and the description, for each of them, of the following parameters: thickness, structure, depth of the roots, color, presence of clay-skins, porosity, mottles, iron or carbonates concretions, drainage.

Climate data

Climate data were provided by Hydrological Agency of Sardinia. In details, precipitation data are available from 1922 to 2008, with holes and errors. The choice of the gages to be used within the SWAT model was based on the percent of available data, with a threshold of 50%. The raingages network chosen for this work is shown in the map on the right (Fig. 2) .

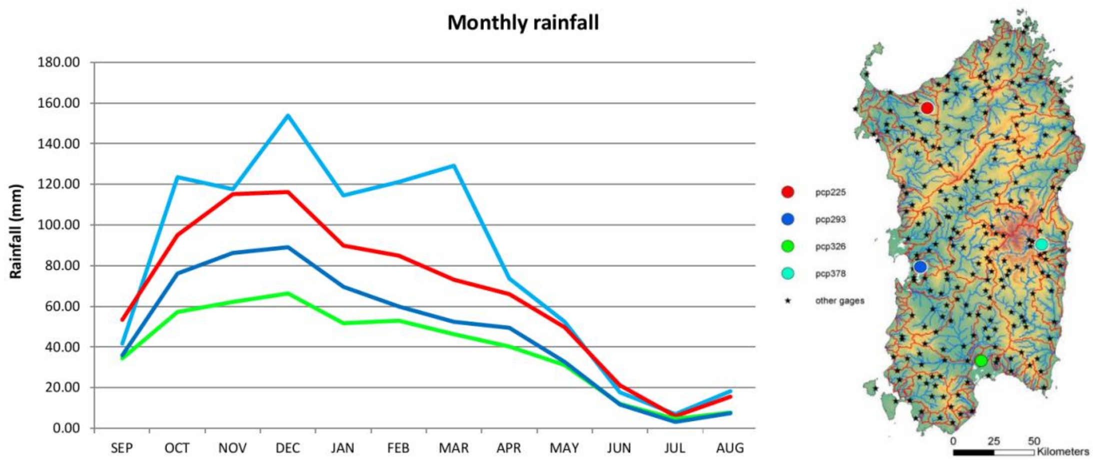


Figure 2.Raingages within Sardinia (right panel) and monthly rainfall distribution on 4 climate gages (left panel).

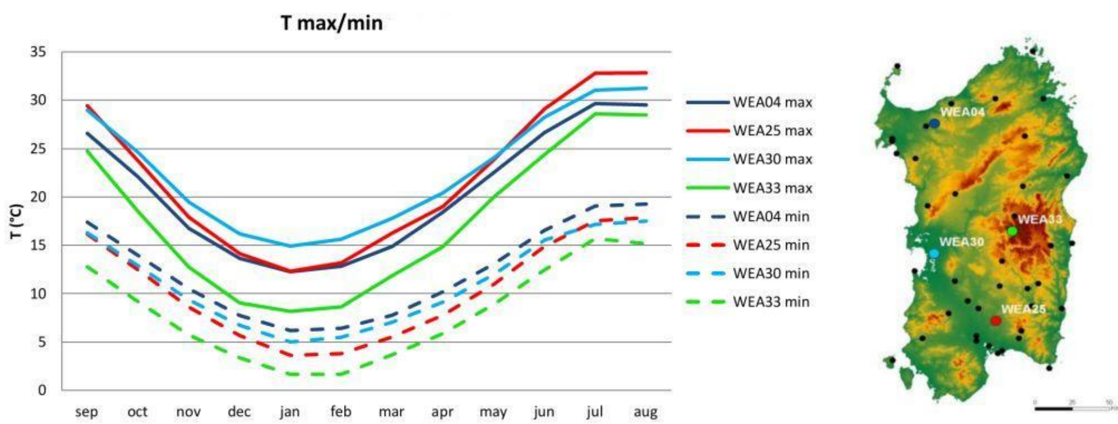


Figure 3. Max/min temperature monthly regime for 4 stations (left panel) and spatial distribution of climate stations in Sardinia (right panel).

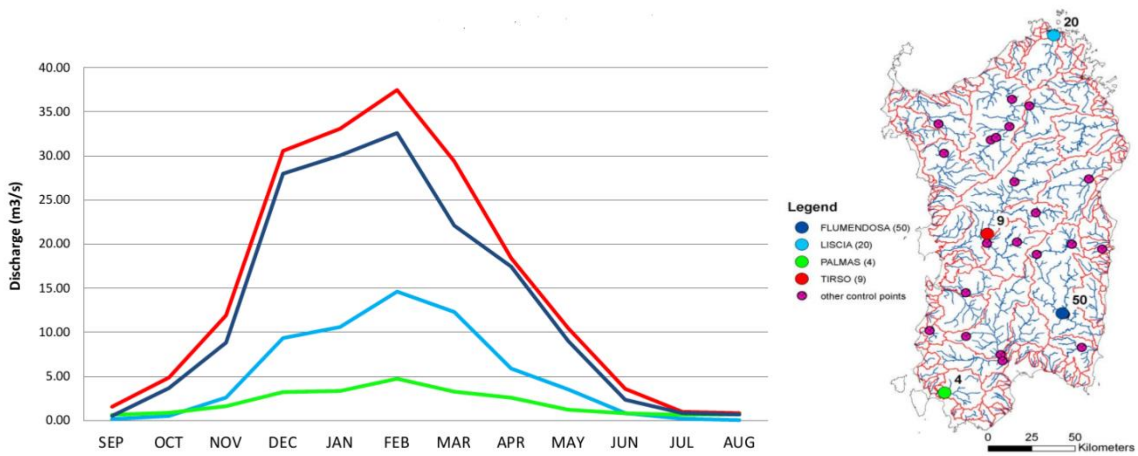


Figure 4. 27 monitoring stations in the region (right panel). In the left panel, we show the stream flow regime for 4 control points.

A method called QQS (Quantile-Quantile and Shuffling) (Marrocu, 2014) was devised to fill the gaps of incomplete time series. This method is a two steps procedure that is based on the use the precipitation data for the region taken from the ECMWF meteorological reanalysis (Dee et al,, 2011). First the simulated data are produced to be alike to the observed data using the quantile-quantile calibration method (Hay et al., 2000). With this procedure the generated rainfall data are usually non-realistic. A too high correlation between the synthetic series and the measured one is observed. To overcome to this problem, an algorithm based on Shackle-Shuffling (Clark et al., 2004) method was applied to the data obtained by the previous calibration allowing to obtain also a reliable spatial correlation. Temperature data was simulated by SWAT's weather generator, using statistics available from Italian Airforce meteo database from 1951 to 1992, referred to 49 climate stations distributed all over the region.

Sensitivity Analysis, Calibration and Validation of the Model

A sensitivity analysis was performed in order to identify which parameters should be modified to obtain a reliable hydrological response in the calibration process. The sensitivity analysis was performed, setting realistic ranges for the parameters, obtaining the parameter ranking. Calibration was carried out using SUFI-2 method (Abbaspour et al., 2011) using the SWAT-CUP tool in which performances and uncertainties are evaluated through specific indexes ranges. The objective function used to calibrate the model for the hydrological cycle is the Nash-Sutcliffe (NS) index and uncertainties were quantified by P-factor and R-factor. Nash Sutcliffe index measures the fitting of simulated data against observed data, P-factor is the percentage of data bracketed by the 95% prediction uncertainty (95PPU) band and R-factor is a measure of the average width of the 95PPU. In order to compare simulated and observed data, 23 discharge control points were chosen. First calibration performances gave good results: the initial average NS value is 0.188 (tab. 1). After calibration, all NX indexes scored higher values with a mean of 0.69. In the example below (Fig. 5) is shown the uncertainty evaluation for one of the 23 control points, with a P-factor of 0.77 and a R-factor of 1.09 obtained after 300 iterations, where the average NS value scored 0.691 (tab. 1).

Tab. 1. Nash-Sutcliffe indexes obtained in calibration using 23 control points

MONITORING GAGE - SUBBASIN ID	STATION	STARTING NS INDEX	FINAL NS INDEX
9	LISCIA	-0.13	0.63
146	COGHINAS A MUZZONE	0.7	0.72
160	BERCHIDDA	0.82	0.85
175	CONCABELLA	0.69	0.69
236	MANNU A PEDRA ALVAS	0.52	0.64
257	MANNU DI OZIERI FRAIGAS	0.68	0.75
317	RIO BUTTULE A BUTTULE	0.66	0.74
328	MANNU DI OZIERI PONTE LEGNA	0.62	0.73
381	TEMO DIGA	0.70	0.71
471	RIFORNITORE TIRSO	0.11	0.64
480	PONTE CEDRINO	0.63	0.72
601	TALORO A PASSERELLA GAVOI	0.08	0.50
703	ARAXISI A ORTO SCIAVICO	0.47	0.69
711	FLUMINEDDU (TIRSO) ALLAI	0.46	0.52
747	FODDEDDU A CORONGIU	0.57	0.57
755	FLUMENDOSA A GADONI	0.88	0.88
879	MOGORO A SANTA VITTORIA	-0.57	0.70
889	FLUMINEDDU A STANALI	0.46	0.46
933	M. SCROCCA AGGREGATA	0.86	0.86
1050	SA PICCOCCA MONTE ACUTO	-1.9	0.80
1070	MANNU DI S. SPERATE A MONASTIR	-2.05	0.67
1113	CIXERRI A UTA	0.24	0.74
1175	MONTI PRANU	-1.17	0.69

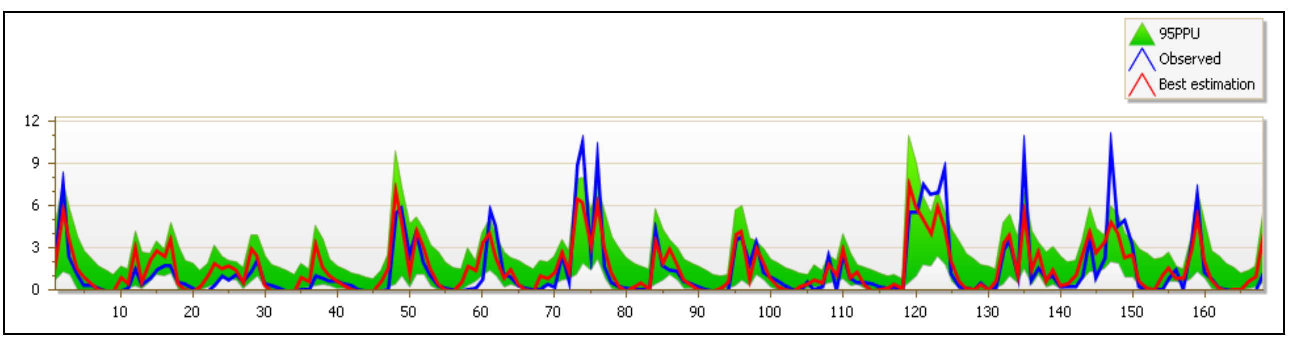


Figure 5. Calibration of the regional model. Best estimation (red line), Observed (blue line) and 995 PPU(green band) for the S. Sperate (ID 1070 in the table above). The NS index scored in this case 0.67.

Validation was performed using 4 different completely independent control points, confirming a good model response for the hydrological cycle as shown in Fig. 6 where a NS index of 0.89 was obtained.

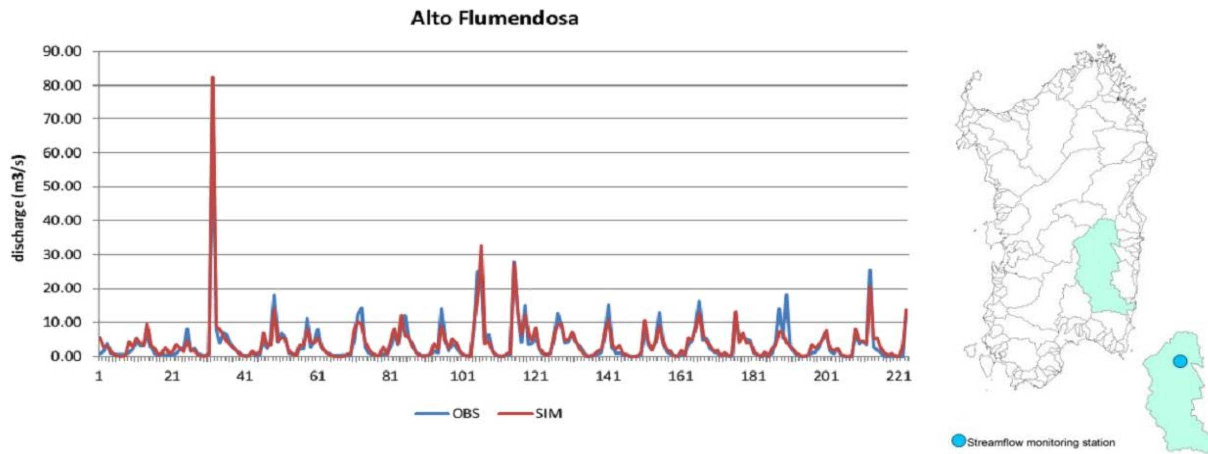
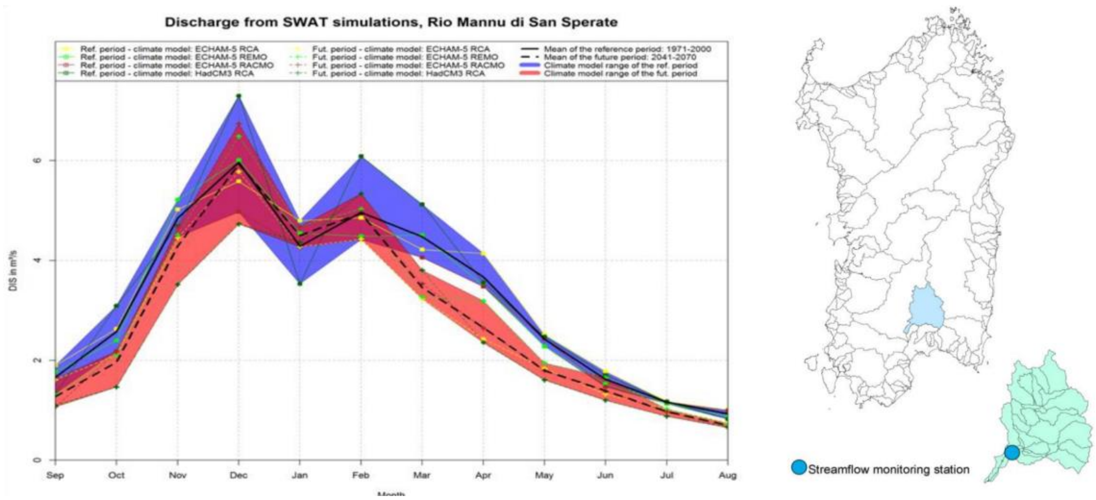


Figure 6. Observed and simulated discharge in one of the validation control points, with a NS index of 0.89

Climate Change Scenarios

With the purpose to evaluate how climate changes could influence the water balance, we developed and tested a semi-automatic procedure to use experimental climate data within SWAT. A small catchment (the San Sperate) of the Sardinian island was used for this purpose. The Ensemble climate data, produced at the European scale, with a 50/20 km resolution were used as input. The Ensemble project consists in the development of a prediction system for climate change, providing low resolution data through several models and covering a range of time of 200 years (from 1900 to 2100). Such low resolution data were first downscaled and bias corrected to a spatial resolution of 1 kilometer for the area under study. The following four dataset of the Ensemble models were used within our hydrological model:

1. RacMO (RMO): KNMI-RACMO2_A1B_ECHAM5-r3 (KNMI)
2. REMo (REM): MPI-M-REMO_SCN_ECHAM5 (MPI)
3. RCA 3 (RCA): C4IRCA3_A1B_HadCM3Q16 (C4I)
4. SMHE (SMHE) ECH_RCA SMHIRCA_A1B_ECHAM5-r3 (SMHI_ECHAM5)



- Figure 7. Climate models show that discharge is going to lower values for the future prediction period (red band) compared to reference period (blue band).

Two different climate scenarios were simulated: a reference period (1971-2000) and a future prediction period (2041-2070). The results of the four climate scenarios are shown in Fig. 7. All models agree that the water budget is decreasing, especially the HCH-RCA model which predicts a decrease of 23 % in the future.

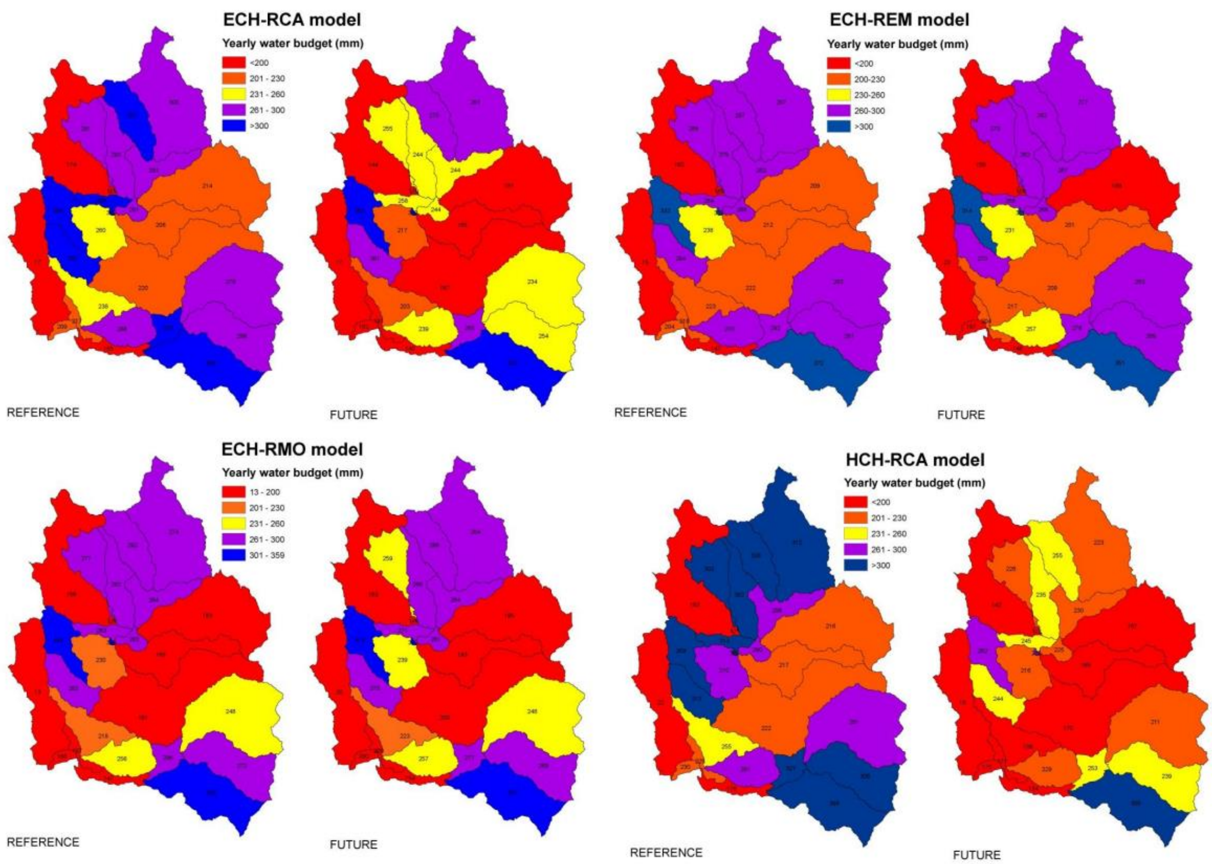


Figure 8. The hydrological model shows that the water budget is going to lower values for the future prediction period and water availability is therefore decreasing.

The hydrological model shows that the water budget is going to lower values for the future prediction period. Water availability is therefore decreasing. Same results can be seen analyzing the flow duration curves (not shown), where it is present a small increase of probability to exceed high discharge values for future prediction period. This is also connected with a higher occurrence of intense precipitations (high surface runoff values). The probability of low flow days increases in the future prediction period. Maximum daily flow increases from reference period to future for winter months, increasing the occurrence of intense rainfalls with high surface runoff values.

Web-based information System

The Sardinia SWAT model results can be viewed and analyzed on a web-based application. This is a Collaborative Working Environment on the web (Cau et al., 2013), that relies on server and client side technologies (e.g. spatialite, OpenLayers web-GIS client, mapserver, etc.) to support decision makers in the field of sustainable water resources management. It works in tandem with ArcSWAT interface. The system exposes hydrological applications and results on the web, through a coherent management of Drivers - Pressure, State, indicators as distributed (in space and time) catchment's variables. This procedure encourages the user to increase the awareness of the effects of subjective judgments or misjudgments on the watershed dynamics.

The system has been particularly designed to allow users, through a user-friendly interface, to run climate scenarios directly from the web and view results and statistics, produce maps and run spatial queries for the main SWAT outputs. In particular, a "Scenarios section" has been set up to input, directly from the web interface, climate data into the SWAT model.

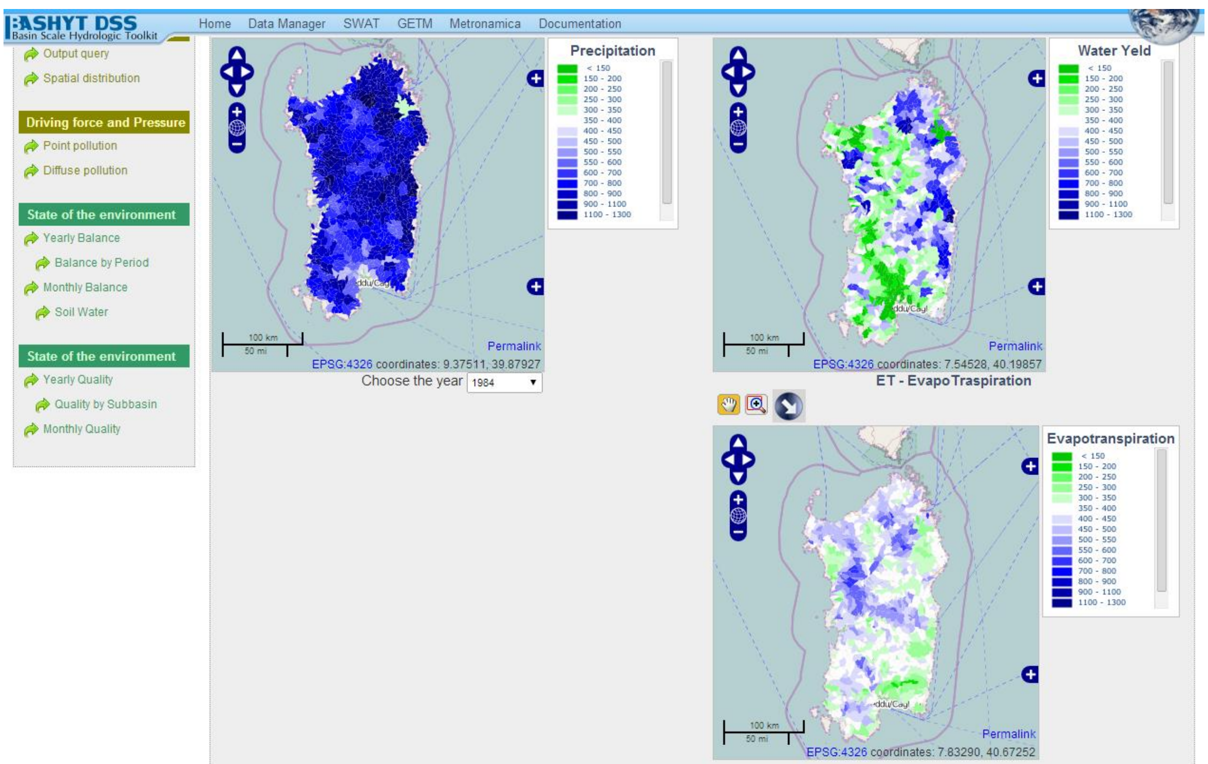


Figure 9. A synthetic report on the water budget of the Sardinia model viewed on the BASHYT interface.

The monthly regional water balance, computed on the basis of the calibrated SWAT run showed an average precipitation of 62.57 mm/month with a water yield of 28.89 mm, 30.1 mm are lost to a evapotranspiration and 3 mm to transmission (e.g. leaching through streambed) and evaporation losses directly from the stream.

Conclusions

The SWAT model was implemented for Sardinia in order to simulate the regional water budget. The model was built up using available data, provided by official sources. Calibration and validation results confirm a good model fit with real data, allowing to estimate also the uncertainties associated with the use of the model. With this calibrated set up, the water budget on a monthly basis has been used to analyze the water budget for the entire island or the period 1924- 2008. The scenarios although run on a small catchment within Sardinia, highlight that the water budget is going to lower values for the future prediction period and therefore water availability is decreasing.

Sardinia SWAT model was deployed on a innovative web-based platform that allow users to analyze SWAT results directly from the web, producing reports, maps, and statistics. Client/server applications for data and computing resource virtualization are the paradigm introduced in the Internet cyberspace. The diversity and complexity of environmental problems imposes the adoption of a cross-disciplinary approach, only possible through the development of problem solving models based on advanced information technologies. One possible way is to set up virtual organizations on the WEB sharing common objectives and providing high value-added complex services, accessible from anywhere. With this approach, we aim at fostering integration of expertise from various fields to create a lively system where end-users and scientists can cooperatively work and create reliable applications.

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Territorial planning in River Uberaba's Watershed, MG, Brazil

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Abstract

The objective of this work was to propose a new methodology to aid in the administration of watersheds. The watershed is, for law, the unit of territorial planning and, for that reason, the study of the morphometric characteristics of a basin is essential for the appropriate administration of the water resources and planning of any activities in an area. This work was accomplished for the municipal district of Uberaba, MG whose main river is Rio Uberaba. The Uberaba River covers five counties, including Uberaba. The studies *conducted in this basin to date, always take into account the basin as a whole, ignoring the particularities of each municipality covered by it. Based on this context, the city of Uberaba was divided into hydrological compartments or sub - basins with the aid of GIS (Geographic Information System) ArcGis 10.1 and the SWAT (Soil and Water Assessment Tool) , more specifically its extension to ArcGis , the ArcSwat . The city was divided into 34 sub -basins and for each were obtained : area (ha) , perimeter (hectares) , length of the main watercourse water (meters) , slope of the sub -basin (%) , length of ramp (meters) and the compactness coefficient (dimensionless) . The low slope (2.74 % - 8.85%) and long lengths of ramps (60m - 91m) reduce the propensity to floods in sub - basins. The high compactness coefficients agree with previous results (1.56 to 2.67). The situations of flooding in the city can be explained by the low soil impermeability, deficiency in urban drainage systems and clearing of permanent preservation areas throughout the basin, especially the APA (Environmental Preservation Area) of Uberaba River.*

Keywords: Water resources management, morphometry, GIS, remote sensing.

Introduction

The morphometric analysis is the science that studies and measures needed to describe the geomorphological landscape topographical variation in its parameters. The characterization of morphometric parameters in watersheds has key role in conditioning linked to water erosion responses generated after significant rainfall events (Christofoletti, 1980). The soil is influenced in different ways and at different magnitudes by erosion, which, in the case of rainfall erosion varies with the characteristics of precipitation, soil type, terrain, cover and soil management and conservation practices support (Wischmeier & Smith, 1978; Marioti et al, 2013.).

The erosion process is mainly influenced by the steepness of the terrain and the length of the slope, and these factors have a direct influence on the rate of speed of runoff of rainwater, ie, the higher the terrain slope, the greater the rate the speed of water runoff. Each type of soil is composed of specific properties (texture, aggregates, porosity, etc.). Thus react differently to the effect of erodibility and some have greater resistance to soil erosion and other water with less resistance. Another factor influencing the erosion process is no vegetation cover on the soil. Soon the vegetation cover protects the soil and takes the drops of rain, but also increases the infiltration capacity of the soil water (Cherobin 2012).

Considering the difficulty in quantifying sediment production in large river basins, as well as the effect of basin scale on hydrosedimentological processes, its estimate has been carried out by means of simulation models, being generally related to soil characteristics (sediment particle size, density, etc..), and climatic factors (rainfall and evaporation) and physiographic (basin area, relief and vegetation cover). Moreover, the relationship depends on the spatial distribution of these factors, the use and land cover in the basin as well as the tendency of occurrence of intense rainfall and its spatial variability (Aragon et al., 2013).

The hydrological model SWAT (Soil and Water Assessment Tool) was developed in the 90s, in the United States, the Agricultural Research Service and the Texas A & M University. The SWAT is a mathematical model that allows different physical processes are simulated in a watershed (Arnold & Allen, 1996). The SWAT has been adapted since its inception, for some specific areas and has been integrated into a Geographic Information System (GIS) allowing the entry of the database, the drafting and editing of environmental scenarios and their representation in the form of graphs and maps , control and simulations, as well as extract and organize the outputs of the model (Andrade, 2013).

The coupling of the geographical hydrosedimentological models (Melo, 2010) information systems has facilitated the use of physics-based models; example is the case of SWAT (Neitsch et al, 2005.) model, coupled to a GIS - ArcSWAT (. Winchell et al, 2009), which has produced good results in Brazil and in several parts of the world (Aragon, 2013) .

The objective of this study was to analyze the morphometric characteristics of Uberaba, MG through GIS, in order to compare morphometric findings for watersheds in the region. Since morphometry is made for basins or watersheds, this paper will propose a new methodology for the integrated management of regional water resources, taking into account local particularities.

Material and Method

Uberaba belongs to the state of Minas Gerais, more precisely, in the area of the Triângulo Mineiro, possessing the following geographical coordinates, 19°45'27 " of latitude to the south and 47°55'36 " of longitude to the west. This municipal district is located approximately to 500 km of Belo Horizonte (capital of the state). The total area of the district is about 4 529,70 km², consequently, the urban perimeter includes 256 km² and found to 764 m of height (Secretaria Municipal do Meio Ambiente, 2004).

By agreement with Cruz (2003), the relief of that municipal district is constituted by surface plane or lightly wavy. Belonging to the Sandstone Plateau-Basaltic of the watershed of Paraná. The soils found in that area are diversified, however most of them possesses medium texture. However, their tenors of sand and clay present oscillations. I bruise, these soils are classified, usually, as Latossolo in different fertility types. Having larger predominance of Latossolo Red distroférrico and Latossolo Red Typical distrófico.

In the Brazilian Southeast area, the climate is influenced by the Atlantic and Tropical masses of Continental, Tropical Equatorial air Continental, for that reason, it usually carts hot and rainy periods. In certain areas of the Triângulo Mineiro they possess annual medium temperature between 20 to 22°C, and in the winter the medium temperature can arrive to 18°C. In the municipal district of Uberaba, according to the climatic classification of Köppen, it presents thermal regimes and pluviométricos, as Aw, megathermic, happening rains in the summer and drought in the winter (Secretaria Municipal do Meio Ambiente, 2004).

The rainiest period of the area of the Triângulo Mineiro corresponds to the time of the hottest year, in other words, in the summer. Therefore, the regime annual medium pluviométrico varies spill of 1300 and 1700 mm (Cândido, 2008). This way, there is a predominance of the tropical climate in the watershed of the river Uberaba, with prevalence of the semi-humid climatic period from 4 to 5 dry months (Cruz 2003).

For the execution of this work the following software were used ArcGIS 10.1 and the SWAT (Soil and Water Assessment Tool), more specifically its extension to ArcGIS, the ArcSwat. Initially, we obtained the Digital Elevation Model (DEM) of Uberaba - Minas Gerais from Brazil and Embrapa Relief site. The letters used were SE-22-ZD, SE-23y-C, SF-22 and SF-XB-23-VA, with scale 1:250 000. The DEM provides the values of altimetry data for the area, and serve as the basis for the discretization of the district into sub-basins and to define the drainage area automatically.

Subsequently, the geometric meshes of the municipalities of Minas Gerais were obtained. These meshes were acquired at IBGE website. In ArcGIS environment, the letters were opened simultaneously, mosaicked and the coordinate system was designed: UTM (Geographic Coordinate System) and Datum SIRGAS 2000 zone 22 S.

After the projection coordinate system, the geometric mesh of Uberaba was inserted on the Digital Elevation Model and subsequently cropped. The database that formed was being exported to a specific folder. After the formation of the required database and the projection of geographic coordinate on "layer" system, a new design was created in Arcswat (Setup Project) and the directory used was a folder created for this purpose, as with the input data required by the software. In Wathershed Delineation menu, set up the system of geographic coordinates, datum and zone, the DEM was cut and inserted through the Stream Definition command, we calculated the area and the number of hydrological compartments to Uberaba (flow Direction and Accumulation).

The direction of flow and totalized flow are generated by a regular grid, taking as the baseline the highest altitude of the terrain. The new numerical grid generated determines the direction of greater elevation of a pixel relative to its eight neighboring pixels. Thus, the numerical description of the direction the water will go after reaching each pixel, which can be represented graphically by means of the application of the steering code (Castro, 2013).

The delimitation of the Uberaba area as well as the sub-basins or hydrological compartments was performed using only the local geometric mesh and the DEM. For the definition of the sub-basins the total area of the municipality, 452.97 hectares, was used. The variables were calculated directly by ArcSwat: Area (ha), perimeter (ha), Ramp Length (m) and average slope (%).

The Circularity Index presented by Miller (1953) cited by Rocha & Kurtz (2001) in a morphometric variable where the higher the value (IC) (observed when comparing sub-basins), will be nearer the same fashion circular, and the greater the danger of flooding (higher water concentration of the tributary main). To calculate the (IC), we used the following equation (1):

$$IC = \frac{12{,}57 \times A}{P^2} \quad (1)$$

Where: IC is the Circularity Index, the Drainage Area (m²) and the Perimeter P (m).

The compactness coefficient (Kc) relates the perimeter of the basin and the circumference of the circle whose area is equal to the drainage basin. According Villela & Mattos (1975), this coefficient is a dimensionless number that varies with the shape of the basin, regardless of its size. The more irregular for the bowl, the greater the coefficient of compactness. A minimum coefficient equal to unity corresponds to a circular basin, having high propensity to flooding and, to an elongated bowl its value is significantly greater than unity, indicating less prone to flooding, with values exceeding 1.47 characterize basins not subject to flood. A bowl will be more susceptible to greater flooding when his Kc is closer to unity. Kc is determined based on the following equation 2:

$$Kc = 0{,}28 \, {}^{P}\!/\!{}_{\sqrt{A}} \quad (2)$$

Where: Kc = Coefficient of Compactness; P = Perimeter (m) and A = Drainage Area (m²).

Results and discussion

Thirty four hydrological compartments were calculated and limited to the city of Uberaba (Figure1). Arraes et al (2010) obtained 8 hydrological compartments for Jaboticabal-SP. In the literature, there are many jobs using Arcswat for determination of morphometric parameters of watersheds, but there are few materials with morphometric studies of local hydrological compartments.

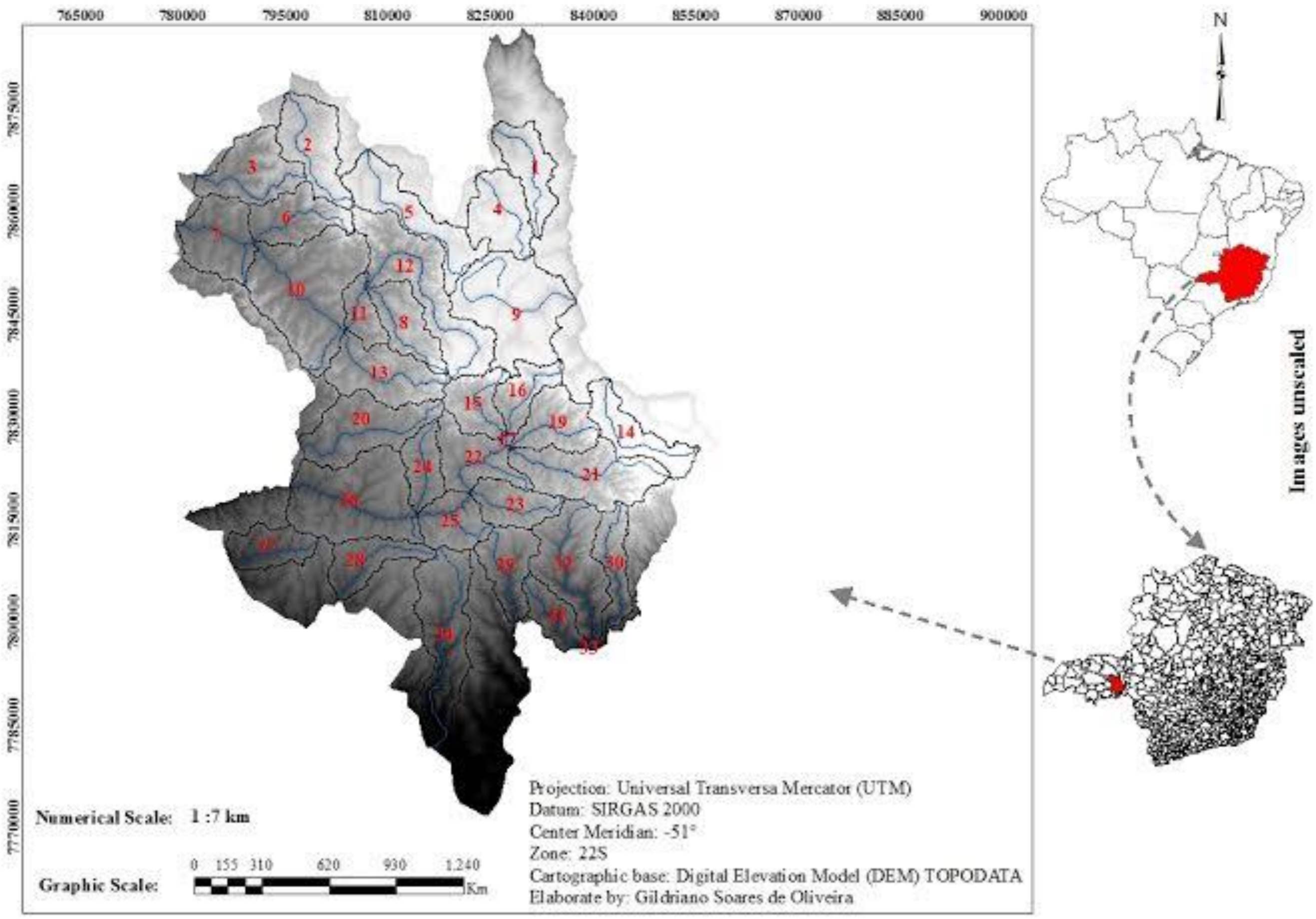

Figure 1. Compartimentos Hidrológicos e localização do município de Uberaba

When comparing the results of the average slope, length of slope, circularity index and coefficient of compactness in this work with those obtained by Valle Junior (2008) to Uberaba River basin, it was perceived similarity. Can be seen in Table 1, the values obtained for each variable and for each of the calculated and limited to the city of Uberaba hydrological compartments:

Table 1. Variáveis analisadas para os compartimentos hidrológicos do município de Uberaba-MG.

Hydrological compartments	Area (Km²)	Perimeter (Km)	Average Slope (%)	Lenght Ramp (m)	Compactness Index (Kc)	Circularity Index (IC)
1	79,10	69,22	3,21	91,44	2,18	0,21
2	108,68	71,41	3,59	91,44	1,92	0,27
3	108,53	66,10	7,37	60,96	1,78	0,31
4	93,93	63,54	2,94	91,44	1,84	0,29
5	121,89	105,66	3,13	91,44	2,68	0,14
6	88,13	60,98	7,43	60,96	1,82	0,30
7	106,61	57,68	4,98	91,44	1,56	0,40
8	78,29	59,88	7,16	60,96	1,89	0,27
9	201,21	101,81	2,74	91,44	2,01	0,24
10	236,82	96,50	6,57	60,96	1,76	0,32
11	43,08	42,85	6,33	60,96	1,83	0,29
12	188,17	120,85	7,51	60,96	2,47	0,16
13	117,40	72,70	6,58	60,96	1,88	0,28
14	83,80	77,27	3,25	91,44	2,36	0,18
15	66,60	51,82	7,34	60,96	1,78	0,31
16	56,03	53,29	8,18	60,96	1,99	0,25
17	2,74	9,52	6,24	60,96	1,61	0,38
18	0,34	4,39	5,92	60,96	2,10	0,22
19	84,33	55,85	8,85	60,96	1,70	0,34
20	132,73	79,84	5,46	60,96	1,94	0,26
21	148,29	86,80	8,10	60,96	2,00	0,25
22	87,79	65,01	5,29	60,96	1,94	0,26
23	66,58	47,98	4,97	91,44	1,65	0,36
24	56,90	47,98	3,77	91,44	1,78	0,31
25	69,67	45,78	5,29	60,96	1,54	0,42
26	207,27	88,26	5,09	60,96	1,72	0,33
27	65,09	49,26	5,07	60,96	1,71	0,34
28	70,59	60,79	4,40	91,44	2,03	0,24

29	79,34	56,77	6,06	60,96	1,78	0,31
30	64,83	63,36	7,68	60,96	2,20	0,20
31	53,05	46,33	6,03	60,96	1,78	0,31
32	148,44	82,58	7,12	60,96	1,90	0,27
33	0,08	2,01	5,06	60,96	1,95	0,26
34	164,00	103,64	5,32	60,96	2,27	0,19

The results showed that there is an inverse relationship between the values of mean slope and the length of the ramp. The lower slopes have greater long ramp. The average slope of hydrological compartments, between 2.74% and 8.85%, rate relief plan as corrugated or smooth. According EMBRAPA (1999):

BACKGROUND: horizontal surface topography, where the unevenness is very small, with slopes varying from 0 to 3%;

SOFT WAVY: busy little surface topography consisting of set of hills, with gentle slopes, ranging from 3% to 8%;

WAVY: busy little surface topography consisting of set of hills having moderate slopes ranging from 8% to 20%;

FORT WAVY: busy surface topography, formed by hills and rarely hills with steep slopes, ranging from 20% to 45%.

Torres et al (2010) reported that by the average slope of the basin can define the type of existing signage in the area and this has a direct influence on the relationship between rainfall and runoff from the watershed, mainly due to the increased speed of runoff, reduces the possibility of water infiltration into the soil.

According Valle Junior (2008), the class of flat relief to undulated occupies 64.67% of the total area of the Uberaba River Basin, thus prevailing in the basin slopes 0-5%. Also, when the obtained typically shorter lengths of ramp slope is greater than 10% and with lengths greater slope ramp was from 0 to 5%. The results are similar to those obtained in the present work. The difference is that instead of working hydrological compartments of the Uberaba River basin, was working compartments of Uberaba. It is noteworthy that the Uberaba River Basin covers other 4 municipalities, and Uberaba: Conceição das Alagoas, Campo Florido, Verissimo and Planura.

The high values of IC and Kc indicate compartments elongated and low propensity to flood. According to Villela & Matos (1965), minimum coefficient equal to unity correspond to a circular basin, having high propensity to flood and for an elongated basin its value is significantly greater than unity, indicating lower prone to flooding, with values exceeding 1.47 characterize basins not subject to flooding. Guidolini et al (2013) determined the (Kc) for the watershed Buracão stream, a tributary of Uberaba River and located in Uberaba, the value of the CI of 1.15 and 0.50, indicating the elongated shape of the watershed and therefore reducing the risk of flooding in the area. For watershed stream Lanhoso important tributary of Uberaba River and also located in the same municipality, the Kc and CI calculated by Torres et al (2007) was

1.40 and 0.50, respectively, indicating that an elongated and somewhat subject to flooding watershed.

Comparing the results for the hydrological compartments of Uberaba with those obtained for regional watersheds and river basin Uberaba, observed similarities. These results demonstrated that the municipal discretization can be an efficient methodology for integrated management of regional water resources, since local conditions will be analyzed, identifying areas at risk to flooding and more susceptible to erosion. Some regions in the Uberaba River Basin have average or high to flooding and erosion trend. This was not observed in this study because only one municipality covered by the basin was studied. The city of Uberaba, during rainy season, suffers from floods, especially in the central region. The explanation is the failure of urban drainage, soil sealing system due to urban sprawl and deforestation of Permanent Protection Areas (APP), with emphasis on riparian (Valle Junior, 2008).

Conclusion

The ArcSwat is efficient for the determination of morphometric parameters.
Hydrological compartments of Uberaba showed up elongated and low tendency to flooding and erosion.
The local discretization for morphometric analysis can be efficiently integrated management of regional water resources.

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Web-based Real Time Flood Forecasting using SWAT model

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ABSTRACT

On 18 August 2008, heavy monsoon rains and poor maintenance caused a breach in the Kosi embankment and one of the most disastrous floods in the history of Bihar, an impoverished and densely populated state in India occurred. The Kosi river changed course and inundated areas which hadn't experienced floods in many decades. Flooding occurred throughout the Kosi river valley in northern Bihar, in the districts of Supaul, Araria, Saharsa, Madhepura, Bhagalpur, West Champaran and Purnea. The flood killed 250 people and forced nearly 3 million people out from their homes in Bihar. More than 300,000 houses were destroyed and at least 840,000 acres of crops were damaged. Villagers in Bihar ate raw rice and flour mixed with polluted water. Hunger and disease were widespread. In June 2013, a multi-day cloudburst centered on the North Indian state of Uttarakhand caused devastating floods and landslides in the country's worst natural disaster since the 2004 tsunami. As of 16 July 2013 more than 5,700 people were presumed dead. Today, with modern equipments and radars we should have been able to predict the floods and expected inundation much earlier and stopped these human disasters. Technical advancements over the years have allowed us to create input data files efficiently for distributed parameter hydrological models for faster accurate calculations. Soil and Water Assessment Tool (SWAT), a distributed parameter GIS-based model developed by the United States Department of Agriculture have been modified for its use as real-time flood forecasting model. Subroutines have been modified to capture the final conditions of the catchment at any desired instant. Integration of the time series analysis of errors with SWAT model outputs has helped miraculously for accurate forecasting. Present paper aims to develop a system to collaborate on web for exchange of required data for real time flood forecasting using SWAT model and providing information products to water managers for early warning.. A real-time flood forecast application study of the Bagmati river basin in Bihar, India, using hydro-meteorological data downloaded from various websites has been demonstrated. Sub-hourly rainfall and water levels of Hayaghat gauge station for 2012 flood season were downloaded from websites www.imdaws, www.hydrology.gov.np and www.fmis.bih.nic. Discharge was calculated using stage discharge relationship. Analysis of web-based data indicates that rainfall in Nepal portion produces peak discharge at Hayaghat after a long time. The lead time at Hayaghat for rainfall of Nepal portion is very high 4-8 days. SRTM – DEM (90 m resolution), landuse of global USGS (2 M), Soil of FAO Global soil (5 M), rainfall of rain gauges of IMD(Indian Meteorological Department) and stream flows of stream gauges of CWC (Central Water Commission) have been used for setting up of SWAT model. Aphrodite gridded rainfall data has been used for simulating monthly and daily flows of last 15 years for calibration and validation of model and observed data have been collected from CWC (Central Water Commission), WRD (Water Resource Department) and IMD (Indian Meteorological Department). Calibration was reasonable with Nash-Sutcliffe efficiency coefficient EF of 0.84 which indicates that simulated values are reliable. Validation of the modified SWAT model was also done using available measured data of year 2005.Nash-Sutcliffe efficiency for validation was found to be 0.7. which is indicative of high predictive power and accuracy of the model. Real time flood forecasting was done for year 2012 using sub-hourly rainfall down loaded from respective websites. Nash-Sutcliffe efficiency for forecasting was found to be 0.65 which is indicative of high predictive power and accuracy of the model.

(Keywords: SWAT, GIS, WEB, simulation, callibration, validation, real time, early warning)

INTRODUCTION

Flood is one of the most recurring, wide spread, frequent natural disasters like earthquakes, cyclones, landslides, drought and volcanic eruptions. Flood is associated with a serious loss of life, property and damage to utilities. More than 520 million people are affected by flood per year in the world. It gives annual deaths of 25,000, extensive homelessness, disaster induced disease, crop and livestock damage and other serious harm (UNU, 2004). The children, women and old age people suffer most during the flood. The causes of flooding in river basins are heavy rainfall, breach of embankments/dams, and release of water from upstream structures and low discharge capacity of cross sections at bridge sites.

On 18 August 2008, heavy monsoon rains and poor maintenance caused a breach in the Kosi embankment and one of the most disastrous floods in the history of Bihar, an impoverished and densely populated state in India occurred. The Kosi river changed course and inundated areas which hadn't experienced floods in many decades. Flooding occurred throughout the Kosi river valley in northern Bihar, in the districts of Supaul, Araria, Saharsa, Madhepura, Bhagalpur, West Champaran and Purnea. The flood killed 250 people and forced nearly 3 million people out from their homes in Bihar. More than 300,000 houses were destroyed and at least 840,000 acres of crops were damaged. Villagers in Bihar ate raw rice and flour mixed with polluted water. Hunger and disease were widespread. In June 2013, a multi-day cloudburst centered on the North Indian state of Uttarakhand caused devastating floods and landslides in the country's worst natural disaster since the 2004 tsunami. As of 16 July 2013 more than 5,700 people were presumed dead. Today, with modern equipments and radars we should have been able to predict the floods and expected inundation much earlier and stopped these human disasters.

Real-time flood forecasting is an important non-structural method which forms the basis of decision pertaining to flood warning, flood control or river regulation. An accurate flood forecast well in advance can help the water managers in taking emergent actions to mitigate some of the adverse effects of flooding. It is important that apart from investing only in strengthening of structural measures, flood forecasting models should also be improved for lead time and accuracy so that the settlements of flood-prone area may be evacuated well in advance and loss of property and lives can be minimized. The accuracy of the forecasts depends mainly on the capability of the model to represent the system and forecast lead time depends primarily on the physiography of the catchment and on the telemetry of the input components essential for using the model. The forecast lead time is constrained by the initial lag (an overall measure of delay in catchment response to rainfall) of the catchment. An effective flood forecasting system mainly includes a ‘model’ which tries to mimic the behaviour of the catchment under study. Many real-time flood forecasting models have been developed so far as discussed in the literature review but none of them have capabilities of forecasting flows on real-time basis. At present flood forecasting is being done by the Central Water Commission for rivers of north Bihar using statistical procedure based on gauge-to-gauge co-relation which takes into account the variation in travel time. But unfortunately the forecast lead time is very short 8-24 hrs only and forecasts are based on gauge-to-gauge co-relation. Also for starting the flood forecast by this method, one has to wait till discharge and water levels are observed in the upstream gauge stations. Hence the forecast lead time is constrained by travel time between two gauge stations.

The operational objective set for the present study is to develop a web-based real time flood forecasting methodology using SWAT model and apply it on Bagmati river basin.

LITERATURE REVIEW

Gosain (1984) carried out an inter comparison of various categories of real time flood forecast models. In order to carry out this study three models, which belong to three different categories, (I) a model based on unit hydrograph theory which was developed for the purpose of real time forecasting, (II) an ARMAX (autoregressive moving average with exogenous input) model and (III) a conceptual watershed model known as NWSRFS (National Weather Service River Forecast System). These three models described above were used on an Indian catchment, namely, Yamuna catchment for the purpose of inter-comparison. The models belonging to different categories were compared with respect to certain common criterion. In this study two criteria were used, one based on the accuracy of the forecasts and another based on the user's requirements of the model. The UH model fared best followed by ARMAX model.

Another class of hydrological models are differential models which are based on conservation of mass, energy, and momentum. SHE (Abbott et al., 1986) is a differential model which simulates water movement in a basin with a finite difference solution of the partial difference equations describing the processes of overland and channel flow, unsaturated and saturated subsurface flow, interception, ET, and snowmelt. In last two decades there has been a breakthrough in the field of computer technology, information system, database management system and computational methods and many new models of both types (black box types and conceptual physical based types) such as ANN-GA (Genetic Algorithm based Artificial Neural network) model, ANFIS (adaptive-network-based fussy interface system), grey model, wavelet based nonlinear model for real time flood forecasting, WMS (window based watershed modelling system) ,MMS (Modular Modeling System) ,HEC-1(Hydrologic Engineering Centre of the US Army Corps of Engineers), HEC-HMS (Hydrologic Modelling System), HEC-2, TOPMODEL, MIKE11 , HEC-RAS, SWAT, etc. have been developed. Kumar et al (2010) and Saif et al. (2008) have applied artificial neural networks approach in modelling various hydrological components. Application of Remote sensing and GIS in Water Resources has brought revolution in the field of hydrological modeling (Sarma, 2009). Eldho et al. (2006) have attempted integrated watershed modelling using a finite element method and a GIS approach. Recent advances in computer hardware and software including increased speed and storage, advanced software debugging tools, and GIS/spatial analysis software have allowed large area simulation to become feasible. The challenge then is to develop a basin-scale model that: (1) is computationally efficient; (2) allows considerable spatial detail; (3) requires readily available inputs; (4) is continuous-time; (5) is capable of simulating land-management scenarios; and (6) gives reasonable results (Arnold et al., 1998).

In the present scenario hydrological models can be classified as (1) stand-alone programs with data loaded via the import and export facilities within the model without help of any

GIS package or (2) GIS-based hydrological modelling systems. Since GISs provide powerful tools for spatial analysis and intuitive visualisation, a GIS-based hydrological model may provide a better tool for real time flood forecasting. SWAT (soil and water assessment tool) model is a recent catchment scale parsimonious semi distributed physically based conceptual model and has capability of integrating different hydrological processes and can be used as a potential flood forecasting model. According to Arnold et al., (1995) although the model operates on a daily time step and is efficient enough to run for many years, it is intended as a long term continuous yield model and is not capable of detailed event modeling. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modelled by SWAT using input data about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. SWAT Model offers such a kind of base which can provide this trade-off. Minimum no. of parameters has been used in SWAT. Curve number technique used by SWAT has minimized parameters to be modeled and gives reasonably good result. The CN method is an empirical model that is based on more than 20 years of studies involving rainfall-runoff relationships. Recently SWAT model has been applied for comparison of two approaches of rainfall-runoff modelling with different data requirements by Bhadra et al (2010).Very recently hourly analysis of hydrological and water quality simulations have been done by Bekele et al. (2008) and development and integration of sub-hourly rainfall-runoff modeling capability within a watershed model has been done by Jaehak et al. (2010).

METHODOLOGY

Two subroutines have been developed and integrated into SWAT model for enabling it for hourly simulation and forecasting flows at outlet points of different sub-basins. Modified version of SWAT takes in sub-hourly rainfall data as input and estimates infiltration and excess rainfall by GAML (Green and Ampt Mein Larson) excess rainfall method. A dimensionless synthetic unit hydrograph is used for overland routing to forecast flows at outlet points of different sub-basins. Evapotranspiration, soil water contents, base flow, lateral flow and snow melt are estimated on a daily basis and distributed equally for each time step. Subroutines have been modified to capture the final conditions of the catchment at any desired instant. Model is updated on real-time basis after each time step. In modified SWAT, capability of event modelling has been introduced. First of all the model is run in continuous mode to simulate the characteristics of the basin and validate the model using the historical flow data. Subsequently the model is run in real-time mode with the initial conditions captured from the historical simulation. After every time step the modified SWAT captures and stores status of the catchment at the end of the interval to be used as the starting status for the next interval. Also an error forecasting model has been developed by time series analysis of previous forecasts. Modifications made in the SWAT model for real-time flood forecasting have been depicted in the flow chart in Figure 1. Time series analysis of errors in hourly forecasts has been performed. An ARIMA model for forecasting error has been developed. Forecasted hourly flows have been corrected accordingly. Integration of simulation capability of SWAT model and error forecasting capability by time series analysis has been done for enhancing the accuracy of real-time flood forecasts. Real time hydrological data are down loaded from three websites www.imdaws, www.hydrology.gov.np, and www.fmis.bih.nic.

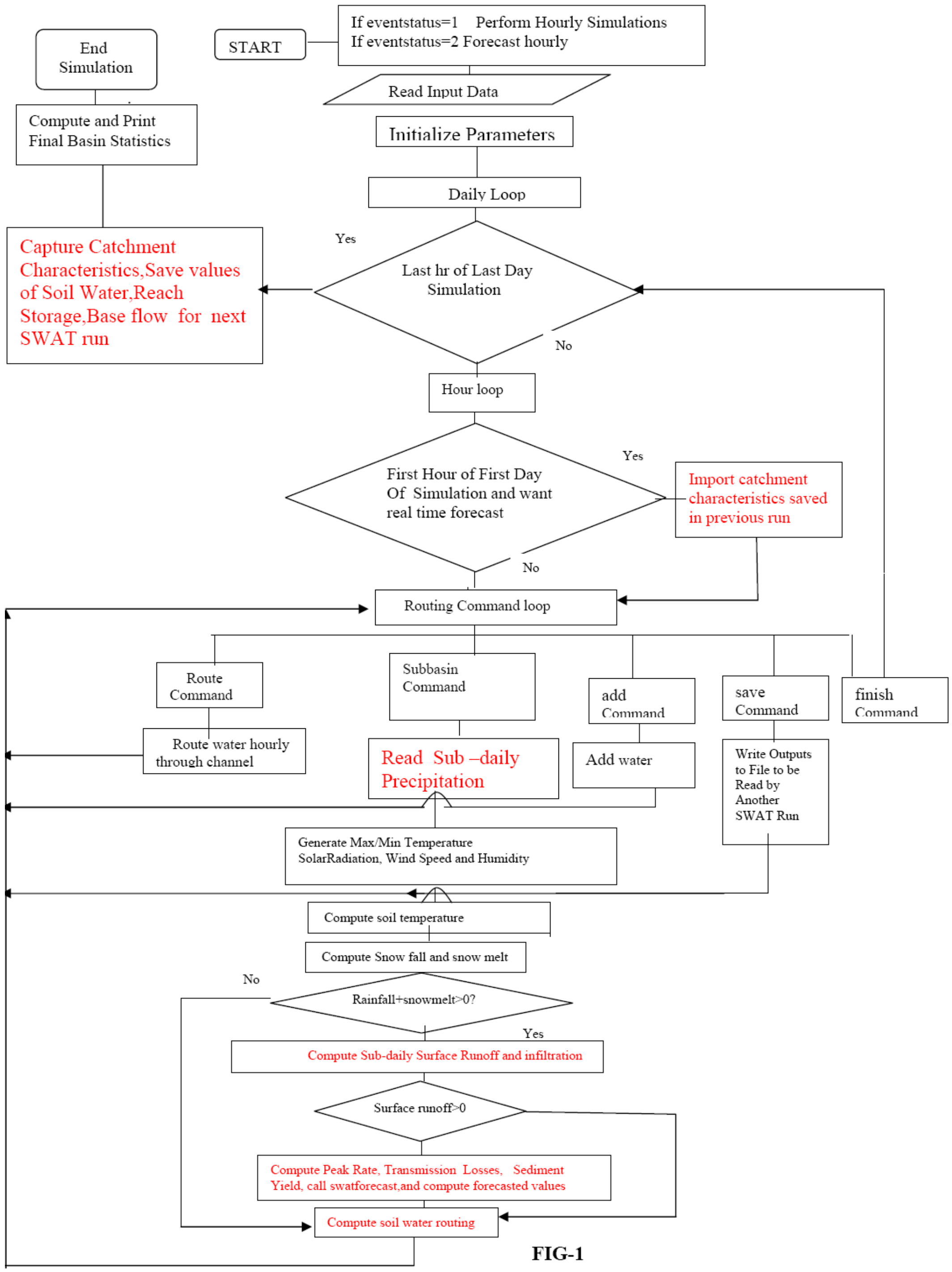

FIG-1

Figure 1: Flow Chart of Modified SWAT Model

STUDY AREA

The Bagmati basin (Figure 2) in Bihar state of India has been taken as the study area since this is an area that is frequently flooded.The river Bagmati, one of the perennial rivers of North Bihar, orginates in the Shivpuri range of hills in Nepal at latitude 27^0 47' N and longitude 85^0 17' E, 16 Km North-East of Kathmandu at an elevation of 1500 m above MSL. It enters Indian territory in Bihar in the village Shorwatia in Sitamarhi district, nearly 2.5 Km north of Dheng Railway station, The main course of the river in its first reach inside Indian territory between Indo-Nepal border to Khoripakar, crosses Samastipur Narkatiaganj railway line near Dheng Railway Station through railway bridge No 89. This bridge has silted up and as such three channels have formed upstream of this railway bridge. These channels after passing through railway brdge nos 90, 91, 91A and 91 B between Dheng and Bairgania stations of N E Rly, again join the parent Channel near village Joriahi at about 2.5 Km south of the railway line. The Bagmati river in this reach flows due south for nearly 15 Km, upto village Khoripakar where the river Lalbakeya joins on its right bank. Above the confluence, the Bagmati has a tendency to shift towards west but the confluence point with lalbakeya remains more or less fixed. In this reach, the river spills on both its banks during high floods inundating areas in the Sheohar block. Therefore, it has been embanked on both the banks together with the banks of the Lalbakeya upto Indo-Nepal border. The Bagmati river basin in India lies in the Gangetic plains which has been built up in the process of land formation. The rivers originating from the Himalayas and falling into the Ganga have played a major role in such land formation process. The sediment brought by them formed inland deltas where the steep slope of the terai converged into the flat slope of the plains. This resulted in the development of meandering and braiding tendencies in the rivers leading to shifting of their courses. Such changes in the river course and avulsions/cut off of the meander loops formed local depressions known as Mauns.

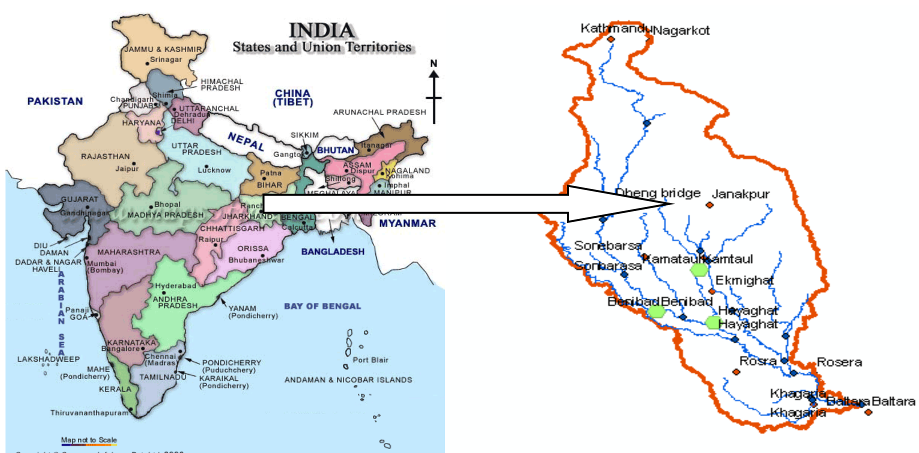

Figure 2 Bagmati River Basin

Model input of terrain, landuse and soil type for present study area are given in Figures 3 to 5

Figure 3. DEM of Bagmati basin

From DEM of study area it can be seen that slope in Nepal portion is very steep and that in Indian portion is flat.

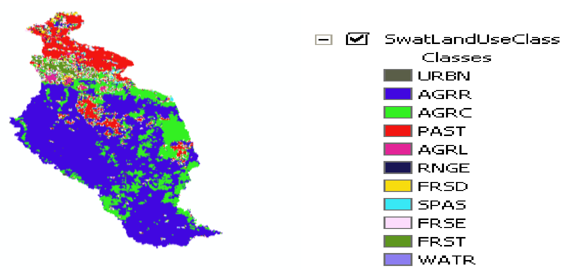

Figure 4 Land use data for the Bagmati basin

The landuse data has been taken from Global USGS (2 M). Figure-4 shows the landuse classes for the study area.

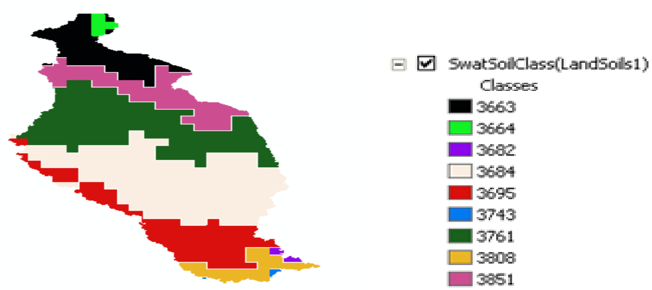

Figure 5 Soil classes for the Bagmati basin

FAO Global soil (5 M) classes are used as input in the model. Figure 5 shows the soil classes for study area. Details of soil types are given in Table-1:

Table-1 Soil properties

SEQN	SNAM	NLAYERS	HYDGRP	TEXTURE	SOL_AWC1	SOL_K1	CLAY1	SILT1	SAND1
3663	3663	2	C	LOAM	0.117	35.65	24	35	42
3664	3664	2	C	LOAM	0.157	28.52	17	36	47
3682	3682	2	D	LOAM	0.175	7.77	24	36	40
3684	3684	2	C	LOAM	0.175	13.92	22	38	41
3695	3695	2	C	LOAM	0.175	14.96	20	40	40
3743	3743	2	D	LOAM	0	6.48	18	44	38
3761	3761	2	C	LOAM	0.175	24.73	20	34	46
3808	3808	2	D	LOAM	0.175	6.17	21	35	44
3851	3851	2	D	CLAY_LOAM	0.137	7.17	27	35	37

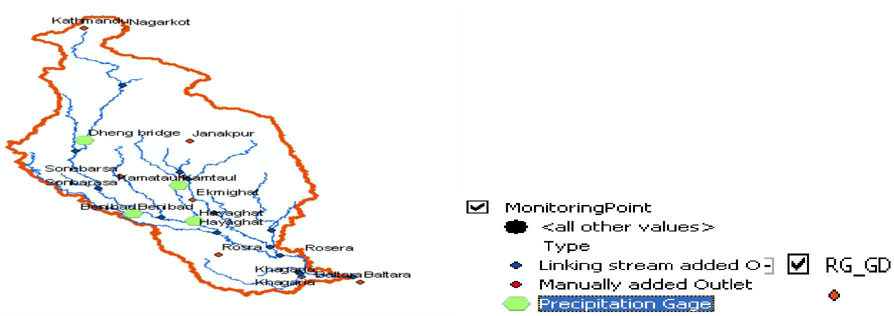

Figure 6 Layout of Bagmati basin alongwith stream network

Stream network is an optional theme which needs to be provided as a shape file. In case it is not provided by the user, the interface generates it using the DEM. In the present case, a shape file of stream network has been obtained by digitizing drainage network since the area is flat and there is a possibility of inaccuracy while generating the drainage. This shape file has been superimposed on the DEM to burn the drainage. The delineated Bagmati basin and its sub-basin has been shown in Figure 7.

Figure 7. Delineated Bagmati basin and its sub-basins

Bagmati basin and its sub-basins were delineated by SWAT model after removing sinks/depressions. Figure 7 shows the delineated Bagmati basin and its sub-basins.

ANALYSIS OF WEB BASED REAL TIME HYDROLOGICAL DATA OF YEAR 2012

Rainfall and water levels of Hayaghat gauge station for September 2012 were downloaded from websites www.imdaws, www.hydrology.gov.np. And www.fmis.bih.nic. Real-time hydrological data downloaded from websites are plotted in form of figures 8-11. Discharge was calculated using stage discharge relationship of Hayaghat. It can be concluded that rainfall of Nepal portion produces peak discharge at Hayaghat after 10 days. Hence correlation between rainfalls of Nepal portion and runoff of Hayaghat is very interesting. The lead time at Hayaghat for rainfall of Nepal portion is very high 4-8 days.

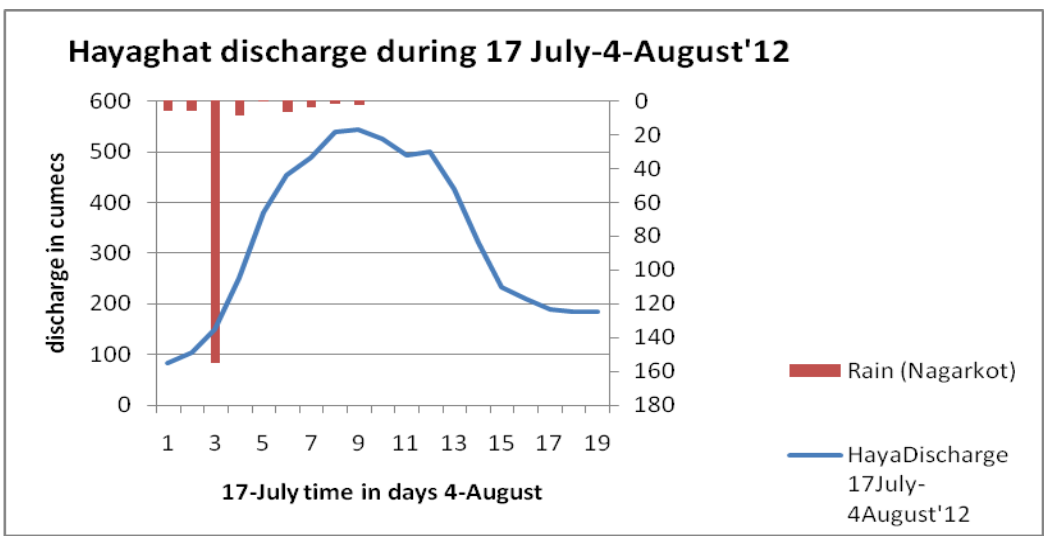

Figure 8 Flood hydrograph of year 2012 on daily scale at Hayaghat for rainfall in Nepal (Nagarkot)

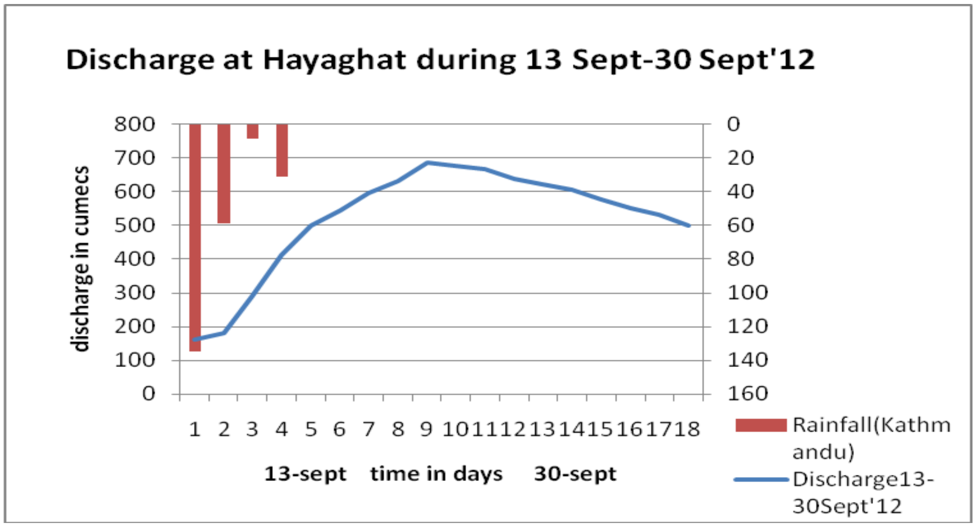

Figure 9 Flood hydrograph of year 2012 on daily scale at Hayaghat for rainfall in Nepal (Kathamandu)

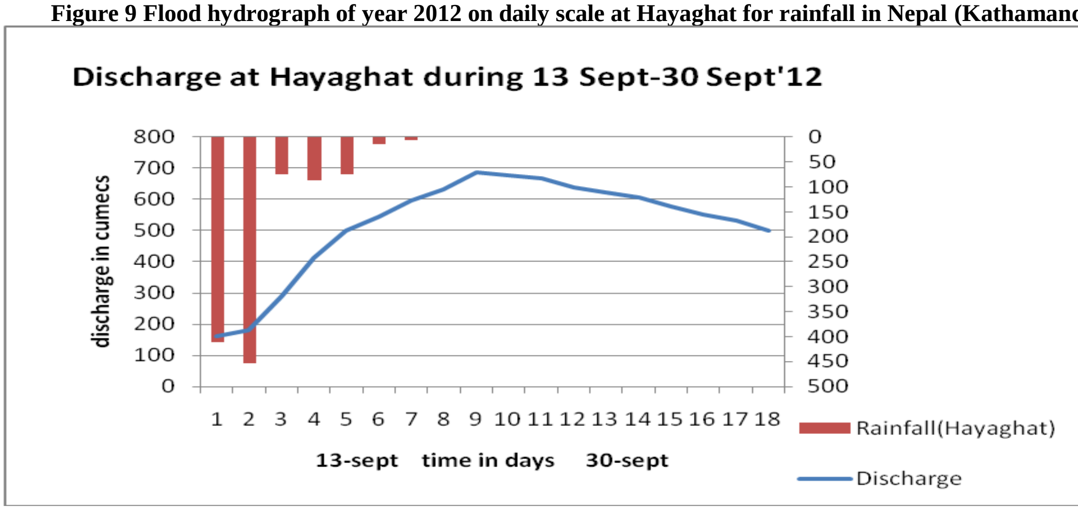

Figure 10 Flood hydrograph of year 2012 on daily scale at Hayaghat for rainfall of Hayaghat

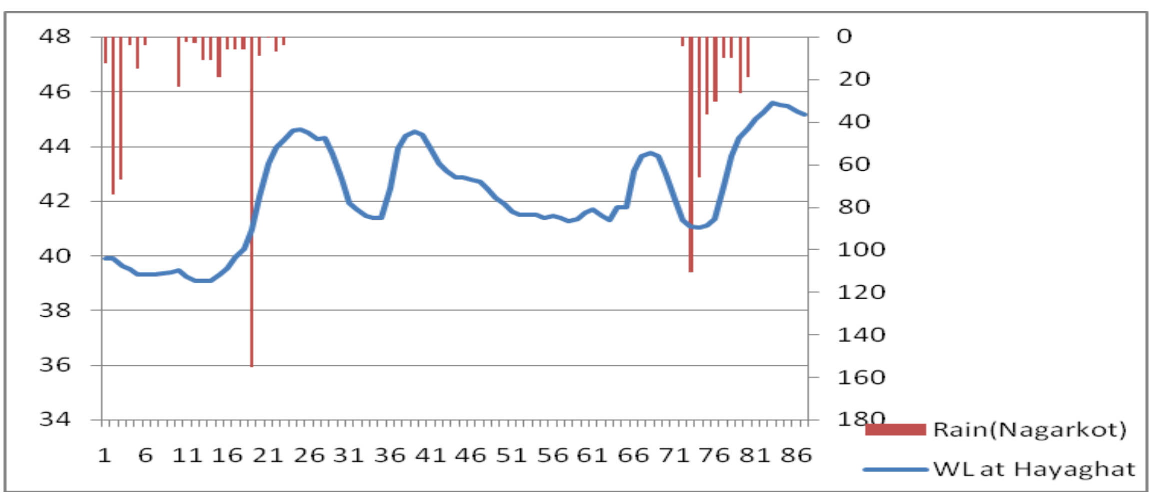

Figure 11 Waterlevel hydrograph of year 2012 on daily scale at Hayaghat for rainfall of Nagarkot (July to September)

From above Figures 8 - 11 it can be inferred that lead time to peak discharge at Hayaghat is more than 3 days with respect to rainfall of Nagarkot and Kathmandu of Nepal.

CALBRATION AND VALIDATION

The daily values of discharges up to Hayaghat have been used for the purpose of model calibration and validation. Measured daily discharge for the year 2004 was used for calibration. Calibrated model was used for simulating flows for the year 2005 for validation. Calibration was reasonable with Nash-Sutcliffe efficiency coefficient EF of 0.84 which indicates that simulated values are reliable. Validation of the modified SWAT model was also done using available measured data of year 2005.Nash-Sutcliffe efficiency for validation was found to be 0.7 which is indicative of high predictive power and accuracy of the model. During calibration it was found that the model is very sensitive to parameters; CN2.mgt(curve number) followed by GW_DELAY.gw, CH_N2.rte, ESCO.hru, HRU_SLP.hru, GWQMN.gw, GW_REVAP.gw and SURLAG.bsn.

RESULTS AND DISCUSSIONS

Real time forecasting was done with help of modified SWAT model for Dheng bridge, Khagaria, Hayaghat, and Benibad gauge stations for year 2004 and 2005. Direct surface runoff hydrographs are obtained after estimating excess rainfall and routing over catchment using a synthetic dimensionless unit hydrograph. Different surface runoff hydrographs due to excess rainfall for successive rainfall increments were derived. The overland surface hydrographs generated by SWAT give the volume of water entering the channel at subasin outlet per unit time due to excess rain only. In the head-water lead time is introduced by catchment lag only. Subsequently, the direct surface runoff entering the channel is routed by Muskinghum method and additional lead time due to travel time is introduced. Figure 12 shows a typical direct surface runoff hydrographs produced by modified SWAT model at Khagaria for the period 10July to 11July-04.

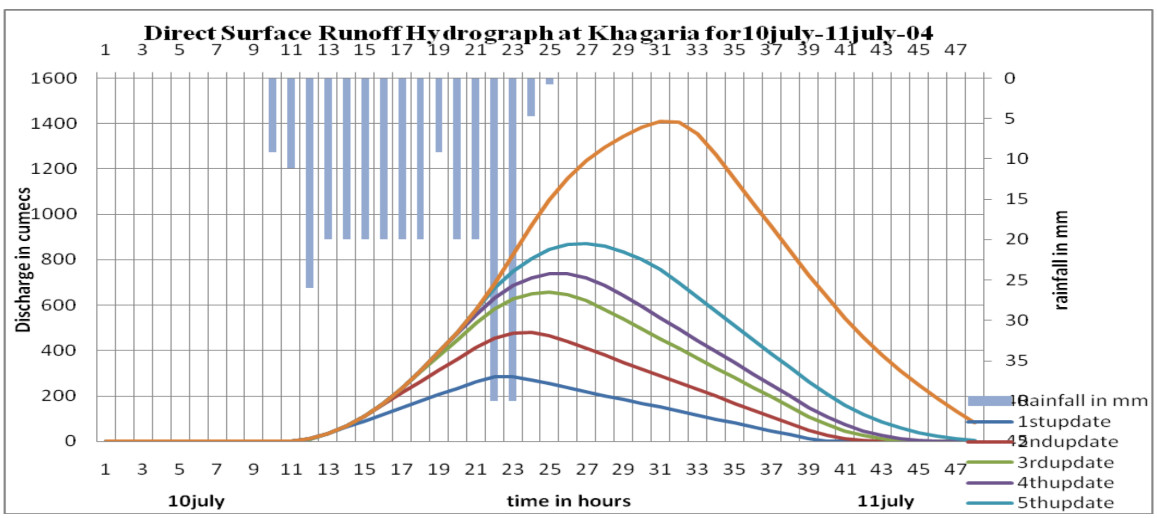

Figure 12 Typical Direct Surface Runoff Hydrograph at pour point near Khagaria

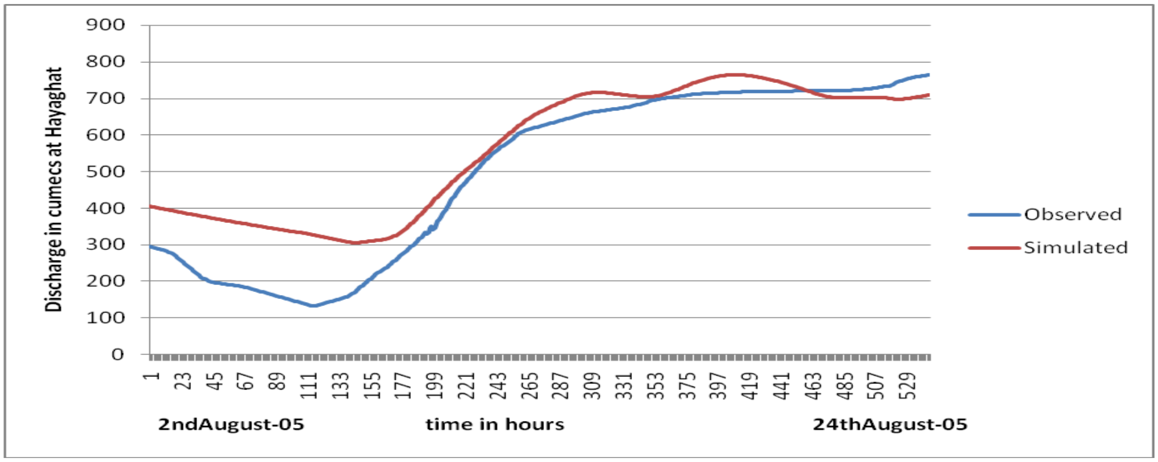

Figure 13 Error Analysis and Validation graph

Validation of the model for hourly simulation at Hayaghat has been shown in Figure 13. It represents a typical graph showing error in simulated flows between 2nd August and 24th August 2005. Nash-Sutcliffe model efficiency co-efficient was estimated for assessing the predictive power of modified SWAT model for hourly simulation of Bagmati river basin. Here the efficiency co-efficient was found to be 0.84 which indicates that the model performed well. The efficiency may further improve with improvement in the input data. However, the systematic error induced in the process was corrected by introducing an error forecasting model. An ARIMA model was introduced for error forecasting. The errors in hourly simulated flows may be due to release of water from reservoirs/agricultural fields or withdrawing of water from catchment for other purposes depending on users need, the information on such entities were not available. The measured discharge data used for error analysis itself has been derived from stage discharge curve because only hourly stage is available and the rating curve is not frequently validated. Hence uncertainty in measured data may also be a source of error. But it is encouraging to note that the error forecasting model is an effective tool to reduce the error considerably under the present situation.

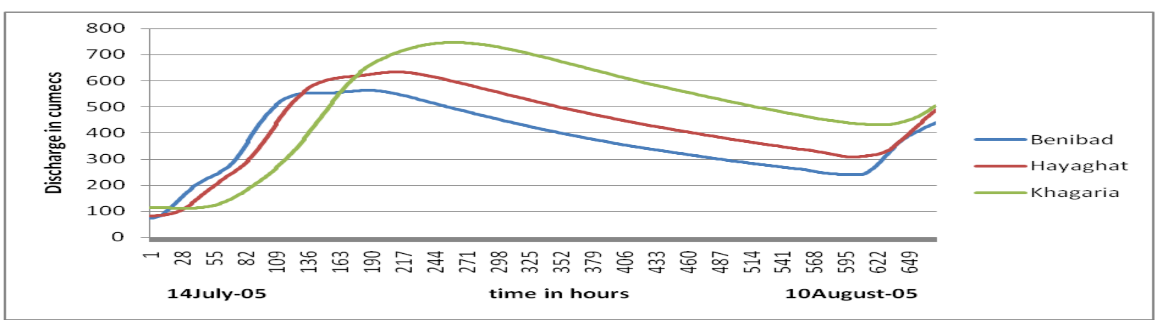

Figure 14.Hydrographs obtained after channel routing at Benibad, Hayaghat and a pour point near Khagaria

Flood hydrographs obtained for Benibad, Hyaghat, and a pour point near Khagaria between 14 July and 10 August 2005, after channel routing, have been shown in Figure 14. Here the lead time obtained is both due to catchment lag and travel time.

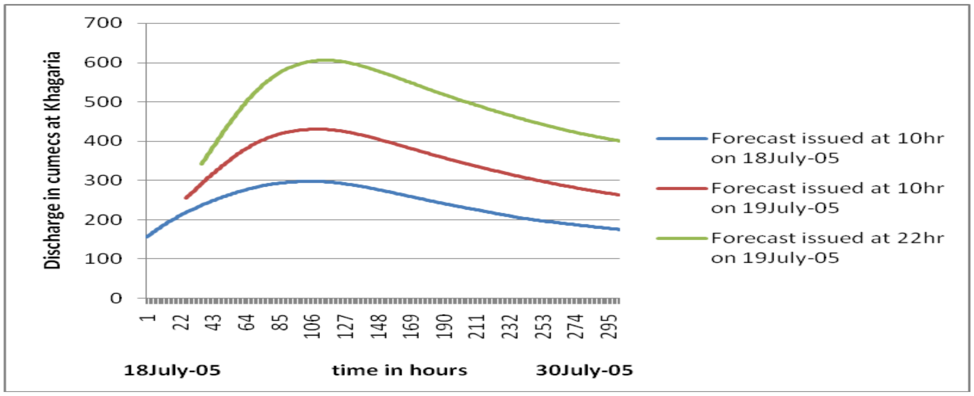

Figure15.Real-time forecasted hydrographs at a pour point near Khagaria produced by modified SWAT model

Flood forecasts issued at three time instances namely 10 hr of 18 July 2005, 10 hr of 19 July, and 22 hr of 19 July 2005 respectively at a pour point near Khagaria produced in a pseudo real-time manner have been shown in Figure 15.Pour point near Khagaria being the most downstream outlet point provides a total lead time of more than 2 days. Figure 16 shows real time forecasts issued on 21-23 September 2012 at Hayaghat.

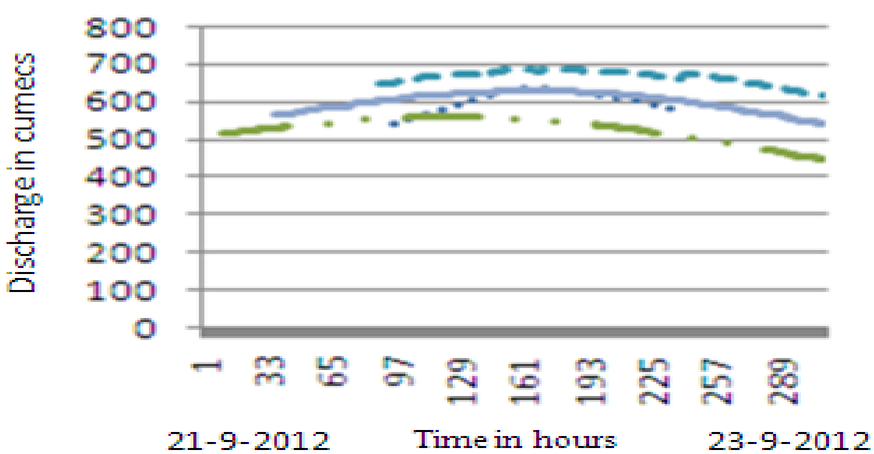

Figure 16 Real time forecasts issued on 21st September (5th hour), 22nd September (13th hour), and 23rd September (17th hour) 2012

CONCLUSIONS

As outcome of the present research work it can be concluded that Modified SWAT model combined with time series error model can be used as an efficient tool for real-time flood forecasting. Modified SWAT model reproduces stream flow hydrographs reasonably under multiple storm events and can be used as a real-time flood forecasting tool with enhanced lead time.

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Drought assessment of future streamflow over the Dakbla river basin in Vietnam

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Abstract

Central highland Vietnam is the source for perennial plantation which produces most of the coffee for Vietnam, by which, it serves as the world second coffee exporter next to Brazil. Additionally, this region is also one of the important sources for hydropower of Vietnam and one of the main tributaries for Mekong river at the downstream. This region has been known prone to drought, especially during dry seasons in March and April. Therefore, simulating drought for this area is significant to study the water supply and water balance for the region in future planning. This study used a Regional Climate Model Weather Research Forecast to derive present day and future climate variable which were used as input to assess the hydrological drought over Dakbla river basin in Central highland, Vietnam. The semi-distributed hydrology model SWAT was calibrated and validated for the period 1980-2005 for the Dakbla river basin. Hydrological drought for the whole catchment is assessed by using Standardized Runoff Index. Information from dynamical downscaling that served as an input to hydrology model will help to assess the future drought situation over the study region.

Keywords: SWAT, WRF, SPI, SRI, climate change.

1. Introduction

Drought is a ‘prolonged absence or marked deficiency of precipitation’ (Trenberth et al., 2013). Several publications have studied the impact of global warming to changing in drought (Trenberth et al., 2013; Dai 2012; Sheffield and Wood, 2008). The United States Environment Protection Agency (EPA) also listed severe drought as a natural disaster. Drought affects natural habitats, ecosystems and many economic and social sectors, from the foundation of civilization - agriculture - to transportation, urban water supply and the modern complex industries (Heim, 2002). Understanding drought and modelling its components have drawn attention of ecologists, hydrologists, meteorologists and agricultural scientists (Mishra and Singh, 2011).

Drought is often classified into three types: meteorological, hydrological and agricultural (Dai, 2011; Wilhite, 2000). Meteorological drought is a period of months to years with below-normal precipitation. Hydrological drought occurs when river streamflow and water storages in aquifers, lakes or reservoirs fall below long-term mean levels. Hydrological drought develops more slowly because it involves stored water that is depleted but not replenished. A lack of precipitation often triggers agricultural and hydrological droughts (Dai, 2011). This study only focuses on the meteorological and hydrological drought over a 25 year period for a river basin in Central Highland region of Vietnam by using drought indices, Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI).

The SPI (McKee et al., 1993) requires only precipitation data as an input, which makes it ideal for areas where data collection is not extensive as in this study region. The SPI is considered as the most appropriate index for monitoring the variability of droughts since it is easily adapted to local climate, has modest data requirements and can be computed at almost any time scale (Ntale and Gan, 2003). SPI is suggested to use as a universal meteorological drought index for more effective drought monitoring and climate risk management by all National Meteorological and Hydrological Services around the world (WMO, 2009). In Asia, many researches have adapted SPI as an effective tool for their countries’ drought monitoring. Yusof et al. (2014) applied SPI to assess rainfall characteristic over Peninsular Malaysia and concluded that the whole peninsula is predicted to have an increasing trend during drought events. Ling et al. (2014) used SPI of 3 months to monitor winter wetness and dryness in Southeast China. Vu et al. (2013) also compared SPI with several drought indices to monitor drought for the whole Vietnam from 50 meteorological stations. Lyon et al. (2009) evaluated drought in Sri Lanka using 3, 6, 9 and 12-month cumulative drought index SPI and found out the 9-month SPI provided the strongest relationships overall.

The hydrological drought index SRI was proposed by Shukla and Woods (2008), which had the similar concept of deriving SPI index but using monthly runoff as input. The Climate Prediction Center in USA is also using SRI index to forecast the hydrological drought by using 3, 6 and 12 months over the entire USA. Wang et al. (2011) applied SRI to simulate the climate change impacts on hydrological drought over Salt Creek Watershed in State of Illinois and they found a significant change of SRI in the future climate. Joetzjer et al. (2013) used SRI 12 month as a proxy for river discharge and as a benchmark for various meteorological drought indices while studying the impact of the anthropogenic radiative forcing on hydrological drought over one tropical river basin: the Amazon and one mid-latitude (Mississippi) river basin. Taylor et al.

(2013) also utilized the SRI index to assess the global impact of climate mitigation on projections of future drought. They used the CMIP3 scenario A1B and CMIP5 RCP 2.6 future emissions scenarios using monthly model outputs from a 57-member perturbed ensemble of climate simulations of the HadCM3C Earth System model, for the baseline period 1961–1990 and the period 2070–2099. Recently, Li et al. (2014) applied SRI to investigate historical drought and wetness episodes in the Upper Nen River basin (China) and they concluded that SRI provides better consistency of drought and wetness conditions at all considered timescales than other meteorological drought indices.

The study region Dakbla river is a small tributary of the Mekong river. The water catchment has a total area of 2560 km^2 (Figure 1) and lies entirely over the Central Highland region of Vietnam. The catchment is covered mostly by tropical forests. The climate of this region follows the pattern of Central Highland in Vietnam with an annual average temperature of about 20-25 °C and a total annual average rainfall of about 1500-3000 mm with high evapotranspiration rates of about 1000-1500 mm per annum. There are 2 main seasons for the Central Highland region: a rainy season from May through to October that stands for 80% of the total rainfall and dry season from November through to April which accounts for 20%, thus it has high risk for drought over this season. The region is suitable for perennial plantations like coffee, rubber or annual plants like cocoa, pepper, sugar cane and cashew in which coffee is the most important crop in the Central Highland.

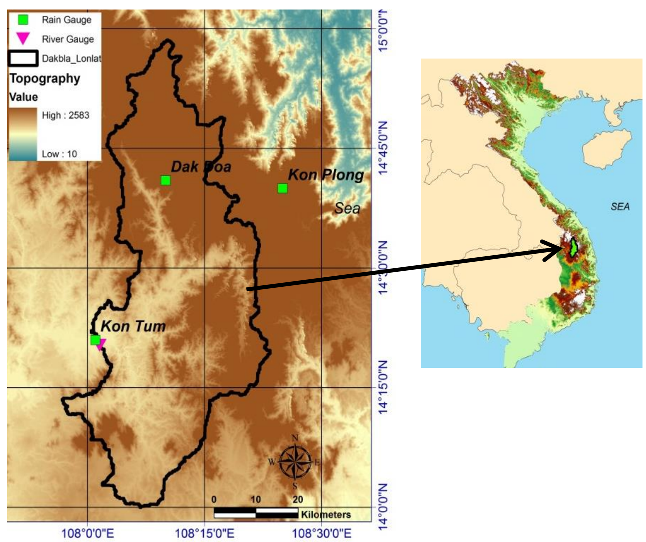


Figure 1. Dakbla river basin and met stations.

Due to funding and research limitations, drought studies over Vietnam and Central Highland region are still very few in number despite widespread severe droughts over this area. There are few studies done by local researchers that might serve as records for the drought phase. A study by Dao (2002) indicated a series of drought events in this area from 1994 to 1998 during the winter-spring season. Tran (1999) pointed out that the wide spread drought in 1997-1998 was related to a strong El Nino year. Nguyen et al. (2007) found that the precipitation in Central Highland, during October, November and April, is highly related to El Nino Southern Oscillation (ENSO). Nguyen (2005) characterized drought over the Central Highland whose studies pointed out that 1998 and 2005 were two typical severe drought events over this region, especially during the winter-spring crop season. Vu et al. (2013) noted that of the El Nino events over the past 40 years, there were strong El Nino events in 1982, 1991 and 1997. These studies suggest that drought over the Central Highland of Vietnam could be strongly related to El Nino. We will use these findings as the basis for our modelling work and study. The overall methodology and data are described ahead.

2. Data

2.1. Station data

Daily precipitation data for period 1980-2005 from 3 rainfall stations in and outside Dakbla river basin were used in the study. This dataset was obtained from the Institute of Meteorology, Hydrology and Environment (IMHEN), Ministry of Natural Resources and Environment (MONRE), Vietnam. The daily data was aggregated to make monthly rainfall as inputs to meteorological drought index SPI. Daily river discharge at Kon Tum gauging station for the above period was also obtained from IMHEN. These served as calibration and validation datasets for the hydrological model SWAT. The monthly data aggregated from the daily runoff was used as an input to hydrological drought index SRI. Locations of the rainfall and river gauging stations are displayed in Figure 1.

2.2. Spatial data input for SWAT model

The spatial input data required for SWAT model consists of the Digital Elevation Model (DEM) of 250 m that was obtained from the Department of Survey and Mapping (DSM), Vietnam. The land use map was obtained from the Forest Investigation and Planning Institute (FIPI) and the soil map was obtained from the Ministry of Agriculture and Rural Development (MARD), both, Vietnam (Figure 2).

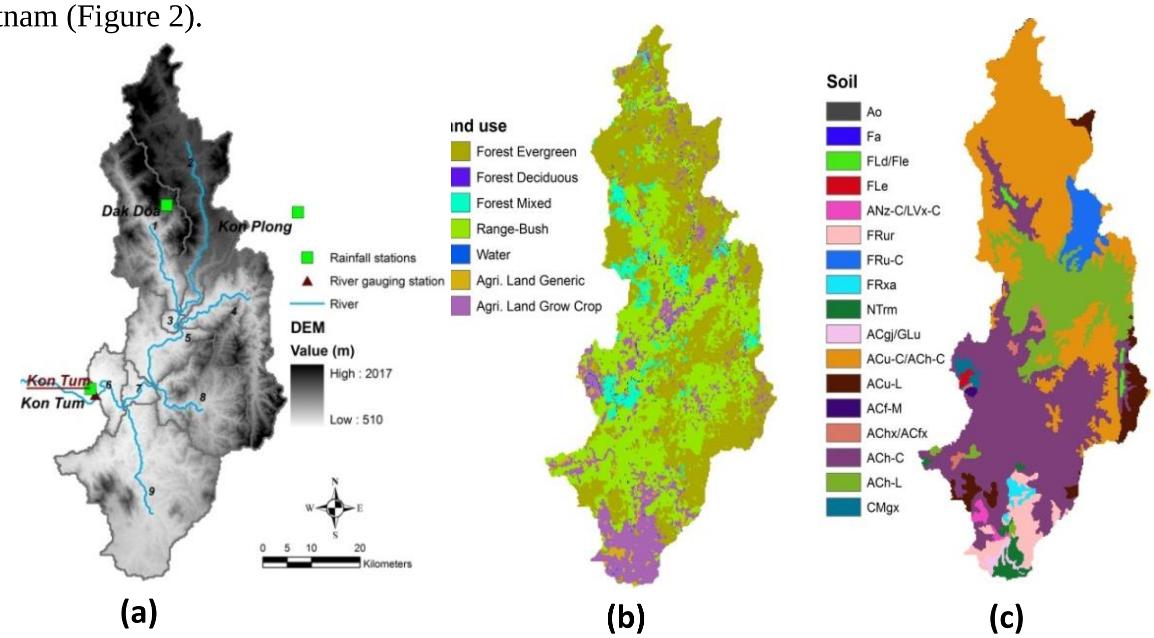


Figure 2. Spatial data input for SWAT model (a) DEM (b) Landuse (c) Soil map

3. Methodology

3.1. Regional climate model – Weather Research and Forecasting (WRF)

Developed at the National Center for Atmospheric Research (NCAR) in the USA, the WRF model is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. The model incorporates advanced numeric and data-assimilation techniques, a multiple nesting capability and numerous state-of-the-art physics options. The model has found wide applications in climate research and in weather forecasting. Additional information can be obtained from: http://www.wrf-model.org.

The WRF model was run at spatial resolution of 30km for the baseline period 1961-1990 using the ERA40 analysis to assess its performance of the present-day climate. Later, the model was run driven by the GCM ECHAM5 T63 over the same period forced under the 20th century experiment to assess the model's performance on the 30-year climatology of the present-day climate. The future climate simulation spanned the period 2071-2100 driven by the GCM ECHAM5 T63 under the IPCC SRES A2 emission scenario. This period has been considered in this study as the emission scenario shows a clear signal of climate change towards the end of the century. For simplicity in reading, GCM ECHAM5 T63 driven WRF is being referred to as 'WRF/ECHAM'.

3.2. Soil and Water Assessment Tool

SWAT is a river basin scale model, developed by the United States Department of Agriculture - Agriculture Research Service in early 1990s (Arnold et al., 1998). It is designated to work for a large river basin over a long period of time. Its purpose is to quantify the impact of land management practices on water, sediment and agriculture chemical yields with varying soil, land use and management conditions. Detailed information and several related publications are available at http://swatmodel.tamu.edu. The calibration and validation in daily scale is run for 1980-1990 and 1995-2005, respectively.

3.3. Standardized Precipitation Index (SPI)

The SPI was first introduced by McKee (1993) by analyzing historical monthly precipitation. A set of averaging periods are selected on a moving window basis to determine a set of time scale of period 'i' months (i = 3, 6, 12, 24, 48). In this study i = 12 is selected in order to assess meteorological drought due to the previous 11 months' data and the last month. Each dataset is fitted to the Gamma distribution that has the density probability function as:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}, \quad for\ x > 0 \tag{1}$$

where $x > 0$ is the amount of accumulated precipitation. Based on each data set, a set of shape parameter $\alpha > 0$ and shape parameter $\beta > 0$ is estimated. $\Gamma(\alpha)$ is the Gamma function that is defined by the integral:

$$\Gamma(\alpha) = \int_{0}^{\infty} y^{\alpha-1} e^{-y} dy \tag{2}$$

After estimating coefficients α and β, we obtain an expression for cumulative probability $G(x)$ that represents a certain amount of rain has been observed for a given month at time scale *i*:

$$G(x) = \int_0^\infty g(x)dx \tag{3}$$

However, Gamma function is not defined by $x = 0$, and there may be no precipitation. If q is the probability of zero precipitation, the cumulative probability of precipitation *H(x)* observed is computed as follow:

$$H(x) = q + (1-q)G(x) \tag{4}$$

The cumulative probability *H(x)* is then transformed into a normal standard distribution with mean $\mu = 0$ and standard deviation $\sigma = 1$ from which we obtain SPI. The SPI is the inverse of the normal cumulative distribution function at the corresponding probability *H(x).*

The drought classification based on SPI is shown in Table 1.

Table 1. Drought category based on SPI values [Adapted from McKee et al. 1993]

SPI Values	**Drought Category**
0 to -0.99	mild drought
-1 to -1.49	moderate drought
-1.50 to -1.99	severe drought
≤ -2.00	extreme drought

3.3. Standardized Runoff Index (SRI)

The SRI was proposed by Shukla and Woods (2008) in order to complement the SPI for depicting the hydrologic aspects of drought. Although SRI and SPI employ similar concepts when based on long accumulation periods, SRI incorporates hydrologic processes that determine seasonal lags in the influence of climate on streamflow. The input for SRI is river runoff. When applied for river runoff in United States, Shukla and Woods (2008) found that the 2 parameter log normal (LN2) distribution provided a better fit at high extremes than the Gamma distribution (which may performed better at low flow). However, the probability function selected will depended on the data series, the Gamma distribution can be used in most European basins, but users can choose other PDF that better fits to their data (Abril and Trevino, 2012).

3.4. Methodology

The SWAT model was calibrated and validated over the period 1980-2005 using 3 rainfall stations and a gauging discharge at Kon Tum. The runoff all over sub-catchments derived from SWAT model was used to calculate the SRI index. The corresponding rainfall value at these catchments was used to simulate SPI index. The meteorological and hydrological drought over the study region was assessed by analyzing SPI and SRI and compared against historical records. SWAT model was used to derive future runoff from future rainfall downscaled by the WRF/ECHAM5 model under scenario A2. Future SPI and SRI were then used to assess the change in drought for the study region by the end of the 21st century. The overall methodology is shown in Figure 3.

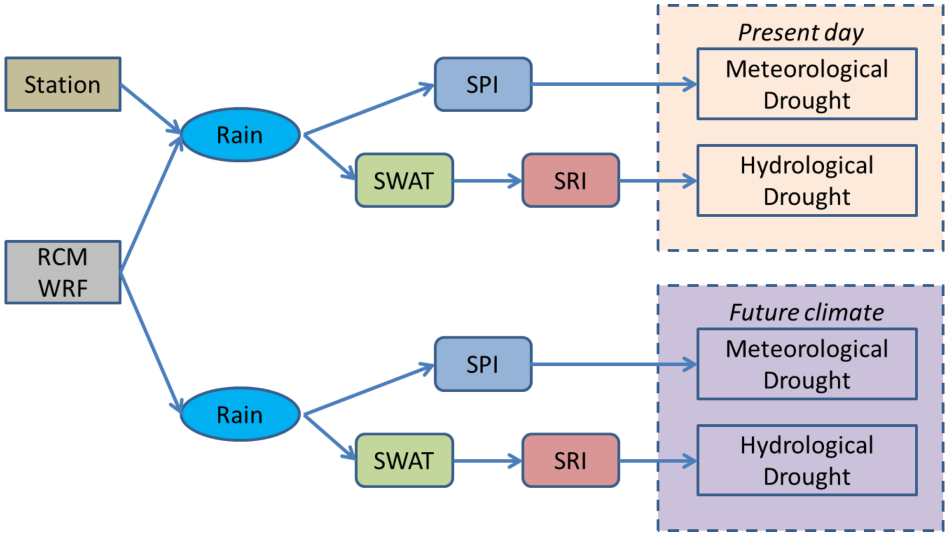


Figure 3. Schematization of the study

4. Results

4.1. SWAT model result

The calibrated and validated SWAT model has been done in our previous study by Raghavan et al. (2012, 2014). The Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination R^2 for monthly flow were found to be around 0.7 for the calibration and the validation steps, shown in Table 2. Figure 4 shows the long time run for 1980-2005 at Kon Tum station in monthly scale. It is therefore possible to use the monthly simulated flow for drought assessment over the Dakbla river basin.

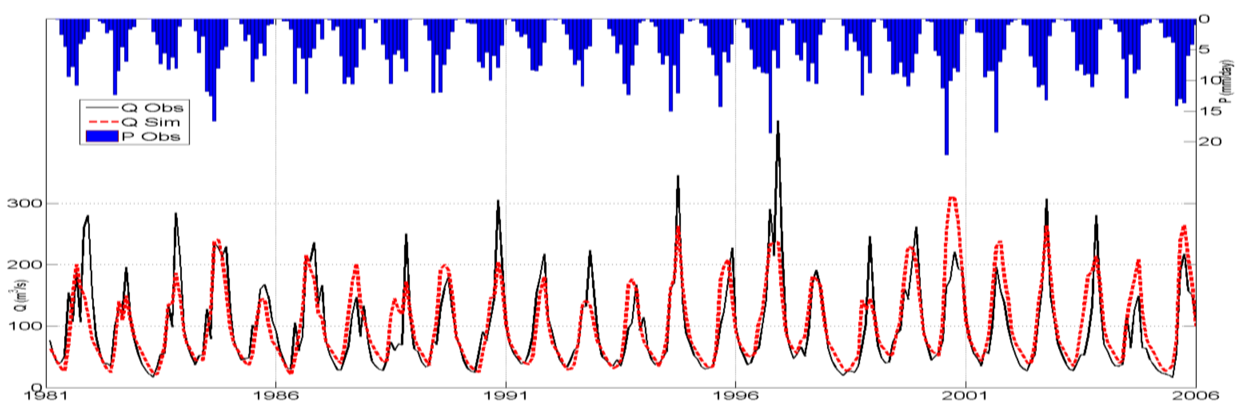


Figure 4. Calibration and Validation of SWAT model

Table 2. Goodness of fits results for SWAT model

Type	Cali	Vali
Coefficient of Determination: R^2	0.72	0.73
Nash-Sutcliffe Index: NSE	0.74	0.66

4.2. Assessing meteorological and hydrological drought at present day climate

The four accumulation period 1, 3, 6 and 12 month scale for SPI and SRI are assessed for the years 1980-2005 done at Kon Tum station (Figure 5). Table 3 shows the correlation value between SPI and SRI for all accumulation period. The differences between the indices increase as the accumulation period decreases, with SPI to SRI correlations dropping from 0.71 for the 12-month period to 0.64, 0.54 and 0.39 for the 6-, 3-, and 1-month period indices.

Table 3. Correlation between SPI and SRI

Accumulation period (month)	Correlation SPI vs SRI
1	0.39
3	0.54
6	0.64
12	0.71

In Figure 5, the value of SPI more than (less than) 0 is indicated as blue color (red color), representing the wet and dry period, respectively. It needs to be mentioned here that the drought begins when SPI first falls below zero and ends with the positive value of SPI following a value of -1.0 or less (McKee et al., 1993). The SPI/SRI 6 and 12 month accumulation clearly show the trend of significant events over 1983, 1986, 1992-1993 and 1998. The interesting finding here is that all these events occur about a year later after the strong El Nino hit Vietnam (Strong El Nino in 1982, 1991, 1997, moderate El Nino in 1986, 1987) (Vu et al., 2013). Both SPI and SRI indices agreed on the same event time and magnitude on these years.

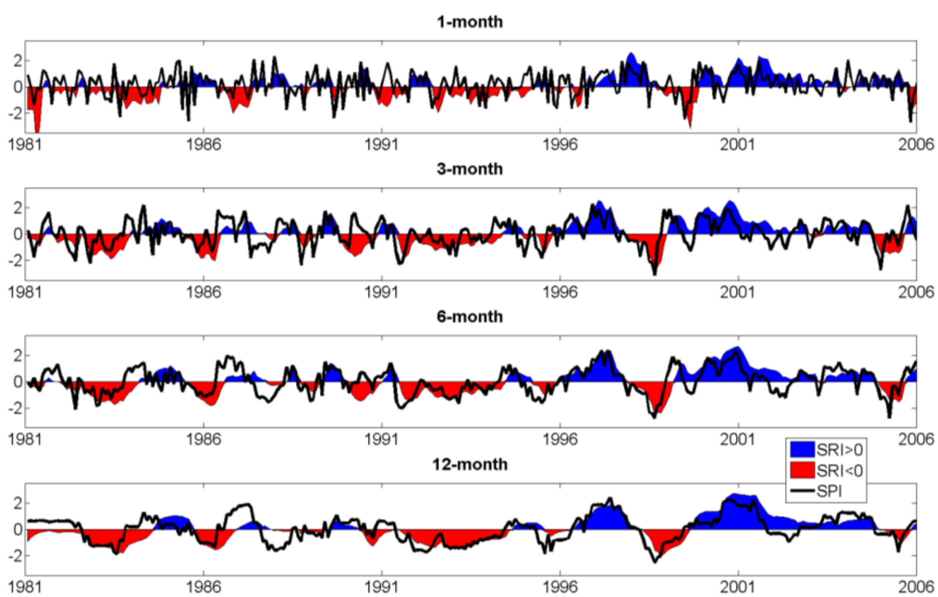


Figure 5. SPI and SRI value for 1, 3, 6 and 12 accumulation months (top to bottom)

Not only the drought indices are assessed at river outlet Kon Tum station, the simulation from semi-distributed SWAT model helps to assess the 9 sub-catchments (delineated from model) meteorological and hydrological drought as shown in Figure 6. All sub-catchments agree on the same extreme and severe drought events in the years of 1983, 1986, 1992-1993 and 1998. This is, therefore, a reasonable finding that the above indices SPI and SRI are able to capture the drought events over the study region.

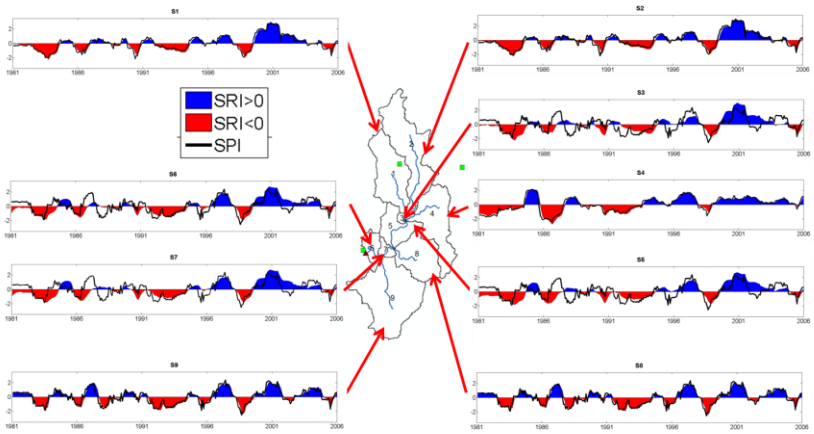
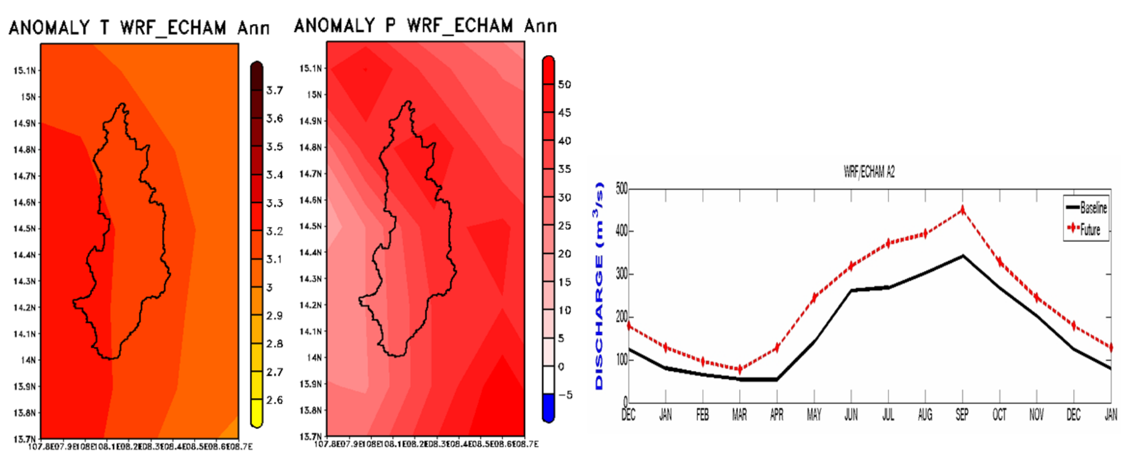


Figure 6. SPI and SRI timeseries at all sub-catchments of Dakbla river basin

4.3. Future climate projections

The future climate projections (temperature and rainfall) derived from WRF/ECHAM are shown in Figure 7. It is seen that there is an increase in temperature and precipitation for the study region by the end of 21st century of about 2.8-3.3°C (Figure 7a) and 10-50% (Figure 7b), respectively. The simulation by SWAT model indicates that the future hydrological streamflow is expected to increase by 33% with respect to the baseline (Figure 7c). This suggests that a wetter climate in the future is likely. So does it imply that future climate would have less drought than the present day climate? This is answered in the next section by analyzing the drought characteristics for present day and future climate.



(a) (b) (c)

Figure 7. Future climate change (a) Temperature Anomaly (°C), (b) Precipitation Anomaly (%), (c) Present day and future streamflow

4.4. Characteristic of future meteorological and hydrological drought

Table 4 summarizes the drought characteristics for SPI and SRI over the baseline 1961-1990 and future 2071-2100 A2 scenario. The 3 characteristics are taken into account are: (1) Number of drought events for the whole study period (2) Drought Intensity: summation of all SPI/SRI values occurred during drought events. It has the negative sign as the values of SPI/SRI for drought are negative and (3) Drought Frequency: the division of total duration of drought period (in months) with total number of months in the study period. Table 4 shows that there are more number of drought events in the future climate (1 event for meteorological drought and 2 events for hydrological drought). However, the Future Drought Intensity and Frequency are lower than the Present day climate due to wetter climate as described in the previous section. Therefore, we can conclude that there are more drought events in the future climate over the study region but they could be lower in intensity and frequency.

Table 4. Baseline (1961-1990) and future climate (2071-2100) drought characteristic

	Present day		Future climate	
Drought Characteristics	SPI	SRI	SPI	SRI
Number of drought events	6	4	7	6
Drought Intensity	-119	-116	-116	-108
Drought Frequency	0.4	0.41	0.38	0.36

5. Conclusions

This paper studied the meteorological and hydrological drought conditions of Dakbla river basin over the Central Highland, Vietnam based on the SPI and SRI indices, respectively. The SRI index was assessed by output of the semi-distributed SWAT model calibrated for the Dakbla river basin while the SPI index was calculated based on the rainfall data. The SPI has higher correlation with SRI when increasing the accumulation period. The 6-month and 12-month SPI/SRI were able to portray the historical drought as observed in local studies. An interesting finding was that the extreme drought events occurred after the strong El Nino about a year. SPI and SRI were also calculated for all sub-catchments based on the simulation outputs of SWAT model. The anomaly (climate change) between future and present day climate from the WRF simulations indicated significant increase in temperature and precipitation over the study region, thus it led to increase in future runoff over the Dakbla river basin. The future meteorological and hydrological drought was characterized by SPI and SRI indices which indicated an increase in future drought events but decrease in terms of intensity and frequency.

Given these results, analyzing the future drought conditions using the RCM results of downscaled future climates under different emission scenarios and pathways would be immensely helpful for adaptation and policy decisions and will be a continued exercise of this study.

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Multi-site evaluation of APEX for crop and grazing land in the Heartland region of the US

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Abstract

The Agricultural and Policy Environmental Extender (APEX) is capable of estimating edge-of-field water, nutrient, and sediment transport and is used to assess the environmental impacts of management practices. Current practice is to fully calibrate the model for each site simulation, which requires resources and data that are not always available. The objective of this study was to compare annual model performance for flow, sediment and phosphorus transport under two parameterization schemes: a best professional judgment (BPJ) parameterization based on readily available data and a fully calibrated parameterization based on site specific soil, weather, event flow and water quality data. The analysis was conducted using data from 19 sites at four different locations representing hydrologic conditions ranging from well to poorly drained soils and management systems covering row crop under different tillage systems and grazing systems. Regional model performance was based on the Nash Sutcliffe efficiency (NSE), the coefficient of determination (r^2) and the regression slope between simulated and measured annualized loads for all site years. Although the BPJ model performance for flow was acceptable (NSE = 0.4), calibration improved it (NSE = 0.8). Acceptable simulation of sediment and total phosphorus transport (NSE = 0.3 and 0.8, respectively) was obtained only after full calibration at each site. Given the unacceptable performance of the BPJ approach, we are now developing a regional APEX parameterization as an alternative approach to expand the utility of APEX to locations where data for full calibration are not available.

Keywords: APEX, calibration, edge-of-field, phosphorus index.

Introduction

In the US, excessive phosphorus (P) loss from agricultural fields continues to degrade fresh water quality. The US Department of Agriculture and the US Environmental Protection Agency implemented the P Index as a component of nutrient management planning on regulated animal feeding operations and for farms enrolled in voluntary Natural Resource Conservations Service (NRCS) cost-share programs in a coordinated effort to reduce edge-of-field P losses (USDA and USEPA, 1999; USEPA, 2003; USDA, 2011). The P index was initially developed in the mid 1990's to assess risk of P loss from agricultural land based on factors such as soil erosion potential, soil test P level, management of applied P and landscape position (Lemunyon and Gilbert, 1994). The USEPA and NRCS mandates led to most US states developing state-specific P indices (Sharpley et al., 2012).

There have been escalating concerns that current P indices have been ineffective at improving water quality. Osmond et al. (2006) demonstrated that indices from different states assigned different levels of risk to similar management scenarios in 12 southern states. Sharpley et al. (2012) highlighted the lack of rigorous testing of most P indices and emphasized the need for science-based assessment and improvement of existing P indices. Furthermore, the lack of sufficient water quality data to test P indices means computer models must be a core component of any strategy to assess and improve P indices (Sharpley et al., 2012; Bolster et al., 2012).

The Agricultural Policy and Environmental eXtender (APEX, Gassman et al., 2010) has successfully simulated edge-of-field runoff, sediment and P loss estimates over varying conditions, making it well suited to generating data needed for assessing P indices. To date, published studies using APEX have focused on evaluating model performance at locations after calibration with measured data from that location (e.g., Senaviratne et al., 2013). More extensive testing of P indices would be possible if the model can be correctly parameterized even for sites that have no measured data to calibrate and validate the model. The objectives of this paper were to develop a best professional judgment (BPJ) parameterization of APEX0806 for estimating edge-of-field runoff, sediment and P losses in the Heartland region of the United States (Iowa, Missouri, Kansas, and Nebraska) and assess the performance of this parameterization using monitoring data from multiple sites in this region.

Methods

Description of the study sites

Four locations were selected across the Heartland region based on the availability of site specific soil, management, weather, and edge-of-field runoff monitoring data. All locations were required to have several years of monitoring data aggregated on an event basis, including flow, sediment and total P transport. Since each location consisted of several drainage areas (or sites), often with contrasting management or land cover, these four locations represent three soil regions, three agricultural systems, two P application methods, and three P source scenarios.

The Knox County, Missouri location includes three adjacent fields (1.6 to 4.4 ha), all managed with a contour no-till corn-soybean rotation from 1991 to 2010. These fields are nearly flat at the top, fairly steep on small portions of the back slopes (5 – 9%) and flatten at the bottom (2-5% slope). All three included a grass waterway with a concrete approach structure and an H-flume installed at the outlet in 1991. Stage was recorded on a 15-min interval and converted to flow rate, and composite, flow proportioned water samples were collected for each event and analyzed for Total P (TP) and sediment. A weather station located less than 500 m from these three fields provided daily precipitation and temperatures. Crop yields were measured using a combine yield monitor. In 1997, 4.5-meter-wide grass filter strips were created on the contour, at 36-meter intervals, in one field and agro-forestry filter strips were created on the contour of a second field. The last field was kept as is as an un-treated control. Hydrology at this location is dominated by a claypan, found at depths ranging from 20 to 60 cm, which causes poor drainage and some subsurface lateral flow. Udawatta et al. (2002) described the location, sample collection and chemical analyses in details. Senaviratne et al. (2012) provided details on yield monitoring and analysis. Senaviratne et al. (2013, 2014) described the simulation of these three small watersheds with APEX.

The New Franklin, Missouri location includes two 0.8-ha grazed watersheds. Each watershed was 107-m long and 75-m wide with a 12% average slope. A 15-m grass buffer was installed at the bottom of one field by fencing cattle away from it, which reduced the grazed area from 8025 to 6420 m^2. In each watershed, 75% of the grazed area was divided into six equal size paddocks separated by an electric fence for rotational grazing. The top 25% of the grazed area was continually grazed. Three cattle weighing 450-590 kg were allowed to graze each paddock for 3.5 days every 21 days. Soils were Menfro silt loam. A weather station was located within 500 m from these two small watersheds. Each one was instrumented from 2000 to 2010 with a 2-foot H flume, an ISCO water sampler (Lincoln, NE, USA), and an ISCO bubbler flow measuring device to record water level, flow rate, sampling time and collect flow-proportioned composite water samples, later analyzed for sediment and TP. Further details can be obtained from Kumar et al. (2008) and Udawatta et al. (2011).

The Franklin County, Kansas location is a terraced field creating six drainage areas ranging from 0.4 ha to 1.5 ha with back slopes of 5-12% and channel slopes up to 0.7%. Profile sampling of soils at the location determined they were of the Summit soil series, with different phases of Summit based on the depth of the horizons. The study was initiated in 1998 to investigate the effect of tillage and fertilizer application method for a soybean grain sorghum rotation. Three replicated treatments were included: no-till deep band fertilizer application, no-till surface applied fertilizer, and chisel disk cultivation. Runoff was monitored from 2001- 2004 via a 90 degree v-notch weir at the downslope end of each drainage area, instrumented with ISCO 6700 samplers (ISCO, Lincoln, Nebraska) to measure flow and collect one composite flow-weighted water sample for each runoff event. Water samples were analyzed for TP and sediment. Daily precipitation was measured at the location during the crop growing season. Other weather variables were obtained from a nearby Ottawa, KS weather station. Zeimen et al. (2006) provided a description of these sites.

The Crawford County, Kansas location consists of ten 30m x 100m adjacent drainage areas with a slope of 0-1%. Each plot was separated on all sides by a soil berm to isolate the runoff and on the downslope end of the plot; the berms were v-angled toward a weir. Runoff from each plot was collected via a 90 degree v-notch weir instrumented with either a 6700 or 6712 model ISCO sampler to measure flow and collect water samples during a runoff producing rainfall event. From 2005 to 2008, five replicated treatments were investigated involving either no till or chisel disk tillage and a combination of commercial N and P fertilizer and/or turkey litter for a soybean-grain sorghum rotation. Water samples were analyzed for TP and sediment. Temperature and winter precipitation data from nearby Parsons weather station complement the on-site precipitation data collected during the growing season. The hydrology of this location is typical of a claypan soil, the Parsons Silt loam, with less than 30 cm of top soil overlying a Btg horizon. Root et al. (1973), Sweeney et al. (2012) and Zeimen et al. (2006) described the location and its soil characteristics.

Description of the Best Professional Judgment parameterization

Subarea delineation and characterization

The first step in an APEX model application is to delineate the drainage areas and define subareas. Each subarea is assumed to have homogeneous soil, slope and management properties. Each site was delineated as simply as possible while maintaining the spatial variability of soils and management features. As a result, the larger sites had distinct subareas for each soil type. Features such as filters, buffers, and grass waterways were represented as individual subareas in order to represent different land cover in these areas. In spite of their small total area, the New Franklin sites were simulated with 18 subareas in order to represent the different paddocks used for rotational grazing and the accurate routing of flow and sediment. For the Knox County watersheds, delineation was conducted using the ArcAPEX interface. For all others, delineation was done and entered manually by the modeler.

Soil and management parameterization

Availability of detailed management information was a selection requirement of the sites. Thus information on crop grown and details (e.g., dates, rates) on field operations such as tillage, fertilization, or harvest, were known for each site and manually entered following the required format of APEX0806 operation files. For the BPJ parameterization, SSURGO soils properties were used. Soil series were identified for each site and general soil information from the SSURGO database (Soil Survey Staff, 2014) for these soils was used. The P sorption coefficient (PSP) was set to 0.5, the default value appropriate for non-calcareous soils without weathering information.

Control and model parameters

Control parameters define the type of output desired, and equations used for specific processes when several are available. Model parameters include S-curve parameters, process threshold values, and equation coefficients. Control and model parameters were set in large part similar to what has been used for the modeling efforts of the CEAP cropland study (Wang et al., 2011). Departures from this parameterization are shown in the appendix: table A1 for the control parameters, table A2 for S-curve parameters, and table A3 for model global parameters.

Full calibration methodology

Part of the difference between the BPJ and calibrated APEX runs are the collection of site-specific soils data. Most watershed scale modeling is done with national or regional soils data. In the US, the SSURGO soils data contain soil map units and provide general horizon data at the scale of about 1:24000 (ranging from 1:12000 to 1:24000). This provides detail down to about 2 to 5 hectares in area. Furthermore, there are many inclusions, complexes, and variations in soils that are not fully described at the scale used for mapping. Because of these reasons, soils in a small area (1/2 to 2 ha) could differ substantially from the general soil map units described by the SSURGO database.

The differences between the SSURGO data and the actual soils in runoff studies used for this experiment impacted soil data that are sensitive inputs to the APEX model, such as available water, hydraulic conductivity, bulk density, and others. Measurement of these soil inputs (particularly available water, hydraulic conductivity, and bulk density) is very difficult, time consuming, and expensive. For some locations, some of these measurements were available (e.g., Knox County). When these were not available, we developed the following process to use site-specific soils data in combination with data from the NRCS Soil Characterization Database to produce a site-specific soils dataset.

The general concept is to collect enough information from the soils on the sites to match data from an official soil in the NRCS National Cooperative Soil Survey (NCSS) characterization database (National Cooperative Soil Survey, 2014) to the soil horizons identified on the site. The minimum data needed are the soil series located on site, and the depth, soil texture, and organic matter content of each soil horizon for a minimum of three soil samples down to 1.5 m for each soil series and each landscape position. Depths to soil horizons were measured and a soil sample from each horizon, later analyzed for total C and soil texture. Soil horizon depths from these cores were used to match them with those from a soil pedon in the NCSS characterization database and obtain bulk density, water content at wilting point and field capacity, and particle size content. Those were in turn used to estimate saturated hydraulic conductivity with the Rosetta model and complete the soil dataset.

For nutrient characteristics, two single composite samples were collected from each soil type in each are that was simulated as a distinct unit in APEX, one from 0 -5 cm, and one from 5-15 cm. These samples were composite of between 15 to 30 cores from each experimental unit. Composite samples were analyzed for total C, total N (TN), total P (TP), pH, anion exchange extractable P, Mehlich 3, and Bray 1. Parameterization was then based on the partition of TN into 2% NO3-N and 98% Organic N (Pennsylvania State University, 2003). In addition, labile P is generally assumed to be half of Mehlich-3 P. Organic P was estimated from TN using an equation developed by Jones et al. (1984). The P sorption coefficient was estimated from clay, carbon, and labile P content using the equation proposed by Vadas & White (2010).

Sensitivity analysis and manual calibration

For each site, sensitivity analysis and manual calibration were conducted to identify and adjust sensitive parameters. Control parameters, which control the equations used to simulate specific processes, and global parameters, which include equation coefficients and threshold values, were considered for adjustment. No soil, management, or subarea specific parameter was considered as those were determined as carefully as possible.

Rainfall/runoff data were first processed to aggregate subdaily and daily runoff values to event values, and rainfall that contributed to these events. For these edge-of-field sites, there was usually no base flow and events were defined by a day without any runoff between them. Rainfall and runoff data were further reviewed to exclude events that were not correctly represented by the data including instances of runoff greater than rainfall or runoff that was significantly lower or higher than expected given other data from that location. Model performance was assessed first by how well it simulated crop yields, then how well it simulated runoff, sediment losses, and TP losses on an event basis using percent bias (PBIAS), coefficient of determination (r^2), and Nash-Sutcliffe efficiencies (NSE), which are described in Moriasi et al. (2007). If the monitoring period was long enough, the data set was split into a calibration and validation data sets. When the monitoring period was not very long, the model was calibrated using one treatment replicate and validated using the other ones. This process led to the identification of process equations and options that gave the best results at each site, and the identification and calibration of the most sensitive global parameters.

Automatic calibration

Once manual calibration was obtained, automatic calibration was conducted using the APEX-PAROPT program (Senaviratne et al., 2014), which uses a step-wise multi-objective, multi-variable optimization algorithm. At that point, control parameters were considered fixed and only global parameters were considered (table A3). In this preliminary analysis, no threshold value for the performance indicators was imposed, other than trying to get the best possible results.

Regional analysis

While it would be ideal to have tools that can give us accurate feed-back on agricultural management and document water quality benefits from agricultural practices on an event basis and without large calibration efforts, the purpose here is to obtain models that can give annual estimates of flow, sediment and TP losses on an annual basis across the different systems that exist in the Heartland region. The regional performance evaluation focused on annualized losses, which represent the annual summation of measured flow volumes, sediment loads, and TP losses during the monitored events at each monitoring site. This does not represent an annual load as monitoring devices were always out of service during freezing weather and malfunctions always cause some events to be missed during the growing season. Annualized loads represent an expression of our results for the purpose of model performance assessment at an annual time step.

Annualized flow, sediment and TP were calculated from monitoring data and model results for each monitoring station, resulting in 97 site years of data. All annualized values across all the monitoring stations of the four locations were then considered together for evaluation of APEX predictions across multiple sites and management. Comparison of measured and simulated data for the BJP and the fully calibrated parameter sets was based on r^2, NSE, and the regression slope.

Results and discussion

Tables 1, 2, and 3 show overall characteristics of the three performance indicators used to evaluate the BPJ and fully calibrated parameterizations of APEX at each of the 19 sites for runoff, sediment, and TP, respectively. Careful data examination was critical in all cases to eliminate events where equipment malfunction was suspected. In spite of this analysis, good model performance was difficult to obtain when sediment loads were very small, or when filter strips were involved. However, all indicators showed improvement in model performance measures from the BPJ to the fully calibrated parameterization. Interestingly, calibration reduced the range of values of each indicator, as indicated by the standard deviation.

Table 1. Overall characteristics of performance indicators for event runoff simulation at the 19 sites.

	PBIAS (%)		**r^2**		**NSE**	
	BPJ†	Calibrated	BPJ	Calibrated	BPJ	Calibrated
Average	21	11	0.56	0.76	-0.06	0.53
median	27	17	0.68	0.82	-0.03	0.70
Min	-88	-33	0.13	0.43	-3.52	-1.36
Max	80	38	0.82	0.94	0.76	0.87
Standard deviation	44	19	0.24	0.15	0.98	0.53

† Best Professional Judgment parameterization

Table 2. Overall characteristics of performance indicators for event sediment loss simulation at the 19 sites.

	PBIAS (%)		**r^2**		**NSE**	
	BPJ†	Calibrated	BPJ	Calibrated	BPJ	Calibrated
Average	-1473	39	0.16	0.33	-2088	0.04
median	-329	36	0.13	0.35	-54	0.12
Min	-6809	-50	0.00	0.00	-13452	-0.68
Max	38	99	0.57	0.68	0	0.53
Standard deviation	2194	40	0.17	0.21	4151	0.37

† Best Professional Judgment parameterization

Table 3. Overall characteristics of performance indicators for event total phosphorus loss simulation at the 19 sites.

	PBIAS (%)		**r^2**		**NSE**	
	BPJ†	Calibrated	BPJ	Calibrated	BPJ	Calibrated
Average	-57	26	0.42	0.54	-10.9	0.21
median	-16	19	0.45	0.61	-1.4	0.39
Min	-402	-45	0.00	0.00	-142.5	-0.96
Max	87	89	0.79	0.73	0.60	0.64
Standard deviation	124	37	0.23	0.18	32.30	0.45

† Best Professional Judgment parameterization

Figures 1, 2, and 3 show the measured versus simulated annualized values of runoff, sediment, and TP, respectively, when all the site-years are analyzed together for the regional analysis. These figures show that, once calibrated, APEX gives acceptable estimates of annualized runoff, sediment, and TP, as shown by the r^2 and NSE values. The regression slope is very good for runoff (0.92), somewhat low for sediment (0.32), and good (0.84) for TP. These figures also show that without calibration, performance at the annual time step across the 19 sites may be acceptable for runoff (r^2 = 0.6, NSE = 0.4), but is not acceptable for sediment or for TP.

Figure 1. Simulated versus measured annualized runoff for 97 site-years in the Heartland region

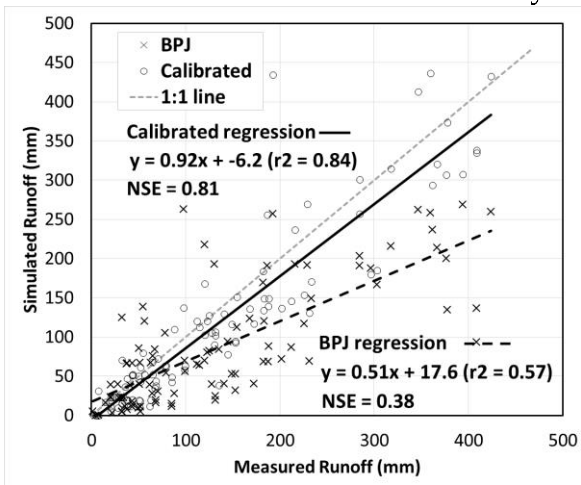


Figure 2. Simulated versus measured annualized sediment loss for 97 site-years in the Heartland region

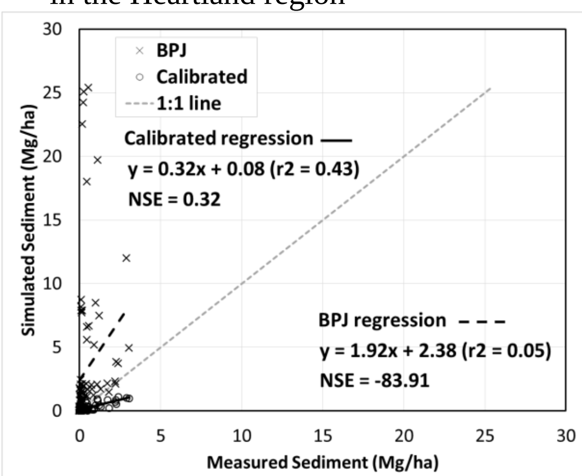
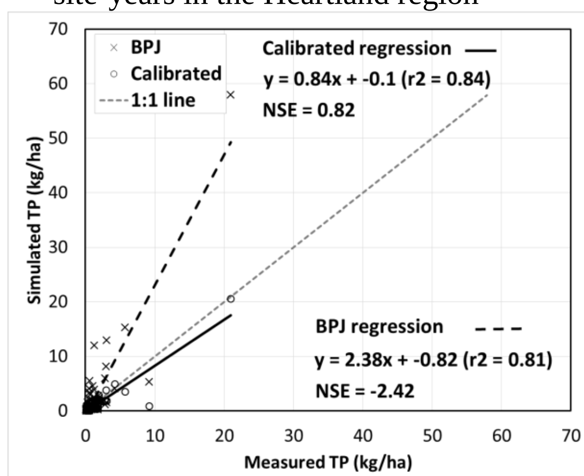


Figure 3. Simulated versus measured annualized total phosphorus loss for 97 site-years in the Heartland region



Conclusion

The performance of the APEX model was assessed for 19 sites in Missouri and Kansas using two parameterization strategies: a best professional judgment parameterization common to all sites and a site specific parameterization derived through systematic calibration and validation of the model. Each parameterization was assessed for model performance using runoff, sediment and P loss monitoring data at each site. The BPJ parameterization resulted in a large range of performance indicators values, some of which indicating acceptable performance but many showing unacceptable performance. The model performance was greatly improved through calibration and the range of indicator values was reduced.

Model performance was also assessed at the annual time step across the 19 sites. Results showed that while BPJ performance for runoff simulation was acceptable, performance for sediment or TP was not. Thus without site specific calibration, APEX could not be used as the basis for sediment or P loss evaluation or for the evaluation of management practices effectiveness to reduce these contaminants. Future efforts will include analysis of the calibrated parameterization and development of a regional parameterization that would provide acceptable performance for most of the sites.

Acknowledgements

The authors are grateful for partial funding for this project through a USDA Conservation Innovation Grant (Agreement Number 69-3A75-12-193).

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Appendix

This appendix lists the control, S-curve and global parameters that were set differently from the CEAP parameterization detailed in Wang et al. (2011).

Table A1. Best judgment parameterization control parameters that are different from the CEAP parameterization

Parameter	Line and variable #	Definition	Value	Comment
IPD	1, 5	print code for output	8	Obtain daily output that can be compared to measured data on a daily or event basis.
ISCN	1, 11	the stochastic CN estimator code variable	0	Use a deterministic method of estimating CN.
NVCN	1, 15	controls how CN is adjusted with soil moisture	0	CEAP parameterization recommended a value of 4 (variable daily CN soil moisture index). Subsequent changes in APEX led to the recommendation of using 0 (variable daily CN as a function of soil water weighted by depth).
NUPC	1, 20	N and P plant uptake concentration code	0	The CEAP parameterization included a value of 0 for cropland and 1 for land enrolled in the Conservation Reserve Program (CRP).
ICO2	2, 7	Constant or dynamic atmospheric CO2 concentration.	0	This parameter was set to a constant concentration given the short simulation periods used.
IGMX	2, 9	number of times the random generator seed is initialized	1	
IDIR	2, 10	data directory	0	data are read from the working directory.
IMW	2, 11	minimum interval between auto mow	1	1 day
IOX	2, 12	oxygen – depth function	0	original O2/depth function
IHRD	2, 17	grazing mode	0	Grazing schedule manually entered
IWTB	2, 18	duration of antecedent period for rainfall and PET accumulation to drive water table	15	
NSTP	2, 19	real time day of the year	0	
ISAP	2, 20	used to print monthly	0	option was not used

		output for 1 subarea.		
RFN0	3,1	Average concentration of nitrogen in rainfall	0.8	Specific deposition numbers can be found on the National Atmospheric Deposition web site: http://nadp.sws.uiuc.edu/NTN/ntnData.aspx
CO2	3,2	CO2 concentration in atmosphere	380	This corresponds to the 2000-2010 average.
QG	3,8	2 year frequency 24-h rainfall intensity.	>0	The 2-yr 24-hr rainfall can be found in the technical paper No 40 (USDC, 1961) at: http://www.nws.noaa.gov/oh/hdsc/PF_documents/TechnicalPaper_No40.pdf
BWD	4,1	Channel bottom width/depth in m/m	0	Not needed since QG > 0.
FCW	4, 2	Floodplain width / channel width	>0	For plots, set so that the floodplain covers the whole plot. For fields, set to 30.
FPSC	4, 3	Floodplain hydraulic conductivity	>0	Use effective Ksat for soil
RFP0	4,6	ratio of return flow relative to (return flow + deep percolation).	0.00 or 0.05	For a small watershed, the size of a field or a plot, most water, if not all, that percolates past the soil profile will be lost from the system because return flow occurs downstream of the field outlet. Return flow is non-existent in a plot and quasi non-existent in a field. Use RFP0 = 0.0 for a plot and 0.05 for a field (several acres).
FL	4,8	Field length (for wind erosion)	0.4	Wind erosion not simulated in this project.
FW	4, 9	Field width (for wind erosion)	0.4	Wind erosion not simulated
ANG0	4, 10	Clockwise angle of field length from north (for wind erosion)	0	Wind erosion not simulated
ACW	5, 3	Wind erosion adjustment factor	0	This insures that wind erosion is shut off.
GZL0	5, 4	Grazing limit for each herd	0	This insures that grazing takes place when specified in management file even if biomass is not present.
DRV	6, 1	Wind erosion equation	4	MUSLE
RCC0	6, 3	USLE_C for channels	0.35	Overridden in subarea file.

Table A2. Best judgment parameterization S-curve parameters different from the CEAP parameterization.

Parameter	Line #	Definition	Value	Comment
SCRP(5)	5	Soil Cover Factor	1.2, 6.95	New parameter in APEX0806. Comparing the S-curve with data from KSU extension publications on residue cover, values of 1.2 and 6.95 gave reasonable estimates given the variability of different crops and field conditions

SCRP(25)	25	Controls soil O2 as a function of the carbon to clay ratio	10.1, 55.9	Williams (October 2012, personal communication, APEX developer, Temple Texas). Only used if IOX > 1.
SCRP(26)	26	Used to generate rainfall distribution at DTHY time intervals.	10.1, 75.95	Williams (October 2012, personal communication, APEX developer, Temple Texas). Only used if flood routing is selected.
SCRP(27)	27	Regulates denitrification as a function of soil water content.	5.01, 50.99	Williams (October 2012, personal communication, APEX developer, Temple Texas). Only used if original (EPIC) denitrification function is selected.

Table A3. Best judgment parameterization model parameters different from the CEAP parameterization.

Parameter	Definition	Value	Comment
2	Root growth-soil strength	1.5	
7	N fixation	0	At 0, fixation meets N demand from legumes.
15	Runoff CN Residue Adjustment Parameter	0	No adjustment on CN as a function of crop residues (New parameter in APEX0806)
28	Upper nitrogen fixation limit by legumes	5	Not used in CEAP parameterization
34	Hargreaves PET exponent	0.6	CEAP value was 0.5. Modified to 0.6 to increase PET.
36	Upper Limit of Daily Denitrification rate	0.05	This parameter will not influence our model because of the denitrification option selected.
40	Fraction of groundwater storage that initiates return flow	0.5	This parameter should not be very sensitive because we already selected to have only 5% of groundwater potentially returning to the channel. The other 95% percolate deeper. Equivalent of GWQMIN in SWAT.
42	SCS curve number index coefficient	1.0	Regulates the effect of PET in driving the SCS curve number retention parameter. A value of 1.0 produces no change in CN.
56	Fraction destroyed by burn operation	0.9	
61	Soil water upward flow limit	0.2	
65	RUSLE2 transport capacity parameter.	0.001	New parameter in APEX0806. Regulates deposition as a function of particle size and flow rate. Range is from 0.001 - 0.1.
66	RUSLE2 threshold transport capacity coefficient	3	New parameter in APEX0806. Range is from 1.0-10.0.
68	Manure erosion exponent	0.5	
69	Coefficient adjusts microbial activity in the top soil layer	1.0	
79	Auto mow lower limit	1.0	New in APEX0806. Not used in these model applications
80	Upper Limit of Nitrification-Volatilization	0.5	New in APEX0806. Maximum fraction of ammonium that can be lost to the combined

			processes of volatilization and nitrification in any given day.
83	Ratio of lateral to vertical saturated hydraulic conductivity	0.51	CEAP parameterization value was 4.
86	N Upward movement by evaporation coefficient	1	New in APEX0806. This coefficient adjusts the amount of nitrate that moves up with water evaporation. If set to 1.0, the concentration of N in water moving up is equal to the concentration of N in the soil layer. Setting the value to 1 is identical to APEX 0604, according to the theoretical documentation.
87	Water table recession coefficient	0.001	New in APEX0806. This value is similar to calibrated values from Williams et al. (2013).
88	Limits daily water table movement	0.001	New in APEX0806. This value is similar to calibrated values from Williams et al. (2013).
89	Water table recession exponent	0.1	New in APEX0806. This value is similar to calibrated values from Williams et al. (2013).
90	Subsurface flow factor	10	New in APEX0806. Range is from 1.0 – 100.0. Traditional value is 2.0. Larger numbers allocate more flow to subsurface and quick return flow.
91	Flood evaporation limit	0.01	New in APEX0806. Range is from 0.001 – 1. Regulates evaporation from channel and floodplain. Small values reduce channel and floodplain evaporation. Set to 0.01 because evaporation from channel and flood plain in these very small watersheds should be minimal.
92	Runoff volume adjustment for NVCN = 0. Similar to parm42 for NVCN = 4	1	New in APEX0806. Range is from 0.1 – 2.0. Williams (October 2014, personal communication, APEX developer, Temple Texas)
93	Sediment yield threshold	1	New in APEX0806. Range is from 0 – 10. Used to count large sediment yield events. Does not affect simulation results. Williams (October 2012, personal communication, APEX developer, Temple Texas)
94	Wind erosion threshold	1	New in APEX0806. Range is from 0 – 50. Used to count large wind erosion events. Williams (October 2012, personal communication, APEX developer, Temple Texas)
95		1	Not used
96	Soluble P leaching KD value	10	New in APEX0806. Range is from 1.0 – 15.0. Williams (October 2012, personal communication, APEX developer, Temple Texas)

Benchmarking algorithms for estimating plant available water for general crop simulations in ALMANAC, APEX, EPIC and SWAT

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Abstract: ALMANAC, APEX, EPIC and SWAT contain generalized plant growth subroutines to predict biomass and crop yield. Environmental constraints typically restrict plant growth and yield. Water stress is often an important limiting factor; it is calculated as the sum of water use from each soil layer divided by the potential plant evapotranspiration. The plant available water in each soil layer is estimated from the difference between water volume at field capacity and wilting point. Reliable estimates of the plant available water are essential for accurate estimates of plant growth and water use. Several pedotransfer methods have been developed to estimate field capacity and wilting point. We tested the ability of Rawls et al.'s (1991) pedotranfer method and two non parametric methods (*k*-nearest neighbor (Nemes et al. (2006a) and K-D tree (Friedman et al. 1977) to estimate field capacity and wilting point based on commonly measured soil properties (% sand, %silt, %clay, % organic carbon, and bulk density). Rawls' model computes field capacity and wilting point directly from measured properties of the selected soil, whereas the nearest neighbor and K-D tree methods lookup these values from a database using soils with similar % sand, %silt, and % organic carbon. Each method was tested for 1050 cropland soil pedons from the NRCS National Soil Characterization Database. All three methods are better at estimating the wilting point than the field capacity. Estimates using Rawls' model fit to pedon data with root-mean-square error (RMSE) of 0.049 and 0.033, for field capacity and wilting point, respectively. The k-NN and K-D tree methods fit slightly better with RMSEs of 0.040 and 0.041 for field capacity, respectively and 0.028 and 0.029 for wilting point. The k-NN method is slowest, taking about 10 times as long to compute as the K-D tree method. Rawls' model was slightly faster than K-D tree method. The non-parametric K-D tree method is therefore a suitable alternative to Rawls regression method and may be more flexible than classic parametric methods.

Keywords: field capacity, K-D tree, nearest neighbor, NRCS National Soil Characterization Database, pedotransfer functions, plant available water, wilting point

Introduction

Plant available water is an important variable in models such as ALMANAC (Kiniry et al. 1992), EPIC (Williams et al. 1984), APEX (Williams et al. 1995), and SWAT (Arnold et al. 1998) that simulate agricultural productivity and environmental quality. Plant available water is estimated from the difference between water volume at field capacity and wilting point. These later variables are often lacking in soil databases, making pedotransfer functions based on other readily-available data a convenient alternative to field measurements. A widely-used PTF for estimating soil moisture is due to Rawls et al. (1991). Briefly, these methods relate water volume at field capacity and wilting point to a number of variables including the proportions of sand, silt, clay, and organic matter content, and bulk density.

Recently, the non-parametric k-nearest neighbor (*k-NN*) learning algorithm has been proposed as an alternative to regression-based pedotransfer functions for estimating field capacity and wilting point in models of water and solute transport (Nemes et al. 2006a,b). The justification for using a non-parametric algorithm in place of a regression-based method is that identifying the right equation, and ensuring that the associated probability distributions of errors will be similar across the data space is rarely easy and may not be possible; parameter estimates can be heavily biased when the sample size is small; and inclusion of additional data, either global or site-specific, will entail redeveloping the equations. Most importantly, non-parametric methods have the advantage that they do not rely on the central limit theorem for applicability and thus are more widely applicable when data are poorly conditioned.

Nemes et al. (2006a) tested a k-NN against estimations made by a neural network (NNet) model, developed using the same data and input soil attributes. They went on to examine the sensitivity of the method to a range of data conditions (Nemes et al. 2006b) and found that the k-NN technique showed little sensitivity to the choice of sample weighting methods; to suboptimal weighting of input attributes; or to differences in data density in parts of the reference data set. However the optimal settings were slightly dependent on the size of the reference data set. The *k-NN* technique and NNet models performed equally well when compared statistically. As a result Nemes et al (2006b) concluded that the k-NN technique "is an effective alternative to other techniques to estimate soil water retention."

However, in neither paper did Nemes et al. (2006a,b) examine the computational efficiency of their proposed method in a processed based agricultural or environmental model. In this paper we compare the k-NN method to the parametric method of Rawls et al. (1991) in EPIC, and benchmarked all both methods with simulations over 40 years. Finding that k-NN is computationally very intensive, making large runs of EPIC/APEX impractical, we investigated the utility of a related non-parametric method, the K-D-tree.

Methods

EPIC

Environmental Policy Integrated Climate (EPIC) is a process simulation model developed to assess the effect of erosion on productivity (Williams et al. 1984). It is a subset of the small watershed model Agricultural Policy/Environmental eXtender (APEX; Williams et al. 1995, 2000; Gassman et al. 2010) which was developed for use in whole farm/small watershed management. EPIC's plant growth and development module is similar to ALMANAC's (Kiniry et al. 1992). The Soil and Water Assessment Tool's (SWAT; REFS) soil and water components are derived from EPIC. Unlike EPIC, APEX and SWAT have components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. APEX and SWAT watersheds can be subdivided as much as necessary to assure that each subarea is relatively homogeneous in terms of soil, land use, management, and weather. They also have groundwater and reservoir components. The use to which land is put, the vegetation growing, and the management of the land all have profound effects upon the flow of water and nutrients through the landscape.

Methods

Regression Pedotransfer Function

Organic matter, density, gravels, salinity, and especially textures all effect soil water characteristics at low pressure. Soil density strongly affects saturation and hydraulic conductivity, and is in turn conditional on soils structure and large pore distribution. Soils with large particles lose water holding and conductance capacity, and salinity can restrict plant water uptake by imposing additional osmotic pressure. High organic matter generally increases water holding capacity and conductivity. As water content at high pressure is determined largely by texture, the influence of aggregation and organic matter may be reduced. These generalizations may be encapsulated in one or more regression equations to predict pant available water. One of the simplest regression-based pedotransfer functions for use in simulation models is Rawls' method (Rawls et al. 1991) which uses % clay (CL), % sand (SN), % organic carbon (OC), and bulk density (BD) to compute field capacity (FC) and wilting point (WP):

$$FC = 0.2576-0.002*SN+0.0036*CL+0.0299*OC/BD \quad (1a)$$

$$WP = 0.026+0.005*CL+0.0158*OC/BD \quad (1b)$$

from which plant available water (PAW) is computed by difference:

$$PAW = FC-WP. \quad (2)$$

Another commonly used regression estimate for soil moisture is Baumer's method (Baumer et al. 1994) which is a more complex equation that also uses cation exchange capacity. Both methods are available in all four models and are user-selectable. Users can select dynamic (annual) or static (once at the beginning of the simulation) computing of the field capacity and wilting point to estimate plant available water.

Nearest neighbor

The k-NN technique uses a 'reference' data set which is searched for soils that are most similar to the target soil, based on the selected input attributes. Nemes et al.'s (2006a) method searches on the same variables used by Rawls' method, %clay, %sand, and %organic carbon divided by dry weight.

In most k-NN studies, the Euclidean distance between the target and the known instances is used as to select the closest match between the target and the reference record. As this can be heavily biased by a referent with large range, it is customary to standardize the reference database and compare standardized target to the database. An alternative is to weight the differences between target and reference elements according to a policy that allows for the different numeric ranges of the referents. Nemes et al. (2006a,b) chose the former approach and first transformed all attributes in the reference data set to standard normal deviates (zero mean and unit variance) using the range, an approach that can be sensitive to the presence of outliers. A further refinement is to decide whether to select the record with the smallest Euclidian distance to the target or average an ensemble of the *k* closest records. If the latter, the number of neighbors to use must be selected. Nemes et al. (2005a,b) determined that the minimum residual was obtained at about

$$k = 0.62\sqrt{N}\ . \qquad 3$$

where *N* is the number of records in the reference database The simple average of the *k* output attributes may be used or a weighted average. As the distribution of Euclidean distances is unknown a sound policy is to give the soil record closest to the target more weight than those further away. Nemes et al. (2006a,b) used weights (W_i) calculated from

$$W_i = \frac{D_i}{\sum_{i=1}^{k} D_i}, \quad \text{where } D_i = \left[\frac{d_i}{\sum_{i=1}^{k} d_i}\right]^p \qquad 4$$

and *k* is the number of neighbors considered, D_i is the relative distance of the *i*th selected neighbor, calculated from d_i the Euclidean distance of the *i*th selected soil neighbor from the target soil. The exponent *p* corresponds to a simple inverse relationship when $p = 1$ and an inverse squared relationship when $p = 2$. Nemes et al. (2006a,b) found the simple inverse relationship had minimum residual sums of squares.

The *k-NN* algorithm requires the Euclidean distance to be calculated from all *N* records in the reference database, which must then be sorted and the *k* closest neighbors found by a binary search. While there are sort algorithms, such as quick sort and heap sort, that sort in *N* log *N* time, this is the shortest expected time the k-NN algorithm can find a set of *k* matches. With very large reference databases (and the larger the database the better the expected outcome), and many iterations of an agricultural or environmental simulation model the k-NN method quickly slows execution and turnaround of simulation problems.

K-D Tree

Unlike the k-NN method in which selection of one or more reference records is conducted on the sorted Euclidean distances between the target and database records, in a K-D tree the Euclidean distance is computed *after* the reference record(s) have been selected. This is made possible by building a search tree in *K*-dimensions. (Note that *K* is the number of dimensions or coordinates for the search in a K-D tree and *k* is the number of reference values to be found in a k-NN search.) A data structure is created to store the *K*-dimensional coordinates of choice points, the nodes where the tree's branches divide. Once the tree is built searches are conducted via the tree.

The K-D tree is a generalization of a binary search but with an important difference: the reference values are stored at the end of the search tree (in computer science jargon, "in the leaves of the tree"). Where binary searches use only the memory required to hold the database, the *K*-dimensional tree must also be kept in memory. This can substantially increase the memory requirement if *K* is large. In theory, a K-D tree can be used with coordinates in any dimensional space, but in practice it is only useful up to about 20 dimensions.

The algorithm for constructing a K-D tree is most easily explained in two dimensions which is similar to the algorithm for building a binary-search tree such as that used in the k-NN algorithm. If we represent a record in the database as a point in Cartesian space, i.e. at (*x,y*) the K-D tree algorithm differs from the algorithm to build a binary-search tree because either the *x*-value or the *y*-value is used to split the set of points in two, depending on the current depth in the tree. The following example will illustrate how a K-D tree can be built using the points [(1, 8), (2, 6) , (4, 0) , (4, 9) , (5, 5), (6, 1), (8, 9) , (10, 6)]. This example will create a balanced tree with all the leaves at the same level. In most instances, a K-D tree is not balanced, with routes from the stem to the leaves of different lengths. The algorithm begins by sorting the list by the *x*-values. The list is then split in two based on the median *x*-value which is 5, resulting in two lists: [(1, 8), (2, 6), (4, 9), (4, 0)] and [(5, 5), (6, 1), (8, 9), (10, 6)]. The root node of the tree has value 5, and coordinates that have an $x < 5$ are in one subtree and coordinates with $x \geq 5$ are in the other subtree. This is equivalent to drawing an ordinate at $x = 5$ such that coordinates to the left of the line goes into the left-hand subtree, and everything else goes into the right-hand subtree. Next we sort both the right- and left-hand sublists, but this time by the coordinates' *y*-values, and split again by their medians. This results in the left-hand sublist with median = 8 being split into [(4, 0), (2, 6)] and [(1, 8), (4, 9)]. This is equivalent to drawing an abscissa at $y = 8$ up to the ordinate $x = 5$. Everything below the line goes into the left-hand subtree, while all other points go into the right-hand subtree. The sublist containing $x \geq 5$ is treated similarly with the median *y*-value of 6 resulting in two sublists of [(6, 1), (5, 5)] and [(10, 6), (8, 9)]. Finally the four sublists are sorted and split on their *x*-values, resulting in eight leaf-nodes. The resulting K-D tree has three levels. The first divides the coordinates by the x-values, the second by the y-values, and the third by the x-values again. This example of 8 coordinates was split three times; a list of 16 coordinates would be split four times. The procedure is repeated recursively until all records have been assigned to a leaf. For databases with *K* dimensions, procedure is the same but with the coordinates taken in turn (… *w, x, y, z*) recursively until all records have been processed. In general, construction of a K-D tree executes in time proportional to $N \log N$ which is comparable to the time for a single k-NN search.

A nearest-neighbor search for a two-dimensional K-D tree is quite similar to a search of a binary-search tree. The main difference is that we have to keep track of the depth in the tree, otherwise we will not know if we should compare the *x*-value of the point or the *y*-value of the point. The expected time to find a reference value that matches a target is proportional to $\log N$. Having found the leaf closest to the target value, it is a simple matter to locate the *k* closest leaves and compute their Euclidean distances from the target, if they are needed as weights to compute a weighted mean.

Soils

The database used to benchmark the pedotransfer functions is the National Soil Characterization Database. The database contains pedon data from analyses for soil characterization and research within the National Cooperative Soil Survey. Included are pedons "representing the central concept of a soil series, pedons that represent the central concept of a map unit but not of a series, and pedons sampled to bracket a range of properties within a series or landscape. Many pedons have incomplete characterizations because only selected measurements were planned" (NRCS 2014). The database was filtered for those records containing % clay, % sand, % organic carbon, soil dry weight, field capacity, and wilting point; 34,873 records were extracted. While the majority of records are of agricultural land, they also include wetland, loess, and volcanic soils.

Comparison

The field-scale agricultural simulation model EPIC was used to benchmark Rawls' method and the nearest neighbor (k-NN and K-D tree) methods to estimate field capacity and wilting point. Continuous corn was simulated in EPIC for 40 years in a field in Bell County, Texas (31.1°N, 97.5°W, 200m elevation) according to the normal practices for the area. Each PTF method was run with 1050 target soils selected at random from the database. That left 33,823 records in the reference set for comparison using k-NN and K-D tree methods. The nearest neighbor (k-NN and K-D tree) methods were used to compute average field capacity and wilting point from $0.62*\sqrt{33823} = 114$ nearest neighbors while Rawls' method was calculated from equation 1. Plant available water was computed from equation 2 and was used by EPIC to compute water stress during the growing season. The model was run using each of the 1050 target soils in turn and the total elapsed time recorded for Rawls' parametric method and for the two non-parametric methods. All three methods were computed annually. The K-D tree was built once at the beginning of each simulation and the 3-dimensional search conducted each day; the k-NN method required a new sort and binary search each year.

Results

The goodness of fit of field capacity and wilting point estimates was tested for the 1050 target soils against their measured values by root mean squared error (RMSE) for both horizons and pedon. In every case the non-parametric methods fit better than Rawls' method, although the differences are small (Table 1). Not surprisingly the fits by pedon were better than fits by horizon because some horizon variation averaged out. Wilting point fit consistently better than field capacity by quite a large margin. Figs 1 and 2 show the plots of observed and estimated field capacity and wilting point, respectively, by Rawls' method and the two non-parametric methods. The small differences between methods are evident in the plots, as are the larger differences between field capacity and wiling point estimates.

The benchmarking (Table 2) clearly show the large overhead imposed by the brute force k-NN search. The overhead imposed by the K-D tree algorithm is smaller and in view of the slightly better fit than Rawls' regression method may be acceptable. The time to construct the K-D tree was 0.156 sec making the computational time for the K-D tree only 0.438 sec/run compared to 0.425 sec for Rawls' method.

Conclusion

Nemes et al.'s (2006a,b) point about the potential problems with parametric estimates of soil water content is, well founded. However, we found that their proposed method is too computationally intensive for a large number of simulations being more than an order of magnitude slower than Rawls' parametric approach, and exactly an order of magnitude slower than an alternative non-parametric method. Interestingly, although the non-parametric methods obtained better fits than the parametric method, the differences were small, averaging less than 15%.

When the time taken to create a K-D tree is taken into account, the small increase in time to estimate soil water using K-D tree seems to be a small cost balanced by the slightly better fit obtained relative to the regression method. Furthermore, as Nemes et al. (2006a,b) points out adding to the reference database does not require recalibration of the regression approach which will facilitate use of all four models by users who may not be in a position to do the necessary analysis.

We used Nemes' procedure for averaging the *k* nearest neighbors in both k-NN and K-D tree algorithms; the 114 nearest neighbors were averaged using inverse distance weighting. We have not investigated whether this is a sound policy for K-D tree, an area for further research. Also, we took a brute force approach to selecting a random test dataset of 1,050 pedons. A better approach would be a jack-knife method in which 1050 pedons are selected at random, one at a time, instead of ensemble.

Although we found that Nemes et al.'s (1991a,b) is computationally intensive for larger simulation projects, their point that non-parametric methods may be better than parametric methods in estimating plant available water seems to hold up. Our proposed K-D tree algorithm avoids the extremely large overhead associated with the k-NN algorithm and would seem to be a suitable alternative to regression-based methods in estimating plant available water.

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Table 1: Goodness of fit as measured by root mean square error for three methods for estimating field capacity and wilting point, computed by horizon and by pedon.

	N	Rawls' model	k-NN	K-D tree
		Field capacity		
Horizons	5263	0.056	0.046	0.048
Pedons	1050	0.049	0.040	0.041
		Wilting point		
Horizons	5263	0.037	0.032	0.033
Pedons	1050	0.033	0.028	0.029

Table 2: Benchmark times for running 1050 EPIC simulations of continuous corn for 40 years using Rawls' parametric model and k-NN and K-D tree non-parametric algorithms for estimating field capacity and wilting point.,

	Benchmark Time				
Estimation method	Hours	Minutes	Seconds	Secs/Run	Runs/Min
Rawls et al. (1991)	0	15	9.14	0.425	141.1
k-NN (Nemes et al. 2006a,b)	3	22	31.27	5.683	10.6
K-D tree (Friedman et al. 1977)*	0	21	10.29	0.594	101.0

*Time to build K-D tree: 0.156 sec

Fig. 1: Comparison of estimated field capacity with NCSS database values by horizon (upper row) and by pedon (lower row) using Rawls method (left column), k-NN algorithm (middle column) and K-D tree algorithm (right column) show that the non-parametric methods fit slightly better than Rawls' parametric method as measured by residual mean squared error (RMSE).

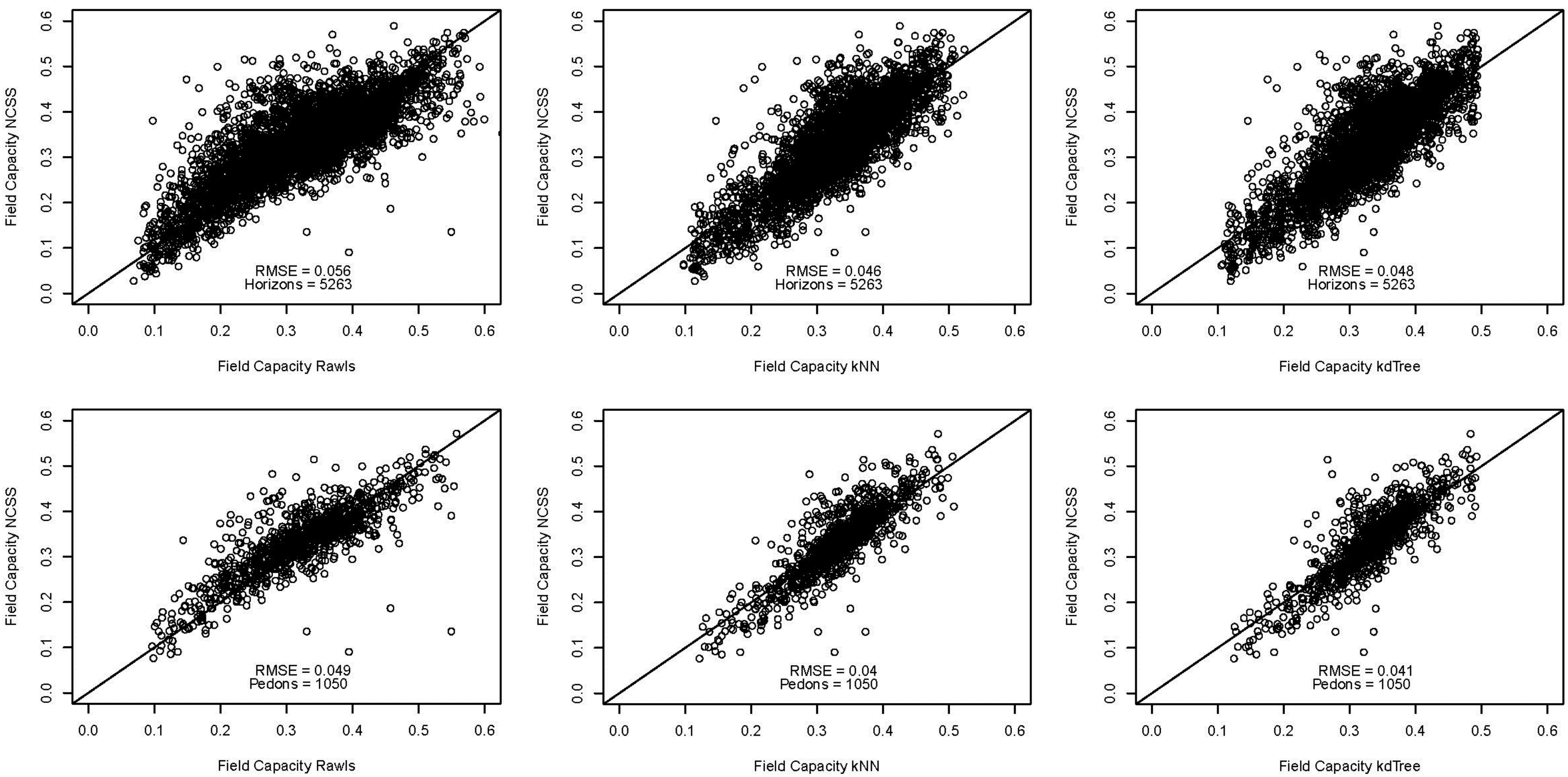
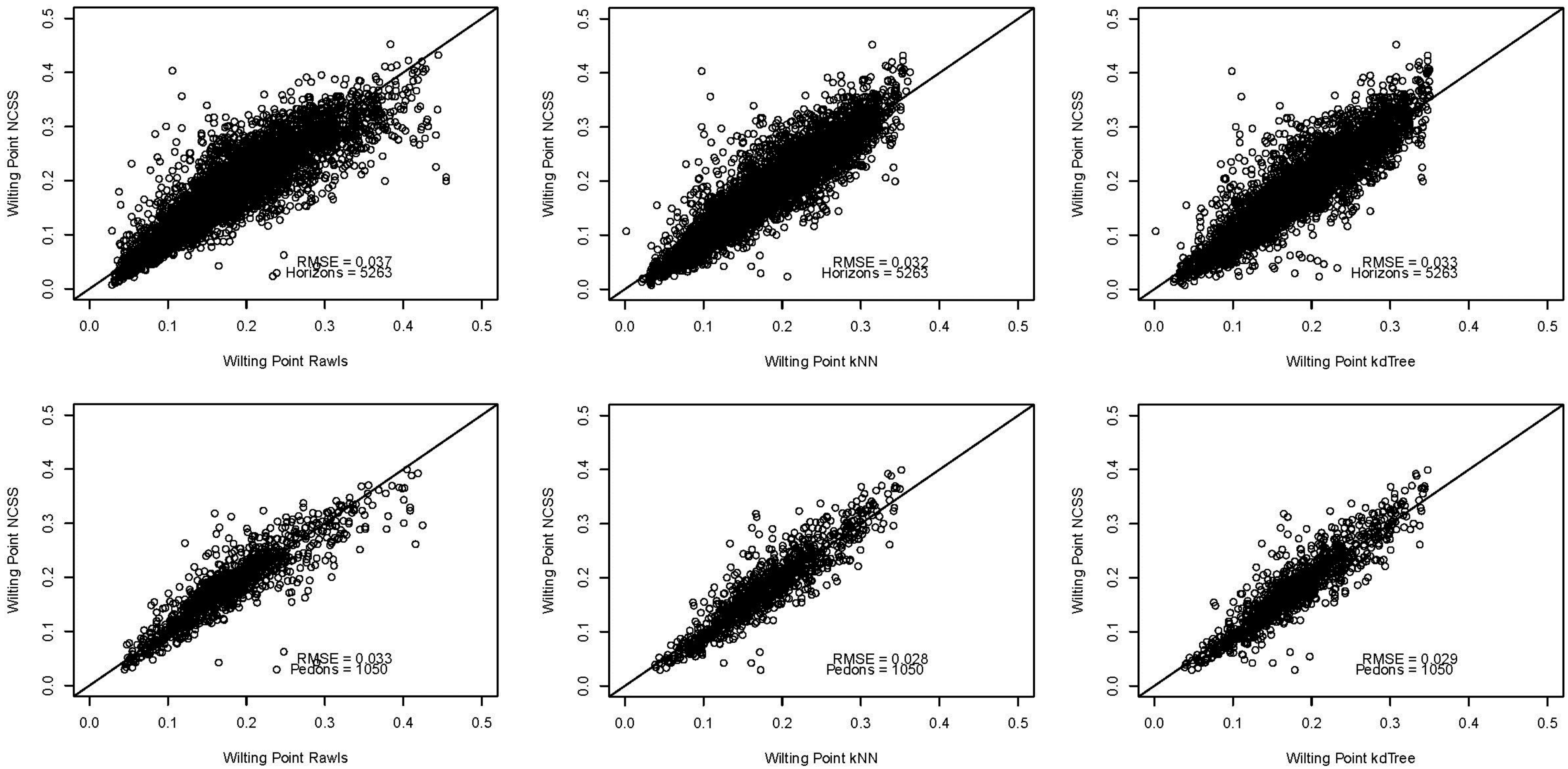


Fig. 2: Comparison of estimated wilting point with NCSS database values by horizon (upper row) and by pedon (lower row) using Rawls method (left column), k-NN algorithm (middle column) and K-D tree algorithm (right column) show that the non-parametric methods fit slightly better than Rawls' parametric method as measured by residual mean squared error (RMSE).



Spectral Response of Winter Maize Production Mesoregions Using MODIS Images

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Abstract

Maize production is fundamental for the Brazilian economy. Second-crop of maize (winter maize) has significant involvement in the production of grains and is of fundamental importance for the Brazilian agribusiness. This study analyzed the time series of the NDVI MODIS satellite to obtain the Standardized Vegetation Index (SVI) for the period, and compared it with the SVI for the current crop year. In general, the crop shows good development, as it can be seen in the evolution of the SVI mesoregions analyzed. Due to the variability of the weather conditions in these regions, the cycles of winter crops change due to the dependence on the agricultural calendar of the first crops, especially soybeans. The results of this study are preliminary and need to be validated using control points at the cultivated areas.

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Keywords: maize, mesoregions, NDVI, geoprocessing.

Introduction

Crop Monitoring is an essential activity due to their strong social and economical influence. Strong oscillation in grain productivity along the years is characteristic for Paraná state, due to the region's frequent climate instability

Since low water periods are serious and recurring climate phenomena that have been affecting the states in the South of Brazil during the last years, we have used data from past periods on plant cover behavior to analyze plant vigor during the critical phases of winter maize crops based on ten-day historical data from 2006 to 2014. This study analyzed the time series of the NDVI MODIS satellite to obtain the Standardized Vegetation Index (SVI) for the period, and compared it with the SVI for the current crop year.

The SVI was obtained from the 16-day NDVI product by means of the application of the method proposed by Park et al. (2008), which enabled quantifying how much the vegetation index of a given 16-day period differs from the average long-term value for that same period. Obtained with the aim of quantifying the anomalies in the form of standard deviation to the average, the SVI is an important index for the monitoring of plant vigor on regional scale. The analysis was performed using 16-day periods because of the relevance of the studied information for short terms, since detailed information is essential for decision making during critical periods for the development of the crops.

The objective of this work was to assess the performance of the Standardized Vegetation Index (SVI) in the indicative monitoring of the development of winter maize crops in the Paraná State, in Southern Brazil. For that purpose, we standardized the MODIS NDVI images with the historical average for each pixel.

Methodology

The study area encompasses the Paraná state, and the method applied focuses on cities with winter maize crop areas larger according to the municipal agricultural production data (Produção Agrícola Municipal, PAM) released by the Brazilian Institute of Geography and Statistics (IBGE), as shown in Figure 1.

We analyzed the time between the (16-day period) of January to the period of April for the 2006 to 2014 agricultural years.

The SVI (Standart Vegetation Index) was obtained from the 16-day NDVI product by means of the application of the method proposed by Park et al. (2008). We used 63 MODIS images, tile h3v11, MOD3Q1 with 250m spatial resolution and temporal 16 days, ranging from January 2006 to April 2014 were used.

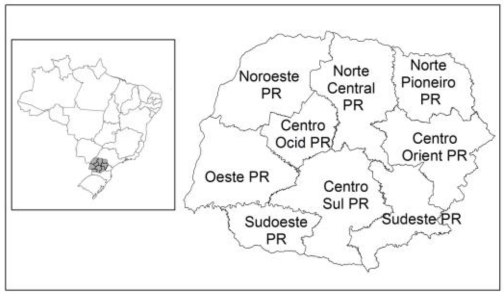

Figure 1. Study area with winter maize production mesoregions in Paraná state.

Table 1 – Standard Vegetation Index (SVI) Ranges.

Values of SVI	Ranges	Legend
SVI ≤ - 2,0	Far below normal	Dark Red
-2.0 < SVI ≤ -1.5	Below normal	Red
-1.5 < SVI ≤ -1.0	Somewhat below normal	Orange
-1.0 < SVI ≤ 1.0	Normal	Yellow
1.0 < SVI ≤ 1.5	Somewhat above normal	Light green
1.5 < SVI < 2.0	Above normal	Green
SVI ≥ 2.0	Far above normal	Dark green

Results and discussion

In the SVI images of the 2006/2014 harvest (Figure 2), from the first to the 16-day period of January 2014 (DOY 33- Day od year) and Febreary 18, the SVI was below normal at the northern region of the Paraná state. In March 2014 (DOY 65 and 81) there was an increase in the area with SVI above than normal, i.e. the vegetation showed above vegetation indexes values than the historical standard for that period. In the 16-day periods of April 7 and April 113 (DOY 97 and 113) there was an increase in areas with NDVI above than normal.

On Figure 2, we observe SVI below normal (red area), indicating that summer crops have been nearly complete in February (DOY 033 and 049). On March (DOY 065), there is indication of planting / germination of winter maize. From DOY 81 on, it can be inferred that the high vegetative vigour indicates potential yield for the 2nd harvest. The Oeste Paranaense and Norte Central Paranaense mesoregions show large SVI (green area), with expectation of good yield potential for the winter maize.

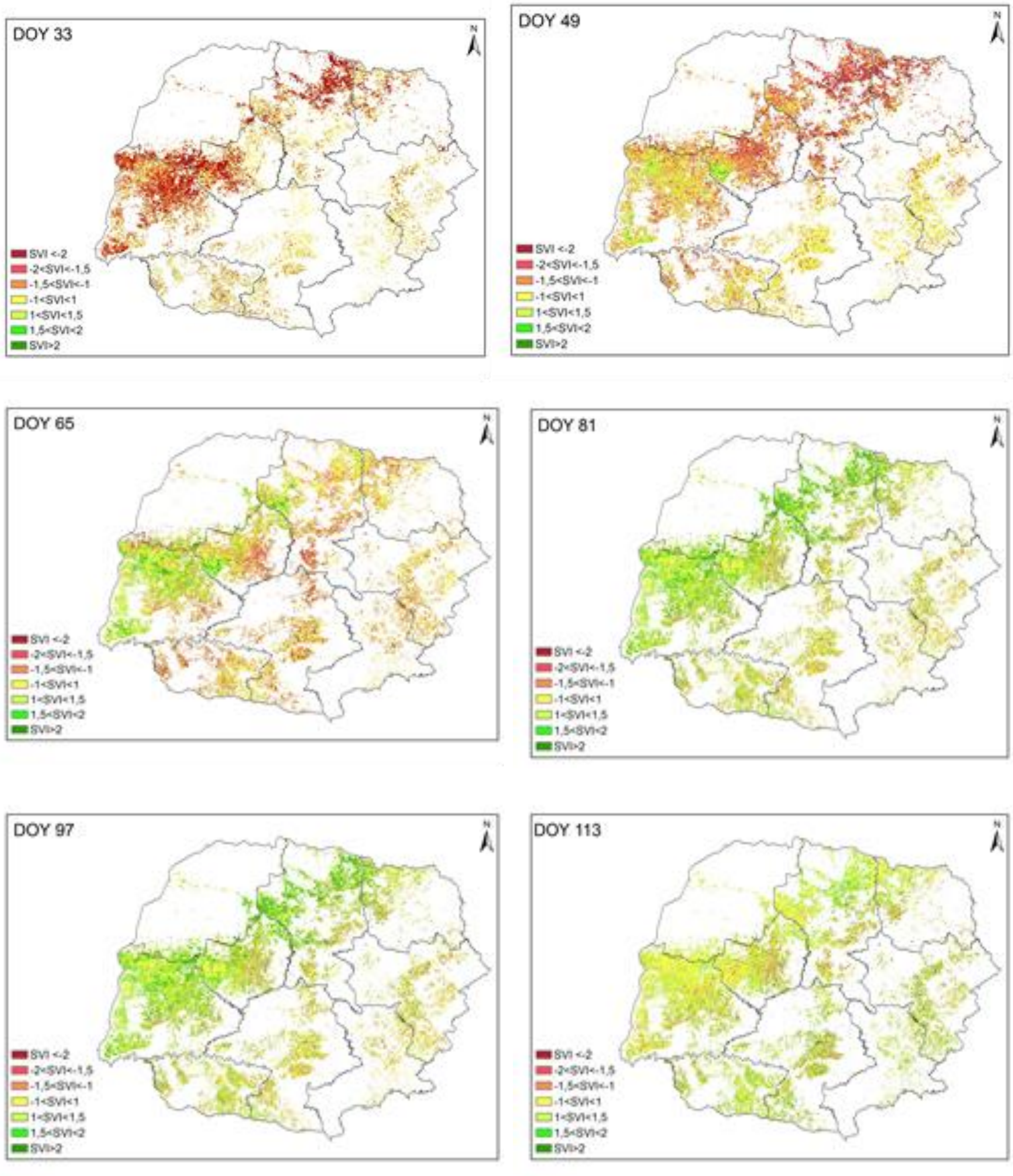

Figure 2. SVI for 16-day periods for DOY 33, 49, 65, 81, 97 and 133/2014, covering the planting, germination, vegetative development, flowering and grain-filling periods of winter maize in the mesoregions in Paraná State. The predominance of yellow and green areas (SVI normal or above normal) characterizes high vegetative development (vigour) of winter maize crops, indicating good yield potential.

Conclusion

In general, the crops showed good development, as it can be seen in the temporal evolution of the SVI for Paraná's mesoregions. In the Oeste Paranaense mesoregion, the images indicate good crop development. Due to the variability of the weather conditions in the regions, there has been variation in the planting season (for winter maize) and in the cycles of winter crops, due to their dependence on the agricultural calendar of the 1st season crops, especially soybeans. The results of this study are preliminary, and need to be validated using control points at the cultivated areas.

The results demonstrated the potential of SVI for monitoring of agricultural crops, and contributing for decision making in agriculture

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Modelagem hidrológica na bacia hidrográfica Ribeirão Pádua Diniz, no noroeste de São Paulo, Brasil

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Abstract

The objective of this work was to propose a new methodology to aid in the administration of watersheds. The watershed is, for law, the unit of territorial planning and, for that reason, the study of the morphometric characteristics of a basin is essential for the appropriate administration of the water resources and planning of any activities in an area. This work was accomplished for the municipal district of Uberaba, MG whose main river is Rio Uberaba. The Uberaba River covers five counties, including Uberaba. The studies conducted in this basin to date, always take into account the basin as a whole, ignoring the particularities of each municipality covered by it. Based on this context, the city of Uberaba was divided into hydrological compartments or sub – basins with the aid of GIS (Geographic Information System) ArcGis 10.1 and the SWAT (Soil and Water Assessment Tool), more specifically its extension to ArcGis, the ArcSwat. The city was divided into 34 sub – basins and for each were obtained: area (ha), perimeter (ha), length of the main watercourse water (meters), slope of the sub –

basin (%), length of ramp (meters) and the compactness coefficient (dimensionless). The low slope (2.74 % – 8.85%) and long lengths of ramps (60 m – 91 m) reduce the propensity to floods in sub – basins. The high compactness coefficients agree with previous results (1.56 to 2.67). The situations of flooding in the city can be explained by the low soil impermeability, deficiency in urban drainage systems and clearing of permanent preservation areas throughout the basin, especially the APA (Environmental Preservation Area) of Uberaba River.

Keywords: Water resources management, morphometry, GIS, remote sensing.

Introdução

Bacia hidrográfica é a unidade de área resultante da compartimentação natural dos terrenos compreendidos por divisores topográficos. É aquela de ocorrência dos processos advindos da integração entre elementos do meio físico e biológico em contato ou não com os culturais. A caracterização geomorfológica de bacias hidrográficas tem-se apresentado como fundamento importante para os trabalhos dirigidos ao planejamento territorial mediante a correlação a outros dados do meio físico (Oliveira e Viadana, 2014).

A água constitui o recurso natural mais importante, por ser fundamental aos outros recursos (vegetais, animais e minerais) e por ter influência direta na manutenção da vida, pois é vital para a sobrevivência dos seres vivos, uma vez que está presente na maioria dos processos metabólicos e ainda interage com todo o ambiente, acumulando as informações dessas interações e, assim, funcionando como indicador ambiental de grande eficiência. A quantidade e qualidade de água das nascentes de uma bacia podem ser alteradas por diversos fatores, entre eles a declividade, o tipo de solo e o uso da terra, principalmente das áreas de recarga, pois influenciam no armazenamento de água subterrânea, no regime das nascentes e nos cursos de água (Torres et al., 2011).

A caracterização morfométrica é um dos principais procedimentos para entender e compreender os processos hidrológicos, a dinâmica ambiental e fornecer informações suficientes para gestão das mais diversas bacias hidrográficas (Rosa e Lucas, 2014).

SWAT (*Soil and Water Assessment Tool*) originou-se a partir da necessidade de se prever o efeito de diferentes cenários de manejo da terra na qualidade da água, aporte de sedimentos e cargas de poluentes em uma bacia hidrográfica respeitando suas condições espaciais para um longo período de tempo (Carvalho Neto, 2011).

Os sistemas de informações geográficas acopladas aos modelos hidrossedimentológicos (Melo, 2010) facilita o uso de modelos de base física; exemplo disso é o caso do modelo SWAT (*Soil and Water Assessment Tool*) (Neitsch et al., 2005), acoplado a um SIG – ArcSWAT (Winchell et al., 2009), que tem produzido resultados positivos no Brasil e no mundo (Aragão, 2013).

O objetivo deste estudo foi mensurar o escoamento da bacia hidrográfica por meio de técnicas de sensoriamento remoto por modelagem Swat.

Material e Métodos

O estudo foi realizado na bacia hidrográfica do Ribeirão Pádua Diniz, com uma área de 332,43 km² e comprimento do leito principal de 43,51 km, localizada na região noroeste do estado de São Paulo (Figura 1), com sistemas de coordenadas UTM, projetados a uma latitude de 7.781.328,77m N e longitude de 581.845,56m E, Datum SIRGAS 2000, Zona 22S, Meridiano Central -51°, incluindo partes dos municípios: Indiaporã, Mira Estrela, Macedônia, Guarani d'Oeste e Fernandópolis.

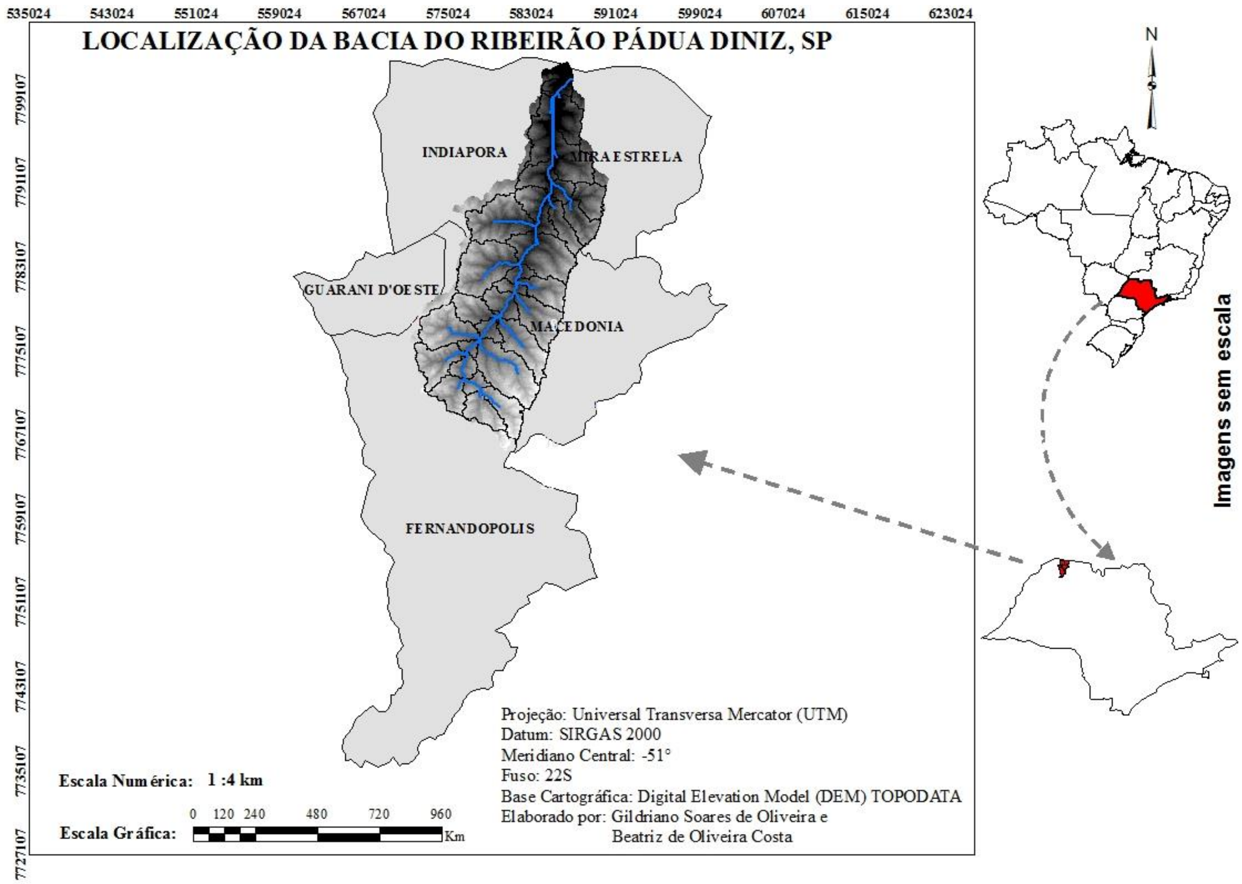

Figura 1. Bacia hidrográfica do Ribeirão Pádua Diniz e partes dos municípios que a compõe.

Segundo a classificação de Koppen o clima é Aw precipitação anual e média de 1.378 mm. O bioma encontrado é floresta tropical e a vegetação da região é característica de floresta semidecídua. Os tipos de solos da área são Latossolos Vermelhos distróficos; Latossolos Vermelhos eutroférricos e distroférricos; Argissolos Vermelhos-Amarelos eutróficos abrúpticos; Argissolos Vermelhos-Amarelos eutróficos; Argissolos Vermelhos-Amarelos eutróficos e distróficos.

Inicialmente, obteve-se o Modelo Digital de Elevação (MDE) de Indiaporã, Mira Estrela, Macedônia, Guarani d'Oeste e Fernandópolis por meio do site Embrapa Relevo. Posteriormente, foram obtidas as malhas geométricas dos municípios citados. Estas malhas foram adquiridas no site do IBGE. No ambiente ArcGIS, as cartas foram abertas simultaneamente, mosaicadas e o sistema de coordenadas foi projetado: UTM (*Geographic Coordinate System*), Datum SIRGAS 2000 e fuso 22 S.

Após a configuração do sistema de coordenadas, as malhas geométricas adquiridas foram inseridas no MDE e posteriormente recortadas. O banco de dados formado foi exportado para uma pasta específica. Após a formação do banco de dados necessário e a projeção de coordenadas geográficas no sistema "*layer*", um novo projeto foi criado em Arcswat (projeto de instalação) e o diretório utilizado foi uma pasta criada para este fim, como com os dados de entrada exigidos pelo software. No menu *Wathershed Delineation*, configurou-se o sistema de coordenadas geográficas, datum e fuso, o MDE foi recortado e inserido por meio do comando *Definition Stream*. Calculou-se a área e o número de compartimentos hidrológicos para a bacia Ribeirão Pádua Diniz (direção do fluxo e Acumulação).

A direção do fluxo é gerada por uma grade regular, tendo como base a maior altitude do terreno. A nova grade numérica gerada determina o sentido de maior altitude de um pixel em relação aos seus oito pixels vizinhos. Assim, a descrição numérica da direção da água irá depois alcançar cada pixel, que pode ser representado graficamente por meio da aplicação do código de direção (Castro, 2013).

A delimitação da bacia Ribeirão Pádua Diniz, bem como as sub – bacias ou compartimentos hidrológicos foram realizadas utilizando apenas a malha geométrica local e MDE. As variáveis foram calculadas diretamente pelo ArcSwat: Área (ha), perímetro (ha), comprimento de rampa (m), declividade média (%) e fator topográfico (LS) O índice de circularidade apresentado por Miller (1953) citado por Rocha e Kurtz (2001) em uma variável morfométrica onde quanto maior o valor de (IC) (observada quando se compara sub – bacias), estará mais próximo da mesma forma circular, e maior o perigo de inundação (concentração mais elevada de água do afluente principal). Para calcular a (IC), foi utilizada a seguinte equação (1):

$$IC = \frac{12,57 \times A}{P^2} \qquad (1)$$

Onde: IC é o Índice de Circularidade, A é a Área de Drenagem (m²) e P é o perímetro (m).

O coeficiente de compacidade (Kc) refere-se ao perímetro da bacia e a circunferência do círculo cuja área é igual a bacia de drenagem. Segundo Villela e Mattos (1975), este coeficiente é um número adimensional que varia de acordo com a forma da bacia, independentemente do seu tamanho. Quanto mais irregular a bacia, maior o coeficiente de compacidade. Um coeficiente mínimo igual à unidade corresponde a uma bacia circular, com alta propensão a enchentes e, para uma bacia alongada seu valor é significativamente maior do que a unidade, indicando menos propensão a inundações. Coeficientes de Compacidade acima de 1,47, caracteriza bacia não sujeita a inundações. O Kc é determinado com base na seguinte equação 2:

$$Kc = 0,28 \, P / \sqrt{A} \qquad (2)$$

Onde: Kc = Coeficiente de Compacidade; P = Perímetro (m) e A = Área de Drenagem (m²).

Para encontrar o fator topográfico ou LS, foi utilizada a equação 3, desenvolvida por Bertoni e Lombardi Neto (1999) para a cidade de Campinas, que se adequou bem as condições brasileiras, partindo da relação experimental da perda de solo com diversos graus de declividade (de 1 a 20%, variando a cada 2%) e de comprimentos de rampa (de 5 a 100 m, oscilando de 5 em 5 m) (Valle Júnior, 2008):

$$LS = 0,00984 \, l^{0,63} \, S^{0,18} \qquad (3)$$

Em que: l = comprimento de rampa (m); S = declividade (%).

Resultados e Discussão

A modelagem permitiu medir separadamente cada compartimento do fluxo hidrológico, aumentando a precisão e descrição física de estudos morfométricos da bacia. Os compartimentos totalizaram em 35. Os resultados obtidos podem ser observados na Tabela 1.

Tabela 1. Principais características físicas de cada sub – bacia.

Cpt	A (ha)	A (m²)	Prt	IC	S	Clp (m)	Cr (m)	Elv (m)	Prtc (m)	Ac (m^2)	LS = 0,00984 $L^{0,63}$ $S^{1,18}$	Kc
1	351.49	3,514,941.78	12,134.75	0.30	5.17	3,751.91	60.96	390.35	12,134.75	3,514,941.78	0.91	1.81
2	196.59	1,965,877.46	11,714.24	0.18	2.22	3,791.89	91.44	383.58	11,714.24	1,965,877.46	0.43	2.34
3	45.47	454,704.71	15,018.26	**0.03**	0.40	7,088.62	121.91	377.14	15,018.26	454,704.71	0.07	6.24
4	859.34	8,593,382.81	18,021.91	0.33	7.32	6,510.30	60.96	401.20	18,021.91	8,593,382.81	1.37	1.72
5	1,229.42	12,294,176.51	25,410.89	0.24	7.00	8,903.98	60.96	405.16	25,410.89	12,294,176.51	1.30	2.03
6	1,323.61	13,236,065.09	27,933.96	0.21	7.59	10,918.75	60.96	414.47	27,933.96	13,236,065.09	1.43	2.15
7	778.05	7,780,507.47	30,336.88	0.11	7.94	11,791.76	60.96	411.48	30,336.88	7,780,507.47	1.51	3.05
8	53.41	534,097.88	7,388.98	0.12	8.53	2,668.28	60.96	392.31	7,388.98	534,097.88	1.65	2.83
9	392.54	3,925,439.24	10,873.22	**0.42**	8.05	3,670.34	60.96	407.27	10,873.22	3,925,439.24	1.53	1.54
10	819.46	8,194,613.77	19,223.37	0.28	8.74	4,211.88	60.96	433.91	19,223.37	8,194,613.77	1.69	1.88
11	729.69	7,296,932.43	24,149.36	0.16	8.24	7,542.40	60.96	434.23	24,149.36	7,296,932.43	1.58	2.50
12	813.78	8,137,775.72	19,343.52	0.27	8.85	5,904.60	60.96	431.81	19,343.52	8,137,775.72	1.72	1.90
13	1,062.33	10,623,315.73	24,509.80	0.22	8.53	5,910.82	60.96	418.56	24,509.80	10,623,315.73	1.65	2.11
14	2,064.76	20,647,575.83	32,619.66	0.24	8.66	8,364.58	60.96	439.62	32,619.66	20,647,575.83	1.67	2.01
15	2,043.38	20,433,756.23	30,577.18	0.27	8.03	8,020.85	60.96	433.08	30,577.18	20,433,756.23	1.53	1.89
16	2,213.80	22,137,997.84	29,976.45	0.31	8.49	8,023.17	60.96	450.48	29,976.45	22,137,997.84	1.64	1.78
17	319.20	3,191,956.84	11,293.73	0.31	8.38	3,227.97	60.96	417.85	11,293.73	3,191,956.84	1.61	1.77
18	938.82	9,388,214.40	20,184.54	0.29	8.17	7,451.04	60.96	450.80	20,184.54	9,388,214.40	1.56	1.84
19	303.14	3,031,366.56	13,516.43	0.21	7.79	3,527.08	60.96	434.97	13,516.43	3,031,366.56	1.48	2.17
20	712.91	7,129,124.55	16,940.60	0.31	7.72	4,514.57	60.96	436.70	16,940.60	7,129,124.55	1.46	1.78
21	1,379.09	13,790,913.45	25,050.46	0.28	7.69	7,805.81	60.96	456.06	25,050.46	13,790,913.45	1.46	1.89
22	814.41	8,144,091.09	19,283.45	0.28	7.90	6,003.07	60.96	458.08	19,283.45	8,144,091.09	1.50	1.89
23	49.53	495,303.63	5,466.65	0.21	8.04	1,452.43	60.96	418.21	5,466.65	495,303.63	1.53	2.17
24	394.44	3,944,385.25	13,516.43	0.27	7.95	3,650.61	60.96	431.18	13,516.43	3,944,385.25	1.51	1.91
25	1,582.36	15,823,552.90	25,711.26	0.30	8.15	7,871.73	60.96	464.91	25,711.26	15,823,552.90	1.56	1.81
26	4.24	42,403.05	1,081.31	**0.46**	4.50	342.84	91.44	412.60	1,081.31	42,403.05	1.00	1.47
27	1,410.76	14,107,582.95	30,697.32	0.19	7.74	9,478.61	60.96	461.96	30,697.32	14,107,582.95	1.47	2.29
28	229.97	2,299,688.48	10,212.42	0.28	7.77	3,376.01	60.96	435.68	10,212.42	2,299,688.48	1.47	1.89
29	1,220.67	12,206,663.63	25,891.48	0.23	8.74	7,558.93	60.96	466.27	25,891.48	12,206,663.63	1.69	2.07
30	2,291.84	22,918,394.21	32,619.66	0.27	8.22	10,882.16	60.96	466.63	32,619.66	22,918,394.21	1.57	1.91
31	446.77	4,467,656.87	13,095.92	0.33	8.92	4,103.11	60.96	448.57	13,095.92	4,467,656.87	1.73	1.73
32	338.95	3,389,536.94	12,855.63	0.26	8.11	3,531.35	60.96	454.99	12,855.63	3,389,536.94	1.55	1.96
33	840.57	8,405,726.82	19,223.37	0.29	8.49	5,150.67	60.96	469.14	19,223.37	8,405,726.82	1.64	1.86
34	843.82	8,438,205.76	20,785.27	0.25	8.80	5,794.94	60.96	475.06	20,785.27	8,438,205.76	1.71	2.00
35	982.13	9,821,266.78	23,368.41	0.23	8.71	7,494.77	60.96	482.52	23,368.41	9,821,266.78	1.69	2.09

Cpt: *Compartimentos;* ***A:*** *Área;* ***Prt:*** *Perímetro;* ***IC:*** *Índice de Circularidade;* ***S:*** *Declividade da sub-bacia em %;* ***Clp:*** *Comprimento do leito principal;* ***Cr:*** *Comprimento de rampa;* ***Elv:*** *Elevação;* ***Prtc:*** *Perímetro de cada compartimento;* ***Ac:*** *Área de cada compartimento (m^2);* ***LS:*** *Fator topográfico;* ***Kc:*** *Coeficiente de compacidade.*

Área da bacia (A) é conceituada como toda a área drenada pelo conjunto fluvial, projetada em um plano horizontal (Christofoletti, 1980). Classificada como parâmetro básico para cálculo de outras variáveis morfométricas, é delimitada a partir dos divisores de água da bacia, é expressa geralmente em Km². Quanto maior a área, maior os esforços de monitoramento, pressupondo também uma maior diversidade de ambientes. A área serve como variável básica para análise, combinada a outras variáveis. A área dos compartimentos hidrológicos da bacia do

Ribeirão Pádua Diniz variou significativamente de 4,24 a 2291,84 ha. Há relatos de estudos de bacias hidrográficas na região leste e central dos Estados Unidos, detectou-se uma relação inversa da capacidade de produção de sedimentos com a área, ou seja, bacias menores produzem mais sedimentos (Valle Júnior, 2008).

O comprimento do rio principal (Clp) serve para evidenciar a diversidade de ambientes que o rio percorre a vazão, a carga de sedimentos que permitem análises de susceptibilidade ambiental, delimitação das áreas de APP, morfologia de foz e indicação de áreas prioritárias para a conservação (Machado et al., 2011). O comprimento dos compartimentos hidrológicos variou de 342,84 a 11.791,76 m.

O índice de Circularidade (IC) dos compartimentos hidrológicos variou de 0,03 a 0,46, o que caracteriza os compartimentos como alongados. Segundo Alves e Castro (2003) valores do índice de circularidade (IC) acima de 0,51 revela que a bacia tem tendência circular favorecendo os processos de inundação (cheias rápidas). Porém, se o valor (IC) for igual a 0,51, nos mostra que o escoamento é moderado havendo pequena probabilidade de cheias. Contudo, os mesmos autores nos mostram que para valores de (IC) menores que 0,51, a bacia é mais alongada favorecendo desta forma o escoamento.

O coeficiente de compacidade (Kc) dos compartimentos hidrológicos variaram de 1,47 a 6,24 e o índice de circularidade (Ic), inversamente proporcional, caracterizou os compartimentos como alongados com baixa propensão à enchente. O Kc é um número adimensional que varia com a forma da bacia, independentemente do seu tamanho, pois, quanto mais irregular for a bacia, maior será o Kc; além disso, destacaram que a bacia será mais suscetível a enchentes quando seu Kc for mais próximo da unidade. Valores de IC abaixo de 0,51 é característica de regiões não sujeitas a inundações.

A declividade (S) dos compartimentos hidrológicos variou de 0,4 a 8,92 %, classificando o relevo como plano a ondulado, segundo Embrapa (1999): **Plano**: superfície de topografia horizontal, onde os desnivelamentos são muito pequenos, com declividades variáveis de 0 a 3%; **Suave Ondulado**: superfície de topografia pouco movimentada, constituída por conjunto de colinas, apresentando declives suaves, variando de 3% a 8%; **Ondulado**: superfície de topografia pouco movimentada, constituída por conjunto de colinas apresentando declives moderados, variando de 8% a 20%; **Forte Ondulado**: superfície de topografia movimentada, formada por morros e raramente colinas com declives fortes, variando de 20% a 45%.

A declividade influencia na infiltração e nos processos erosivos fluviais e pluviais, assim como na tipologia da vegetação. Contribui para a formação do solo e serve de indicador na definição de áreas de risco e restrição de uso. A declividade dos rios pode ser associada à velocidade do escoamento, transporte de sedimentos e conformação das APPs (Machado et al., 2011).

O comprimento de rampa (Cr) dos compartimentos hidrológicos variou de 60,96 a 121,91 m. Este índice é definido como sendo a distancia média em que a água da chuva teria que escoar sobre os terrenos de uma bacia, caso o escoamento se desse em linha reta desde onde a chuva caiu até o ponto mais próximo no leito de um curso d’água de uma bacia (Villela e Mattos, 1975). A importância deste parâmetro está no cálculo do tempo de concentração da bacia hidrográfica.

Com relação ao fator topográfico (LS), reflete o impacto do comprimento de rampa e da declividade média na erosão do solo (Wischmeier e Smith, 1978). Embora a relação exata permaneça incerta, assume-se que um fluxo de acumulação maior e uma velocidade de escoamento mais rápido são, respectivamente, associados com um comprimento de rampa maior e maior inclinação, e que a taxa de erosão reduz, quando a declividade chega a certo limiar (Rao et al., 2014). O LS dos compartimentos hidrológicos variou de 0,07 a 1,73. O Perfil topográfico permite identificar a diversidade dos vários ambientes dentro da bacia, em função da altitude e da distância percorrida.

No geral, a bacia apresentou perfil alongado, com baixa propensão a inundações (Figura 2).

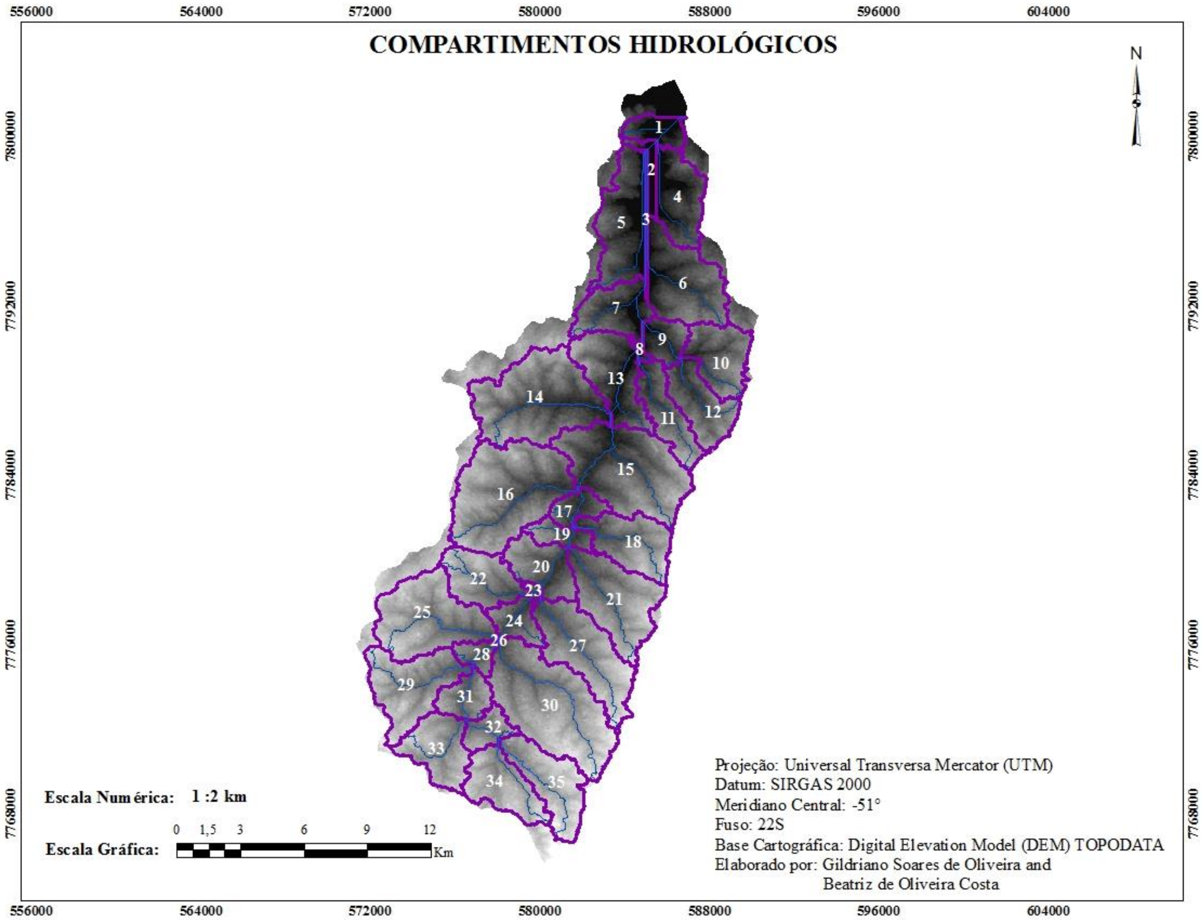

Figura 2. Trinta e cinco compartimentos hidrológicos gerados no ArcSWAT.

Conclusão

Ao longo de sua extensão os compartimentos hidrológicos não apresentaram um formato circular, mas sim uma forma relativamente alongada que indica para uma baixa tendência a enchentes.

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Erosion Prediction using SWAT model in Córrego Tijuco Watershed, São Paulo State, Brazil

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Abstract

The erosion process in rural areas is concern to environmental quality due to agricultural inputs, which can be pollutants if not managed properly. This study manly focuses to determine the average of the LS of the Universal Soil Loss Equation, and to carry out the erosion caused by rainfall and runoff modeled with the Modified Universal Soil Loss Equation (MUSLE), (Williams, 1975), using the Soil and Water Assessment Tool (SWAT) in Córrego Rico Watershed, São Paulo State, Brazil. The process of configuring SWAT for modeling the watershed was developed in a geographic information system - ArcGIS, and the land use, topographic and soil data was translated in a digital data base. The study area increase the processing of the cultivate area by converting citrus orchards to sugar cane crop. And, the removal of topsoil can be a serious concern. So, this paper analized the sediment yield effect of land use and make detailed study about the watershed characteristics. Finding the land use and sediment yield, can make the best suggestion most suitable for better soil conservation practices.

Keywords: List both specific and general terms that will aid in searches.

Introduction

The watershed is a configuration of the terrain and the surface water hydrology influenced by the erosion process due to the movement of water over the land. The erosion process in natural watersheds is influenced by many factors, such as geomorphology, soil, slope, land use and manly the farming practices. The effect of land use on erosion process is a major concern in mostly all the countries in the world (Burton & Pitt, 2001).

As the watershed computes the local directions of flow and the gradual accumulation of water moving down slope across the landscape (Smith, 2010), many researches has focused on modeling this area to identify the linkages between management and water runoff.

Many characteristics of the landscape determine a high erosion process that develop soil degradation and water pollution due to formations of gullies and ravines that dissected the area of the watershed, and modeling soil erosion can contributed for evaluating sediment yield, to determine the sediment contribution to drainage net and to identify the susceptible areas to erosion (Phomcha et al., 2011; Betrie et al., 2011).

For erosion to occurs is necessary the mainly natural agents, as water and wind, each contributing a significant amount of soil loss each year in Brazil, and it may occur at an alarming rate causing serious loss of topsoil, reducing crop production potential, lower surface water quality and damaged drainage networks (Burton & Pitt, 2001).

One of the watershed modeling most used is the *Soil and Water Assessment Tool* (SWAT) model (Arnold *et al.*, 1998), which is an effective applicative tool made to understanding better the different environmental conditions in a wide range of scales of watersheds, mainly in water quality and land use management. The model has many different application categories that can be used to simulate a variety of watershed problems (Gassman et al., 2007).

The model results has showed a satisfactory agreement between daily observed and simulated sediment concentrations and to identify soil erosion prone areas and assess the impact of BMPs on sediment reduction using SWAT in different scenarios (Tibebe & Bewket, 2010; Betrie et al., 2011). However, only a few studies have examined the erosion in watershed with two different soil units, comparing to field work and the Universal Soil Loss Equation (USLE).

Phomcha et al. (2011) demonstrated that the simulated sediment discharge was found to be lower than originally estimated for some months, particularly during seasons prone to flooding, but most of the predicted values were close to those graphically and statistically observed with correlation coefficient and Nash-Sutcliffe coefficient above than 0.70.

The estimated soil loss rates by the Soil and Water Assessment Tool (SWAT) model was realistic compared to what can be observed in the field and results from previous studies in long-term average soil loss provides a useful tool for soil erosion assessment from watersheds and facilitates planning for a sustainable land management in Ethiopia (Tibebe & Bewket, 2010).

This study manly focuses to use the SWAT model to understand the erosion caused by rainfall and runoff in watershed within two soil units modeled with the Modified Universal Soil Loss Equation (MUSLE), (Williams, 1975), in Córrego Tijuco Watershed, São Paulo State, Brazil.

Material and Methods

Watershed Characterization

The Córrego Rico Watershed is located at Northeast of the State of São Paulo, Brazil (Figure 1), at the 9th unit of the Water Resource Management Units (UGRHIs) of the State Water Resource Management System and State Water Policy (SIGRH), called Pardo/Moji-Guaçu Rivers, with an approximately area of 8008 ha, projected coordinate system in a latitude of 7652337m and 7628137m N, longitude of 756463m and 794623m E; Córrego Alegre, UTM, Zone 22S, in a Transverse Mercator projection.

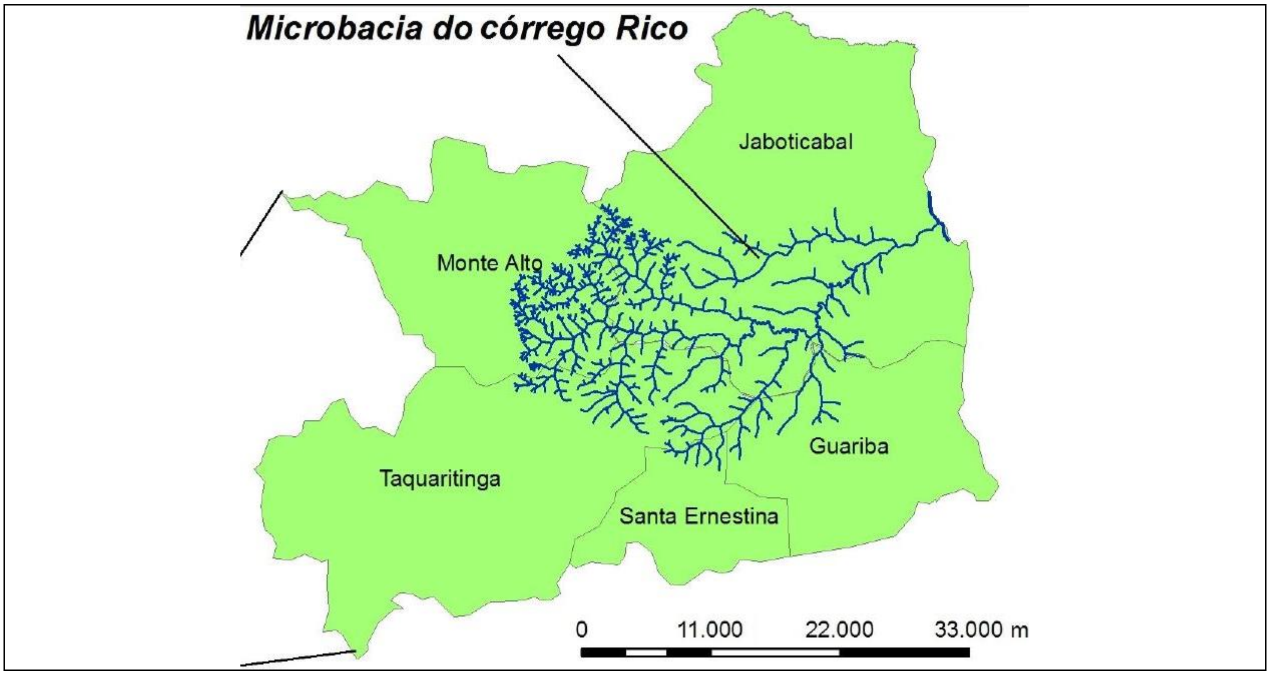

Figura 1. Córrego Rico watershed, São Paulo State, Brazil.

The climate is tropical with annual rainfall of 1400mm, and temperature ranging from 22ºC in summer and 18ºC in winter. Altitude varies between 488 to 700m. The major soil series were identified as Latossolo and Argissolo (Oliveira et al., 1999; Oliveira, 1999).

Methods

The ArcSWAT model (Winchel et al., 2010) is an ArcGIS interface tool for soil and water assessment that is a physically-based continuos-event hydrologic model developed by the USDA Agricultural Research Service (ARS). To create a project was incorporated all customized geographical information system (GIS) functions in a ArcMap project file. The setup working directory and geodatabases were created to store the parameters needed for SWAT model run.

The Córrego Rico watershed delineation was done by using a combination of the DEM, digitized network and other inputs. The Digital Elevation Model (DEM) setup was made in a data base conceded by Embrapa Relevo Project (Miranda et al., 2011) in the South American Datum 1969 (SAD 69) UTM Zone 22S projection, 90 m resolution, and grid position of 756.46 km to 794.63 km east, 7628.14 km to 7652.34 km north.

The original DEM SRTM was interpolated to 20 meters of spatial resolution using a spline filter and the projection coordinate system was converted to Córrego Alegre. A grid map was created that masks out a part of the DEM grid that defined the main channel of the Córrego Rico watershed to determine the average monthly rate out of reach during a time step (m^3/s). To compare the USLE data a mask was manually delineated by a draw appear by the boundary of the watershed area of interested, that is to be the same area that was developed a USLE erosion prediction done by Arraes (2009). This tributary from Córrego Rico Watershed is called Córrego do Tijuco subbasin (Figure 2).

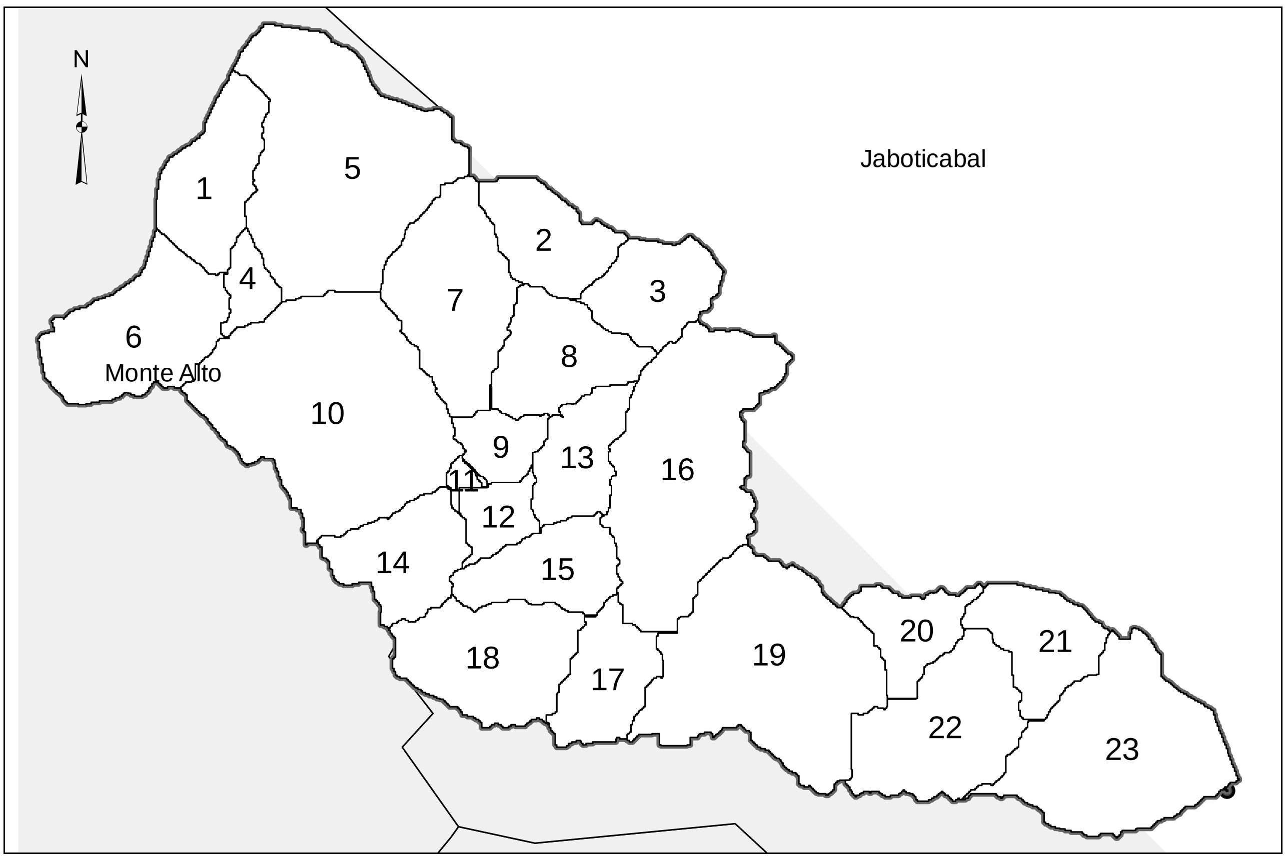

Figure 2. Drainage network and subbasin outlets of the Córrego do Tijuco watershed, São Paulo State, Brazil.

The stream definition function was made in the entirely area by a watershed delineator method based in a discretization of the watershed areas into smaller increments, such as subbasins. The identification of the optimal division of a model to predict a desired variable (Migliaccio & Chaubey, 2008) was done to have the same spatial resolution as Arraes (2009), so the model can predict flow values on similar subbasins.

The flow direction and accumulation, soil, land use and slope inputs were done due to its main channel, and defined the routing network in a discretization scheme by grid cell (Neitsch et al., 2010). A reach routing command structure was used to route and add flows (William & Hann, 1973). The stream definition was based in the DEM with a flow direction and accumulation of a threshold area for stream and subbasin definition of 150 ha and 3750 cells. The number of subbasins created was 23, and each one possesses a geographic position in the watershed and is spatially related to one another. The delineation was defined by surface topography, so the entire area within a subbasin flows to the main channel to Córrego Rico watershed (Pissarra, 2002, Arraes, 2009). The drainage network and stream juncture points were displayed on the map of the watershed (Figure 2).

The land use, soil and slope definition was according to Pissarra (2002) and Arraes (2009) and the slope definition was according to EMBRAPA (1999) classification. The weather stations data was obtained from the Weather Stations located at the Rural Engineering Department and Exact Sciences Department at the University of the State of São Paulo, Brazil.

Results and Discussion

The model was made on scenarios of land uses from Córrego Rico Watershed (Table 1). The main land uses were: SC1: soil without vegetation; SC2: sugar cane on first Stage; SC3: sugar cane on second stage; SC4: sugar cane to harvest; SC5: mecaniuzed harvest; FRST: native forest; WATER: water; URBAN: urban areas e PASTURE: pasture (Tabela 1).

Tabela 1. Land uses at Córrego Rico and Córrego Tijuco watersheds; San Paulo State, Brazil to SWAT model - *Soil and Water Assesment Tool.*

Uso do Solo	Area [ha]	% .Area
SC1 --> SC1	6779.15	12.04
SC2 --> SC2	14959.94	26.57
SC3 --> SC3	3540.08	6.29
SC4 --> SC4	3128.54	5.56
SC5 --> SC5	6370.21	11.31
Forest-FRSE	3472.93	6.17
Water --> WATR	121.93	0.22
Pasture --> PAST	3693.62	6.56
Sugarcane --> SUGC	14247.27	25.3
Total	56313.68	

The study indicated that urban and suburban development significantly affected the magnitude the erosion process. Basin to basin variation in size of the average of the LS parameter of the Soil Loss Equations (Table 1.)

Sub	Area(ha)	Length(km)	Soil	CPMN	USLE_K	USLE_LS
1	270.28	3.4	PVA4	SC1	0.07	1.82
2	217.68	2.55	PVA4	SC1	0.07	1.67
3	214.44	2.49	PVA4	SC5	0.07	1.25
4	74.72	1.63	PVA4	SC5	0.07	1.64
5	810.28	5.27	PVA4	SC5	0.07	1.73
6	388.28	3.56	PVA4	SC1	0.07	1.95
7	411.48	3.9	PVA4	SC5	0.07	1.58
8	265.32	3.08	PVA4	SC5	0.07	1.31
9	103.32	1.82	PVA4	SC5	0.07	1.5
10	875.2	5.31	PVA4	SC5	0.07	1.42
11	18.96	0.96	PVA4	SC5	0.07	1.5
12	98.92	1.75	PVA3	SC5	0.06	1.36
13	191.28	2.87	PVA4	SC5	0.07	1.1
14	243.28	2.5	PVA3	SC5	0.06	1.03
15	223.84	3.4	PVA4	SC5	0.07	1.15
16	711.48	5.84	PVA4	SC5	0.07	1.31
17	212.28	2.74	PVA4	SC5	0.07	0.84
18	365.8	3.53	PVA3	SC5	0.06	0.98
19	747.88	5.15	LV45	SC5	0.04	0.87
20	162.52	2.52	LV45	SC5	0.04	0.9
21	224.2	2.57	LV45	SC5	0.04	0.84
22	401.92	3.8	LV45	SC5	0.04	0.76
23	596.32	4.91	LV45	SC5	0.04	0.82

The results of this study indicated that, the highest LS factor occurs at hillslopes areas, at PVA4 soil unit. Changes in land uses contributed to hillslope erosion. In the area, agricultural land use increased the sediment yield. This conclusion was enforced by the K factor and sediment delivery to the river. It will be necessary to cover the area along the drainage net, indicating restabilization of hillslopes following reforestation.

Conclusion

The model has identified the erosion sources spatially and determined the main areas that has a major concern for erosion process.

Acknowledgements
To Dr. Kati White Migliaccio and Dr. Yuncong Li from the University of Florida/TREC;
To UNESP/FCAV for financial research support.

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Modelagem de erosão laminar em bacia hidrográfica utilizando geoprocessamento: estudo de caso da microbacia do Rio Uraim, Pará - Brasil

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Abstract

The hydrous erosion is a natural process that jointly with other processes are responsible for the modelling of the terrain. However the inadequate agricultural practices and the disordered occupation of the soil facilitate and accelerate this process turning it an agent of destruction of the primary productivity and of the fertility of the soil, in addition to impacting the hydrous bodies for the sedimentation on river bed action. In this scenery the mathematical models appear, fast and economical methods capable to esteem the erosion, among them the Universal Equation Loss Soil (USLE) that esteems the quantitative of loss soil by the correlation of the following factors: rainfall erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), covering and handling (C), conservationist practices (P). In this sense the present work intended to measure the annual loss of soil in the micro watershed of Uraim river (relevant spring for the municipal district of Paragominas) for the years of 1984 and 2010, through the application of the USLE. Starting from the comparative analysis of the values in the two years of studying of soil loss, it was checked that even with *considerable increase of the erosive processes which resulted in the elevation of the loss annual average of soil of 23,034 (t.ha-1.year-1) in the year of 1984 to 36,694 (t.ha-1.year-1) in the year of 2010, the annual classification of soil loss for the two analyzed years it was the same, medium (15 to 50 t.ha-1.year-1), because of the low values found to the erodibility of the soil (K) and topographical factor (LS).*

Keywords: USLE. Environmental modeling. Geographic information system.

Introdução

No seu aspecto físico, a erosão é a simples realização de uma quantidade de trabalho que desprende e carreia material do solo, este trabalho é realizado por agentes com potencial cinético, como a chuva e os ventos. No caso da chuva, a capacidade erosiva está diretamente relacionada com a energia cinética das gotas de água bem como o volume de precipitação em uma determinada área, neste caso o impacto da gota da chuva desprende as partículas do solo enquanto o escoamento superficial é o maior agente transportador (BERTONI; LOMBARDI NETO, 2010).

A erosão hídrica é um fenômeno natural responsável pela modelagem do relevo. Este fenômeno é causado pela ação de agentes naturais sendo, portanto, denominada de erosão geológica ou lenta. Porém as práticas agrícolas inadequadas, o pastoreio esgotante, a exploração indiscriminada das florestas e a ocupação desordenada do solo facilitam e aceleram este processo, tornando-o um agente de destruição da produtividade primária, da fertilidade do solo e impactando os corpos hídricos pela ação de assoreamento. Quando há interferência antrópica, a erosão hídrica passa então a ser denominado de erosão acelerada (VALENTIN, 2008).

A erosão acelerada do solo tem uma relação direta com a escassez de alimentos e com a fome, sendo de fundamental importância, a luta contra o processo erosivo, principalmente quando este se manifesta na forma de erosão laminar, que age de forma pouco perceptível, reduzindo progressivamente a produtividade do solo, carreando silenciosamente a camada mais ativa, rica em matéria orgânica, micronutrientes e macronutrientes por meio de enxurradas caracteristicamente barrentas (BERTONI; LOMBARDI NETO, 2010).

Este trabalho propõe-se em estimar a perda anual de solo por erosão laminar na microbacia do rio Uraim para os anos de 1984 e 2010, por meio da utilização de técnicas de geoprocessamento e aplicação da Equação Universal de Perda de Solo (EUPS).

Materiais e Métodos

A microbacia hidrográfica do rio Uraim (Figura 01), localizada na mesorregiões paraenses, está distribuída entre os municípios de Paragominas e Nova Esperança do Piriá. O clima é classificado como mesotérmico e úmido com temperatura média anual de 25ºC e umidade relativa do ar em torno de 85%, predominam os latossolos amarelos e possue relevo predominantemente plano a suavemente ondulado com altitude média de 20 metros (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2010). (NUNES, 2011).

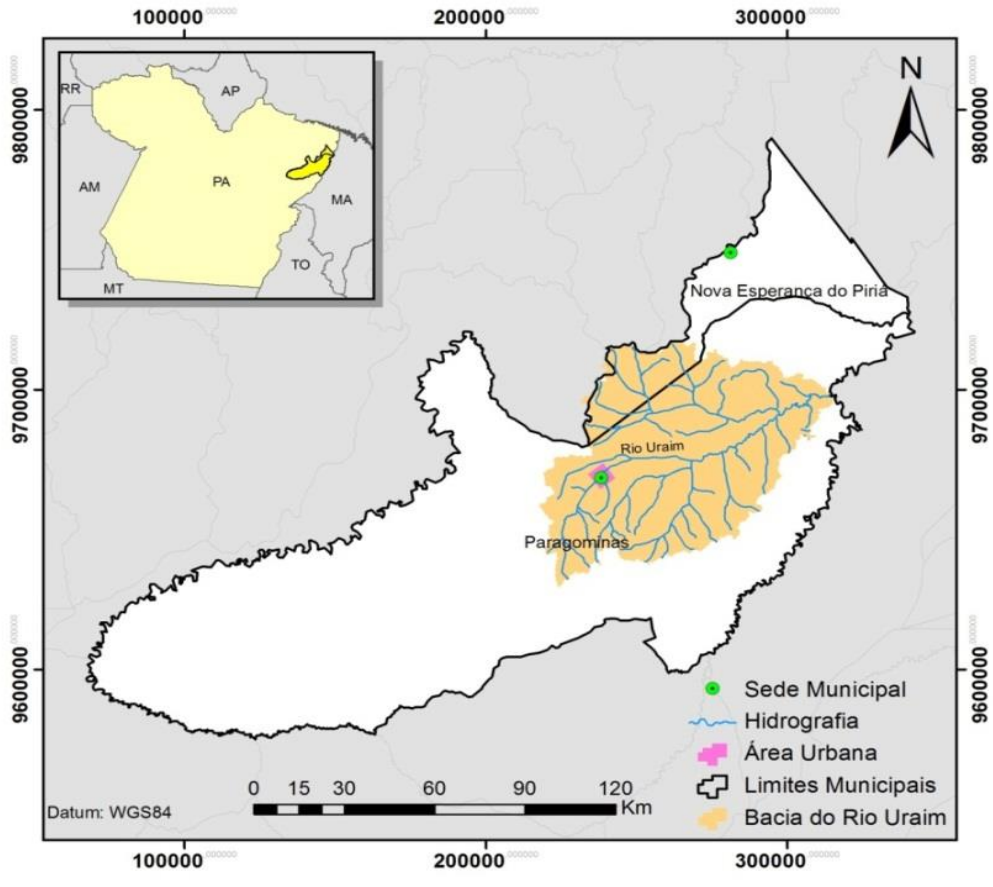

Figura 1 – Localização da Área de Estudo: Bacia do Rio Uraim.

A base de dados foi composta de material cartográfico vetorial, imagens de sensores remotos e modelo digital de elevação (MDE). Toda a base de dados foi georrefenciada utilizando o *Datum World Geodetic System* 1984 (WGS84) e projetada no sistema Universal Transversa de Mercator (UTM), fuso 23 sul (FEITOSA, 2006; VALLE JUNIOR, 2008).

Os materiais cartográficos em formato *shapefile* foram obtidos de diversas fontes, classificação dos solos (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA, 1999), divisão geopolítica (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2012), drenagem fluvial e localização de estações pluviométricas (AGÊNCIA NACIONAL DE ÁGUAS, 2012).

As imagens orbitais foram obtidas no catálogo de imagens disponibilizado pela Divisão de Geração de Imagens do Instituto Nacional de Pesquisas Espaciais (DGI/INPE), as imagens do sensor *Thematic Mapper* (TM) do satélite Landsat V, bandas espectrais 3, 4 e 5, referentes aos anos de 1984 e 2010.

O MDE utilizado foi oriundo do *Shuttle Radar Topographic Mission* – SRTM - (ARAÚJO, 2006; JARVIS et al, 2008; VALENTIN, 2008).

Para realização da modelagem de erosão foram utilizados os softwares GRASS GIS 6.4 (licença livre), ArcGIS 10 (licenciado para a UFRPE) e Hidro 1.0 (GRASS, 2011; ENVIROMENTAL SYSTEMS RESEARCH INSTITUTE, 2010; AGÊNCIA NACIONAL DE ÁGUAS, 2009).

Utilizou-se o algoritmo Topogrid referenciado nos estudos de Hutchinson (apud VALENTIN, 2008) com finalidade de refinar e tratar os dados altimetricos do SRTM. Para possibilitar a aplicação, o MDE oriundo dos dados SRTM refinados, foi desdobrado em planos de informações de variáveis morfométricas, altimetria, declividade e áreas de acumulação de fluxo. Os dados morfométricos foram utilizados na delimitação da microbacia do rio Uraim e na correção de imagens de satélite (ARAÚJO, 2006).

Foi utilizada a EUPS para estimar a perda de solo por erosão laminar na área de estudo. Para o cálculo do Fator R(erosividade da chuva) na microbacia do rio Uraim foram utilizados dados de 18 estações pluviométricas localizadas dentro e no entorno da mesma. O critério para seleção destas estações pluviométricas levou em consideração a existência de registros pluviométricos no período de 1990 até 2010, possibilitando assim a obtenção de uma série histórica de 20 anos. Os dados de precipitação para cada estação foram obtidos do Sistema de Informações Hidrológicas (Hidroweb) disponibilizado pela Agência Nacional de Águas (2012).

Os valores do fator K (relação entre perda de solo e o Fator R) relacionados aos solos encontrados na área de estudo são oriundos de compilação de valores disponíveis em literaturas referentes a unidades pedológicas semelhantes.

O fator topográfico (LS) - Fator Topográfico de comprimento de declive (L) foi obtido a partir do MDE no SIG GRASS (HENGL; REUTER, 2009) e gradiente de declividade (S) por meio de álgebra de mapas adotando-se os coeficientes m=0,4 e n=1,3 (NETELER e MITASOVA 2005).

Com o objetivo de espacializar a erosão laminar por meio de geoprocessamento, as variáveis C (Variável Antrópica de Uso e Cobertura do Solo) e P (Práticas Conservacionistas) podem ser analisadas de forma conjunta em função do uso e cobertura vegetal. Adotou-se a o fator P como uma constante igual a 1, representado o pior cenário possível de perda de solos, não considerando a existência de práticas conservacionistas tendo em vista a dificuldade de obtenção de um valor confiável de P quando se utiliza técnicas de geoprocessamento (ALVES, 2000; VALLE JUNIOR, 2008). O fator C foi obtido por meio de equação com regressão linear sobre NDVI (Índice de Vegetação pela Diferença Normalizada) (CORRÊA; PINTO, 2011; KARABURUN, 2010).

As imagens do *Landsat* V utilizadas neste trabalho, foram submetidas às seguintes técnicas de Processamento Digital de Imagens (PDI), correção geométrica, conversão dos valores de pixels em radiância, correção atmosférica e retificação radiométrica.

Resultados e Discussão

A precipitação média anual na microbacia do Uraim e em seu entorno no período considerado (1990 a 2010), foi de 1856,678 mm, apresentando uma estação chuvosa de dezembro a junho e uma estação seca de julho a novembro, e os meses de março e abril, apresentaram a maior intensidade pluviométrica: 368,133 mm e 335,098 mm respectivamente.

Constatou-se que ocorreu uma concentração do potencial erosivo na estação chuvosa, principalmente entre os meses de janeiro a maio (Figura 2). A erosividade da chuva no período chuvoso correspondeu a aproximadamente 93,84% do total anual, enquanto no período seco, esse valor foi de aproximadamente 6,15%.

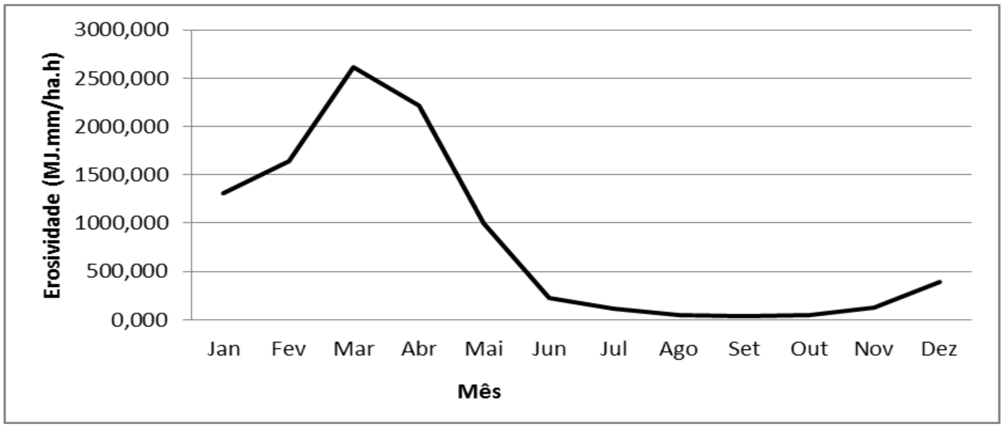

Figura 2 - Distribuição Mensal da Erosividade (EI30) nas microbacia do Uraim.

A distribuição espacial do fator R para a microbacia do rio Uraim está representada na Figura 3, e possui valores de erosividade que variam entre 8658 a 10213 MJ.mm/ha.h e a média anual de erosividade é 9534,22 MJ.mm/ha.h.

As unidades de mapeamento de solos que ocorrem na microbacia do Rio Uraim são Latossolos Amarelos, Plintossolos e Argilossolos Vermelho Amarelos. Na Tabela 1 verifica-se os valores de K para os solos citados assim como sua cobertura na microbacia e sua fonte. A Figura 4 representa a distribuição espacial dos três valores do fator K encontrado na Microbacia.

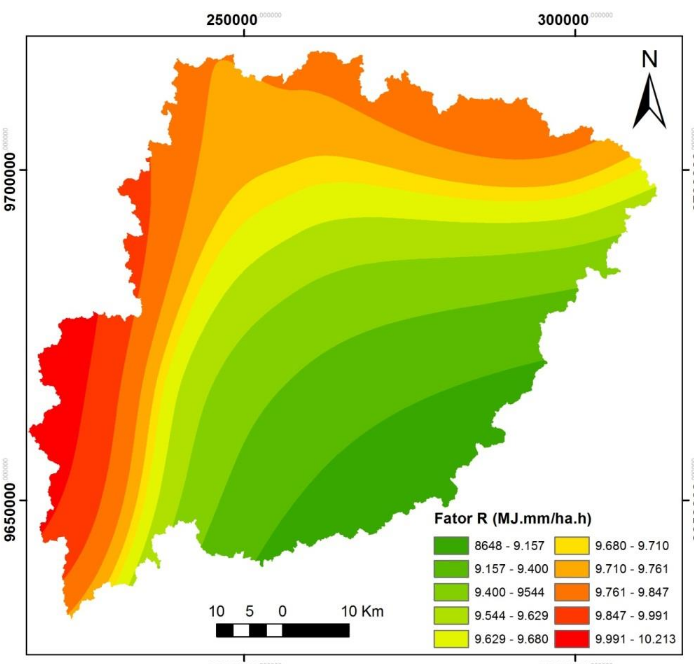

Figura 3 - Distribuição espacial do fator R.

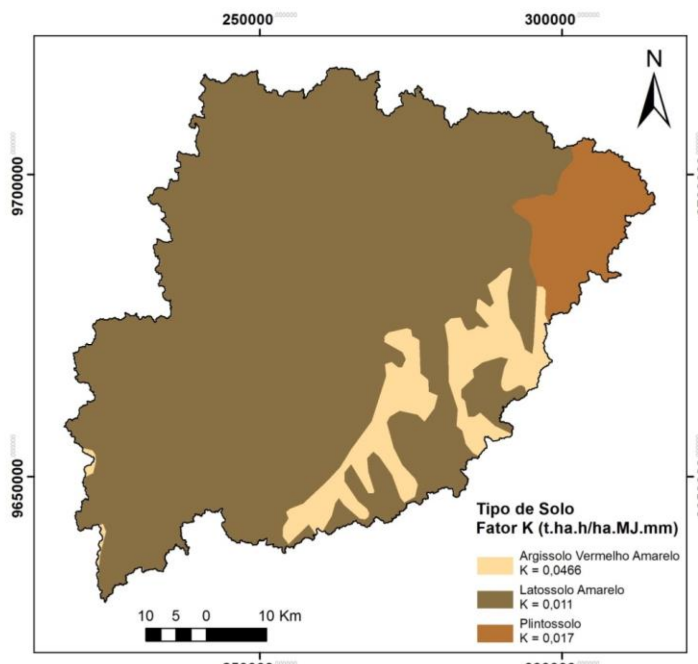

Figura 4 - Distribuição das unidades de mapeamento de solos da microbacia do Uraim

Tabela 1 – Unidades de mapeamento de solos e fator K da microbacia do Uraim.

Solos	Fator K (t.ha.h/ha.MJ.mm)	Área (ha)	%	Fonte
Latossolo Amarelo	0,011	428.511,80	84,16	(OLIVEIRA, 2009)
Plintossolo	0,017	35.213,20	6,92	(MARTINS et al., 2011)
Argilossolo Vermelho Amarelo	0,0466	45.415,30	8,92	(MANNIGEL et al., 2002)
Total	-	509.140,30	100	-

O fator topográfico (LS) apresentou a média de 1,6167 na microbacia do rio Uraim, os resultados obtidos estão tabulados em 7 (sete) classes do fator LS apresentados na Tabela 2. Os resultados do fator topográfico também foram espacializados em forma de carta de distribuição espacial (Figura 5).

Tabela 2 - Fator Topográfico (LS)

Fator LS (adimensional)	Área (ha)	Cobertura Relativa (%)
0 – 1	181.220,00	35,59
1 – 2	17.8875,30	35,13
2 – 3	61.290,00	12,04
3 – 4	28.218,00	5,54
4 – 5	15.996,00	3,14
5 – 10	31.503,00	6,19
10 – 70	12.038,00	2,36
Total	509.140,30	100,00

A partir dos resultados obtidos, é possível observar o predominiode duas classes do fator LS: a classe com valores entre 0 – 1 e a classe entre 1- 2. Estas duas classes, totalizam juntas, uma área de 360.093,42 ha, o que representa 70,71% da cobertura da área total da microbacia. Observou-se também a grande relação do fator LS com a declividade, estando em conformidade com a afirmação de Valentin (2008), de que o gradiente de declividade é o mais importante elemento no condicionamento da origem e evolução do processo erosivo. No mapa de declividade classificado segundo as normas da Empresa Brasileira de Pesquisa Agropecuária (1999), predominaram as classes de relevo plano e de relevo suave ondulado (Figura 6), que possuem juntas uma área de 425.826,18 Hectares (ha), o que representa 83,64% da cobertura total da área da microbacia (Tabela 3), e estas características do relevo explicam a predominância de locais com baixos valores do fator LS.

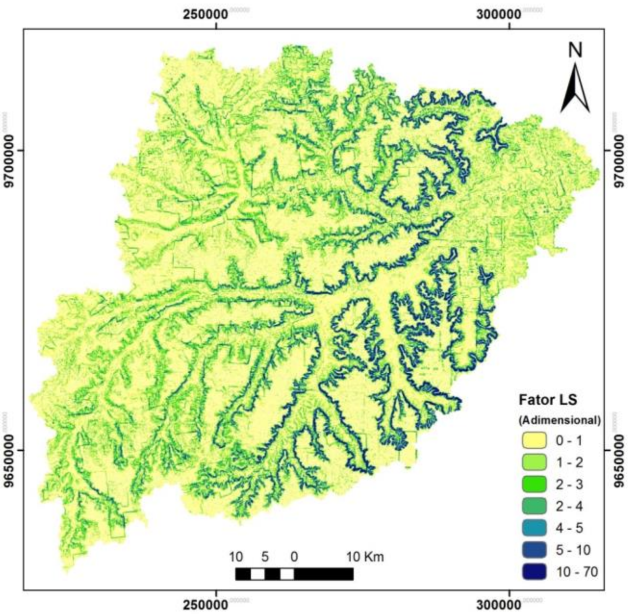

Figura 5 - Distribuição espacial do fator LS modificado.

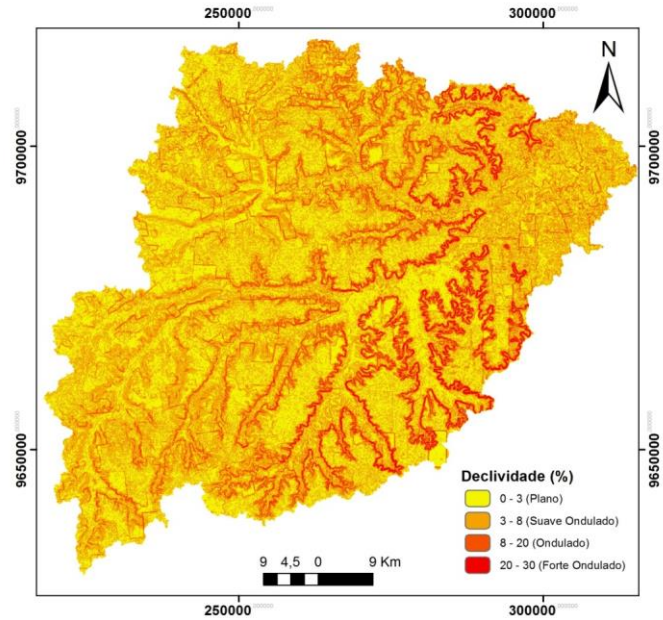

Figura 6 – Classes de Relevo e Declividade da microbacia do rio Uraim.

Tabela 3 - Classes de Relevo e Classes de Declividade.

Classe de Relevo*	**Classe de Declividade* (%)**	**Área (ha)**	**Cobertura Relativa (%)**
Plano	0 a 3	182.787,20	35,90
Suave Ondulado	3 a 8	243.046,00	47,74
Ondulado	8 a 20	69.436,10	13,64
Forte Ondulado	20 a 45	13.871,00	2,72
Total		509.140,30	100,00

Comparando as Figuras 5 e 6 percebe-se ainda, que há uma grande semelhança visual entre o mapa do Fator LS e o mapa de declividade principalmente nas áreas dos divisores de drenagem e locais de mudanças na orientação de vertentes. É possível observar que nas áreas de fluxo convergente e nas áreas de maior declividade das vertentes os valores do fator LS tendem a ser mais elevados enquanto nas áreas de menor declividade e de fluxo divergente os valores do fator LS são menos elevados, este resultado demonstra claramente a eficiência do método desenvolvido por Moore e Burch (apud VALENTIN, 2008) em descrever o fator topográfico diante da complexidade do relevo.

Segundo Stein et al. apud Borges (2009), os valores de CP entre 0 a 0,1 estão associados a terrenos com cobertura total por formações florestais tais como floresta nativa, mata ciliar, floresta em regeneração e reflorestamento, estas classes de cobertura são as que propiciam a melhor proteção do solo contra os processos erosivos. Na microbacia do rio Uraim estas classes foram predominantes em ambos os cenários estudados, entretanto houve uma grande redução no ano de 2010 na representatividade em áreas ocupadas por estas. Pode-se observar na Tabela 4, que estas classes representavam 67,86% em 1984 e reduziram-se a 48,56% da área total da microbacia em 2010.

Tabela 41 - Valor de CP nos cenários analisados

Fator CP (adimensional)	**Cenário de 1984**		**Cenário de 2010**	
	Área (ha)	**Área (%)**	**Área (ha)**	**Área (%)**
0,0 - 0,1	345.478,40	67,86	247.215,60	48,56
0,1 - 0,2	110.881,80	21,78	119.405,50	23,45
0,2 - 0,3	32.341,10	6,35	56.697,20	11,14
0,3 - 0,4	12.467,70	2,45	32.030,10	6,29
0,4 - 0,5	3.908,70	0,77	16.655,50	3,27
0,5 - 0,6	1.785,40	0,35	8.983,20	1,76
0,6 - 0,7	1.033,90	0,20	6.256,80	1,23
0,7 - 0,8	687,60	0,14	6.885,30	1,35
0,8 - 0,9	310,80	0,06	8.864,70	1,74
0,9 - 1,0	244,90	0,05	6.146,40	1,21
Área Total	**509.140,30**	**100**	**509.140,30**	**100,00**

As classes de fator CP com valores entre 0,1 a 0,5 estão particularmente associadas ao uso e ocupação das áreas por atividade de pecuária, práticas agrícolas diversas e por vegetação natural muito degradada. Já as áreas que possuem valores do fator CP situados entre 0,5 a 1,0 estão associadas ao uso e ocupação do solo por áreas urbanas, desmatamentos, vegetação degradada com cobertura pouco densa e solo exposto. No caso do solo exposto, os valores do fator CP são bastante próximos de 1,0 (ARAÚJO, 2006; GURGEL, 2011; VALENTIN, 2008). No ano de 1984, as classes de uso e ocupação de menor capacidade de proteção do solo com maior representatividade em área ocupada, possuem valores de CP maiores que 0,1 e menores que 0,3, ocupando 28,13% do total da área da microbacia. No ano de 2010 as áreas cujo valor do fator CP está situado entre 0,4 a 1,0 aumentaram expressivamente em representatividade em relação ao cenário de 1984, evidenciado uma maior quantidade de áreas de vegetação degrada, ocupação urbana e de solo exposto.

Na Tabela 5, verifica-se que na microbacia fora sem predominantes as áreas com baixo PNE, representando 52,81% da área total da microbacia. Estes resultados estão associados ao relevo plano e suave ondulado e de solos profundos (latossolo amarelo) com baixa erodibilidade que são condições predominantes nesta microbacia hidrográfica.

Tabela 5 - Classes do potencial natural de erosão para a microbacia do rio Uraim.

Classes do PNE*	**PNE ($t.ha^{-1}.ano^{-1}$)***	**Área (ha)**	**Cobertura Relativa (%)**
Baixo	0 -100	268.888,78	52,81
Médio	100,1 - 200	101.230,17	19,88
Alto	200,1 - 600	93.823,79	18,43
Muito Alto	600,1 - 1000	20.007,60	3,93
Extremamente Alto	>1000,1	25.190,02	4,95
Total	-	509.140,30	100,00

As áreas com PNE igual ou acima de alto representam 27,31% da área total da microbacia e comparando a Figura 6 com a Figura 7, verifica-se que nas áreas onde predominam os altos valores do PNE são as áreas com relevo mais movimentado (ondulado e forte ondulado) com argissolo vermelho amarelo, este fato evidencia a inter-relação existente entre PNE com o relevo e solos conforme afirma de Valle Junior (2008). As pequenas áreas com alto valor do PNE ocorrem associadas às nascentes, principalmente as mais ramificadas, aos divisores de água mais elevados e aos entalhes nos vales.

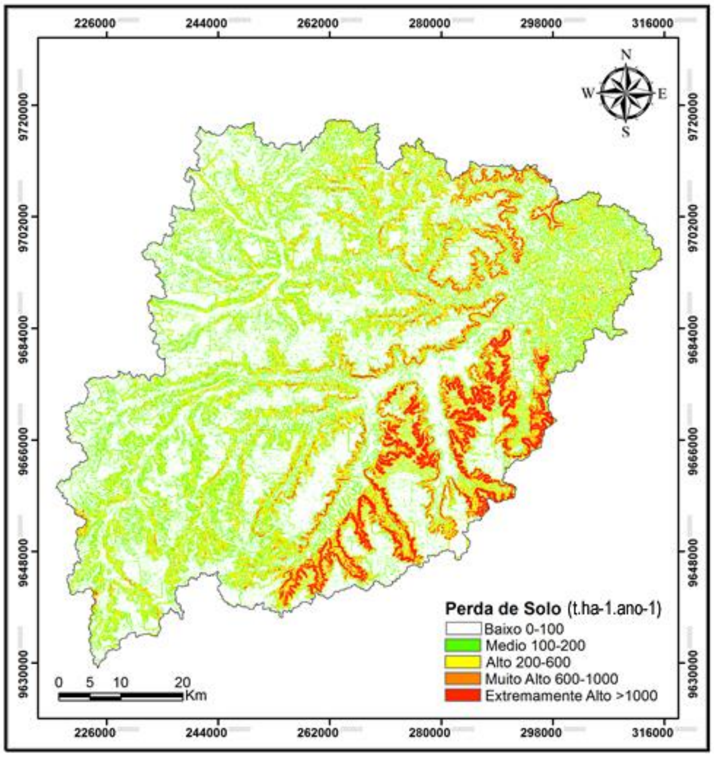

Figura 7 – Potencial Natural de Erosão na microbacia do rio Uraim.

Adotando-se a classificação de Valle Junior (2008), onde as perdas de solo ($t.ha^{-1}.ano^{-1}$) são consideradas como sendo: menor que 10, nula a pequena; de 10 a 15, moderada; de 15 a 50, média; de 50 a 120, média forte; de 120 a 200, forte e maior que 200, muito forte, geraram-se as Tabelas 6 e 7, nas quais se evidencia que na microbacia hidrográfica do rio Uraim é predominante a classe de perda solo "nula a pequena". Esta classe de perda de solo corresponde a 312.314,61 ha para o ano de 1984, o que representa 61,34% área total da microbacia (Tabela 6). Para o ano de 2010 a classe predominante de perda de solo corresponde a 256.399,88 ha, o que representa 50,36% da área total da microbacia (Tabela 7).

A partir do comparativo das Figuras 8 e 9 e das Tabelas 6 e 7, percebe-se que no ano de 2010 houve aumento de áreas com perda de solo "Forte" (120-200 ton.ha/ano) e "Muito Forte" (> 200 $t.ha^{-1}.ano^{-1}$), o que contribuiu para a elevação da perda média de solo de 23,034 $t.ha^{-1}.ano^{-1}$ no ano de 1984, para 36,694 $t.ha^{-1}.ano^{-1}$ no ano de 2010, portanto houve um incremento de 13,660 $t.ha^{-1}.ano^{-1}$ (Tabela 8). Este aumento na perda média de solo segundo Valle Junior (2008), pode ser explicado pela intensificação da dinâmica de uso e ocupação do solo, fato que ocorreu na microbacia no intervalo analisado, sendo tal retratado pelo aumento dos valores do fator CP.

Tabela 6 – Erosão Laminar no ano de 1984

Erosão Anual*	**A ($t.ha^{-1}.ano^{-1}$)***	**Área (ha)**	**Cobertura Relativa (%)**
Nula a pequena	< 10	312.314,61	61,34
Moderada	10 a 15	48.748,93	9,57
Média	15 a 50	99.585,56	19,56
Média forte	50 a 120	30.581,34	6,01
Forte	120 a 200	8420,16	1,65
Muito Forte	> 200	9489,75	1,86
Total	-	509.140,36	100,00

Tabela 7 - Erosão Laminar no ano de 2010

Erosão Anual*	**A ($t.ha^{-1}.ano^{-1}$)***	**Área (ha)**	**Cobertura Relativa (%)**
Nula a pequena	< 10	256.399,88	50,36
Moderada	10 a 15	44.076,73	8,66
Média	15 a 50	120.218,22	23,61
Média forte	50 a 120	54.762,07	10,76
Forte	120 a 200	16.652,22	3,27
Muito Forte	> 200	17.031,22	3,35
Total	-	509.140,36	100,00

Tabela 8 - Erosão Laminar anual Média em 1984 e 2010.

Ano	**Média A ($t.ha^{-1}.ano^{-1}$)**
1984	23,034
2010	36,694
Incremento	13,660

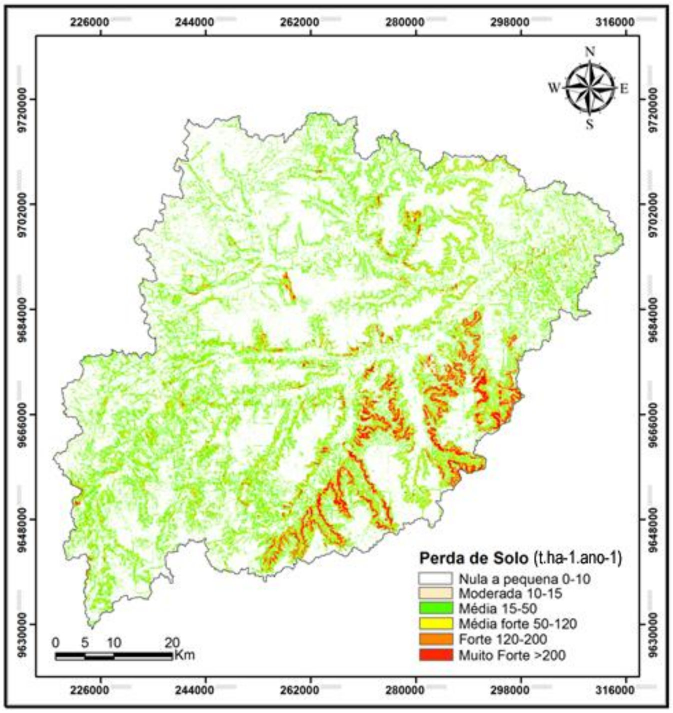

Figura 8 – Perda anual de solo na microbacia do rio Uraim no ano de 1984.

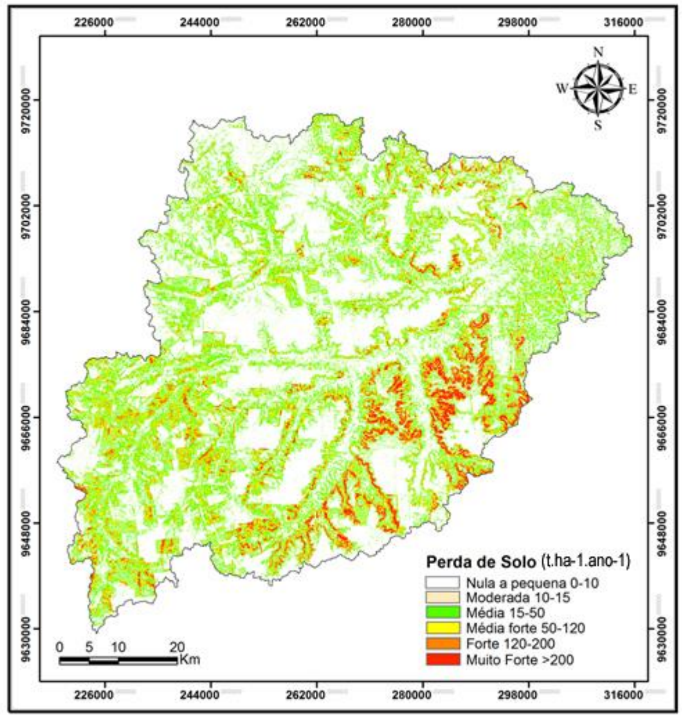

Figura 9- Perda anual de solo na microbacia do rio Uraim no ano de 2010.

Conclusão

O método utilizado para o cálculo do fator LS modificado, permitiu estimar este parâmetro com maior detalhamento e representatividade espacial, assim como o método para o cálculo do Fator CP baseado na equação de regressão do NDVI, permitiu estimar os valores deste parâmetro rapidamente e uma grande área.

A aplicação da EUPS na microbacia do rio Uraim possibilitou a determinação da perda anual de solo para os anos de 1984 e 2010, evidenciando assim a intensificação de processos erosivos ocorrido no período, corroborado pelo aumento da perda anual média de solo de 13,66 $t.ha^{-1}.ano^{-1}$ encontrada para o ano de 2010 em relação a 1984.

Para os dois anos analisados 1984 e 2010, a classe de perda anual de solo predominante encontrada na microbacia foi a "baixa ou nula" (0-10 $t.ha^{-1}.ano^{-1}$).

A redução da representatividade das classes que melhor protegem o solo significa que houve a conversão das formações vegetais descritas em outras classes de uso e ocupação que promovem uma menor proteção contra os processos erosivos.

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Spatial distribution of corn water requirements in the Sao Paulo state, Southeast Brazil

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Abstract

Landsat satellite images and agrometeorological data were used together for modelling the actual evapotranspiration (ET) and crop coefficient (K_c) in irrigation pivots composed with a mixture of corn hybrids from a commercial farm for grains and silage. The daily ET averaged values were between 1.1 and 4.4 mm day^{-1}. After developing relationships between K_c and the accumulated degree-days (DD_{ac}) they were applied in the Sao Paulo state to obtain the large-scale water requirements (WR) inside the corn growing regions, during the growing seasons (GS) from March to August. Highlights are for the "Presidente Prudente", with the highest averaged pixel WR values of 400 and 350 mm GS^{-1} for respectively grain and silage production. The lowest ones were for "Itapetininga", which presented averages of 310 and 255 mm GS^{-1}. The results from the current research are useful for planning the corn water productivity improvements, according to the commercial purpose, including both, irrigation and rainfed conditions.

Keywords: Evapotranspiration, degree-days, crop coefficient.

Introduction

In the Southeast region of Brazil, one of the main crops is corn (*Zea mays L.*), which has been realized in two times of the year. The first-harvest crop is between October and November, with the seed sown at the start of the rainy periods, whiles the second-harvest crop, this is done from February to March. In both case, the purposes are either for human consumption or for animal feed.

Soil moisture is important to maintain yield at optimum levels, being the water deficit, the main climatic risk for the second-harvest corn crop, which is attenuated in high-altitude areas (Ko e Piccinni, 2009). Water stress can affect the vegetative growth, crop development and the physiological processes, reducing yield, which, in turn, is a linear function of the actual evapotranspiration – ET (Traore et al., 2000; Payero et al., 2006).

Knowledge about water variables on a large scale is important when aiming the rational management of the natural resources. For this purpose, tools such as remote sensing from satellites and Geographic Information Systems (GIS) can be used (Teixeira, 2010).

Corn crop and its growing regions in the Brasilian Southeast region are inside of the priority contexts from the national Ministry of Agriculture, aiming the development and applications of Earth observations to assess agricultural climatic risks, based on agrometeorological indicators.

For the current study, due to its applicability, the SAFER (Simple Algorithm For Evapotranspiration Retrieving) algorithm (Teixeira et al., 2013, 2014) was used to estimate ET. To take into account the corn water requirements (WR), specific relations for grains and silage between crop coefficients (Kc) and the accumulated degree-days (DD_{ac}) were elaborated, similarly with has been done for grapes in the Brazilian Northeast (Teixeira et al., 2022).

The objective of the current research was to combine geo technologies for modeling the corn water variables on a large scale, for both commercial goals, grains and silage production, in the growing regions of Sao Paulo State, Southeast Brazil, to subsidize improvements on the water productivity, under the conditions of rapid increase of corn second-harvest crop. Modelling is done in irrigated pivots of a reference farm in the Northwesten side and later up scaling the corn water requirements to the entire State, with emphasizes in the main corn growing regions.

Material and Methods

Figure 1 presents the location of the São Paulo state in the Southeast Brazil, corn growing regions, the agrometeorological stations used, and the corn central-pivots in the “Bonança” commercial farm, where the Landsat images where used for modelling.

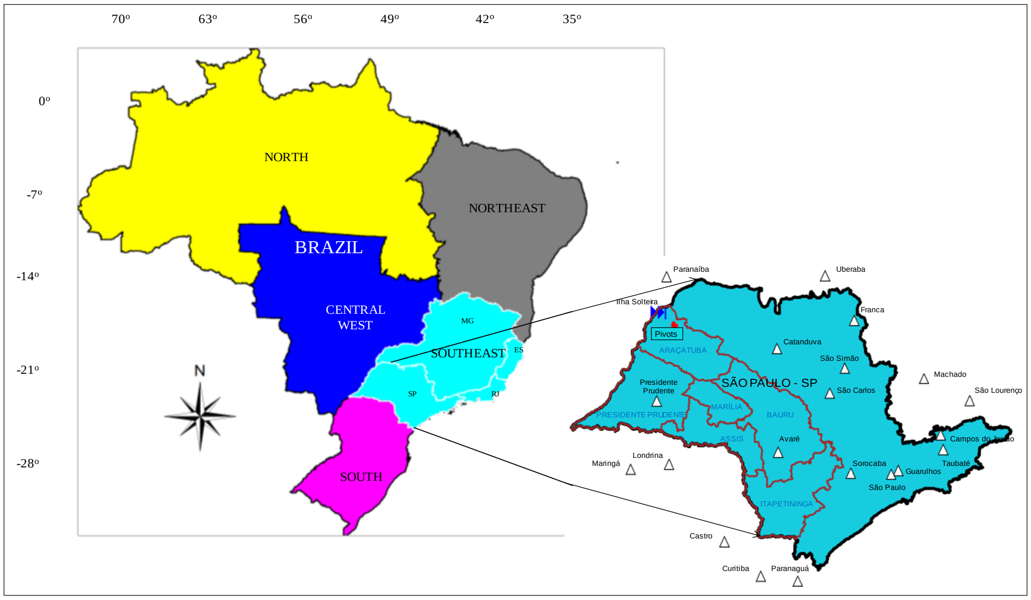

Figure 1. Location of the São Paulo state, highlighting corn growing regions, the agrometeorological stations used, and the corn central-pivots of “Bonança” farm where the Landsat images where used for modelling in the Southeast Brazil.

Data for 2010 from an agrometeorological station located in Ilha Solteira-SP were taken for ET and K_c modelling, throughout the application of the SAFER algorithm (Teixeira et al., 2013, 2014). Landsat 5 images for the days 03/22, 04/07, 04/23, 06/10, 06/26, 07/12 and 08/29 were used for this year, together with temporal interpolations of these images covering complete corn crop growing seasons for each corn irrigation pivot in the “Bonança” commercial farm.

After developing specific regression equations, which relate the crop coefficients (K_c), with the accumulated degree-days (DD_{ac}), taking the basal temperature (T_b) as 10°C (Teixeira et al., 2012), the equations were applied together with weather data for the year 2012, from 20 agrometeorological stations of the National Meteorological Institute (INMET) in the Southeast Brazil, involving Sao Paulo State (see Figure 1). With interpolation of these data in the entire State, the spatial distribution of the corn water requirements (WR) for grains and for silage were up scaled, extracting the main corn crop growing regions for analyses.

In the current study, only the visible and the near infrared bands from Landsat 5 were used for ET estimations in the irrigation pivots, being the surface temperature (T_0) estimated as a residual in the radiation balance equation.

From Landsat 5 images, for retrieving α_0, firstly the planetary albedo for each satellite band (α_{p_b}) is calculated as:

$$\alpha_{p_{band}} = \frac{L_{band} \pi d^2}{R_{a_{band}} \cos\varphi} \quad (1)$$

where L_{band} is the spectral radiance for the wavelengths of the band, d is the relative earth-sun distance; $R_{a_{band}}$ is the mean solar irradiance at the top of the atmosphere for each band ($Wm^{-2}\mu m^{-1}$) and φ the solar zenith angle.

α_p is calculated as the total sum of the different narrow-band $\alpha_{p_{band}}$ values according to weights for each band (w_{band}).

$$\alpha_p = \sum w_{band} \alpha_{p_{band}} \tag{2}$$

The weights for the different bands are computed as the ratio of the amount of the incoming shortwave radiation from the sun in a particular band and the sum of incoming shortwave radiation for all the bands at the top of the atmosphere.
The daily values for surface albedo (α_0) according to Teixeira (2010):

$$\alpha_0 = a\alpha_p + b \tag{3}$$

where α_p is the planetary albedo and a and b are regression coefficients, which for a 24-hour period was considered as 1.70 and 0.13, obtained from field and satellites measurements (Teixeira et al., 2008,Teixeira, 2010).
NDVI is an indicator related to the land cover obtained from satellite images as:

$$NDVI = \frac{\alpha_{p_{(NIR)}} - \alpha_{p_{(RED)}}}{\alpha_{p_{(NIR)}} + \alpha_{p_{(RED)}}} \tag{4}$$

where $\alpha_{p_{(NIR)}}$ and $\alpha_{p_{(RED)}}$ represent the planetary albedo over the ranges of wavelengths in the near infrared (NIR) and red (RED) regions of the solar spectrum, respectively.

T_0 was estimated by:

$$R_n = RS\downarrow - \alpha_0 RS\downarrow - \varepsilon_0 \sigma T_0^{\ 4} + \varepsilon_a \sigma T_a^{\ 4} \tag{5}$$

where $RS\downarrow$ and T_a are the 24-hour values of the incident solar radiation and air temperature, R_n is the daily net radiation, ε_0 and ε_a are, respectively, the surface and atmospheric emissivities, and σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).
Following Teixeira (2010) ε_0 and ε_a were calculated as:

$$\varepsilon_0 = a_0 \ln NDVI + b_0 \tag{6}$$

$$\varepsilon_a = a_a (-\ln \tau_s)^{b_a} \tag{7}$$

where τ_s is the short-wave atmospheric transmissivity defined as the ratio of RS↓ to the incident solar radiation at the top of atmosphere, and a_0, b_0 , a_a and b_a are regressions coefficients which, from Teixeira (2010), were considered, respectively, 0.06, 1.00, 0.94 e 0.10.

The Slob equation was used for R_n:

$$R_n = (1-\alpha_0)RS\downarrow - a_l\tau_w \tag{8}$$

Because of the thermal influence on longwave radiation via the Stephan Boltzmann equation, previous study investigated whether the variations of the a_l coefficient from Eq. 8 could be explained by variations in 24 hours T_a (Teixeira et al., 2008):

$$a_l = cT_a - d \tag{9}$$

where c and d are regression coefficients found to be 6.99 and 39.93 (Teixeira, 2010).
Having calculated the SAFER input parameters, the ET was acquired from the 24-hour data on reference evapotranspiration (ET_0) by Penman-Monteith equation (Allen et al., 1998):

$$\frac{ET}{ET_0} = \exp\left[e + f\left(\frac{T_0}{\alpha_0 NDVI}\right)\right] \tag{10}$$

where e and f are the regressions coefficients, being 1.0 and -0.008, respectively, for the Sao Paulo Northwestern conditions (Hernandez et al., 2014).
The average values of ET/ET_0 in the buffered areas of the pivots gave the crop coefficient (K_c) values, allowing their relations with the accumulated degree-days (DD_{ac}):

$$K_c = gDD_{ac}^{\ 2} + hDD_{ac} + i \qquad (10)$$

where g, h and i are specific regression constants determined in the current research by the coupled use of satellite and weather measurements.
The spatial distribution of WR was then obtained, considering ET under potential conditions (Teixeira et al., 2012):

$$WR = K_c\ ET_0 \tag{11}$$

Results and Discussion

Figure 2 shows the ET spatial distribution for different Days of the Year (DOY) during the period of the commercial second-harvest corn crop from March to August 2010, in the "Bonança" farm, located in the Northwestern side of Sao Paulo State, Southeast Brazil. ET in each buffered pivot areas under optimum moisture conditions was considered as the ET potential conditions. The effects of characteristics that distinguish crop from grass are integrated into the crop coefficient (K_c) (Allen et al., 1998), which multiplied by ET_0 gave the corn water requirements (WR).

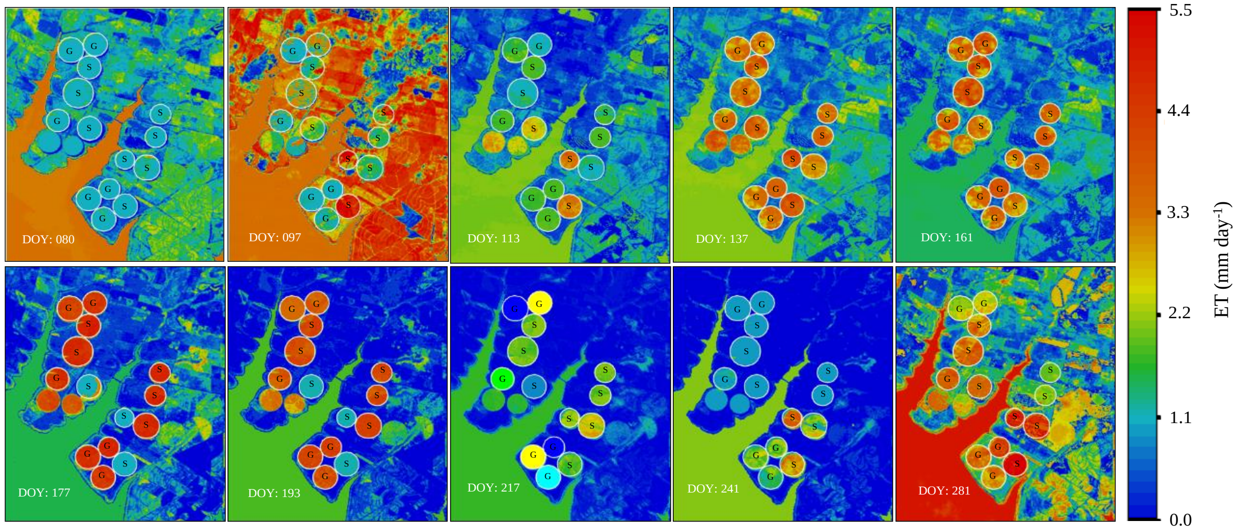

Figure 2. Daily actual evapotranspiration (ET) in irrigation pivots of the "Bonança" comercial farm, located in the Northwestern side of Sao Paulo State, Southeast Brazil. DOY means "Days of the Year" and the letters G and S inside the pivots are grains and silage, respectively.

For grains (G), the mean values of ET ranged from 1.5 to 4.4 mm day^{-1}, while for silage (S) they were between 2.8 and 3.9 mm day^{-1}. In the Northwestern China, Ding et al. (2013) found similar daily corn ET rates for grains, averaging 3.5 mm day^{-1}, through field experiments and modelling, giving confidence for the application of SAFER with the visible and infrared bands of the Landsat images in the current study.
The "Bonança" farm has pivots with corn, soybeans, beans and sugar cane. However, to relate K_c as a function of accumulated degree-days (DD_{ac}) for corn crop, the values of ET/ET_0 from SAFER results were used. It were considered the average pixel values inside the buffered area of six pivots of corn for grain (G) and eight for silage (S), under optimum soil moisture conditions and a basal temperature (T_b) of 10 ^oC (Figure 3).

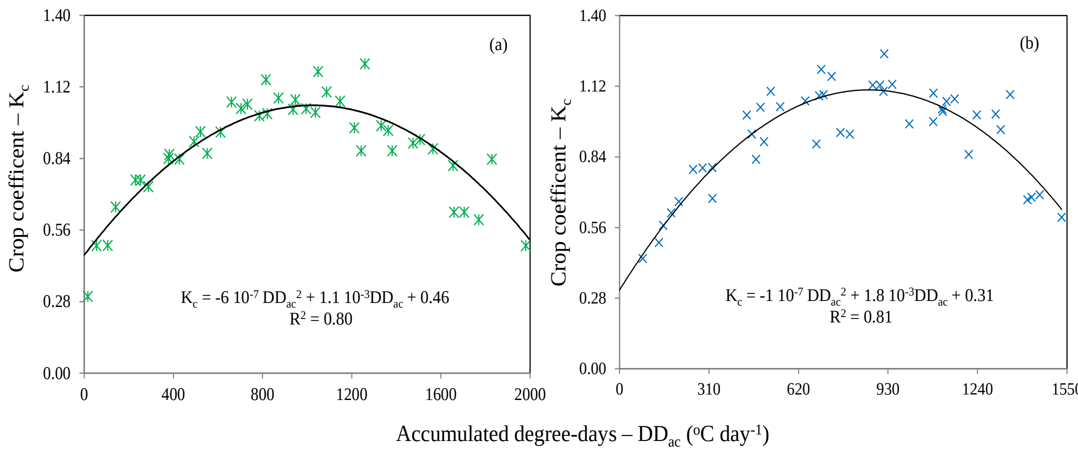

Figure 3. Relations between the average values of crop coefficient (K_c) and the accumulated degree-days (DD_{ac}) for corn crop in the Northwestern side of Sao Paulo State, Southeast Brazil. (a) for grains; (b) for silage. A basal temperature (T_b) of 10 ºC is considered.

K_c at different corn crop stages, were between 0.3 and 1.2. This range is in agreement with the values reported by DeJonge et al. (2012) during their ET modelling improvements in Colorado (USA) and with the tabled values of the standard work from Allen et al. (1998), what brings confidence for using the SAFER algorithm with acceptable accuracy without the thermal band. The advantage of using the equations depicted in Figure 3 is the possibility of up scaling K_c values to different thermal conditions (Teixeira, 2009). In the current research, they were applied to estimate the large-scale WR values, which is a key parameter for water productivity assessments.

Ten pivots were selected in the "Bonança" farm from Figure 2, to take as reference water consumptions, being five for grains and five for silage, to estimate ET for different growing seasons (GS). This is useful for comparisons with the corn growing regions of Sao Paulo State.

Figure 4 shows the spatial variations of the ET totals, in the Northwest side of São Paulo state, Southwest Brazil.

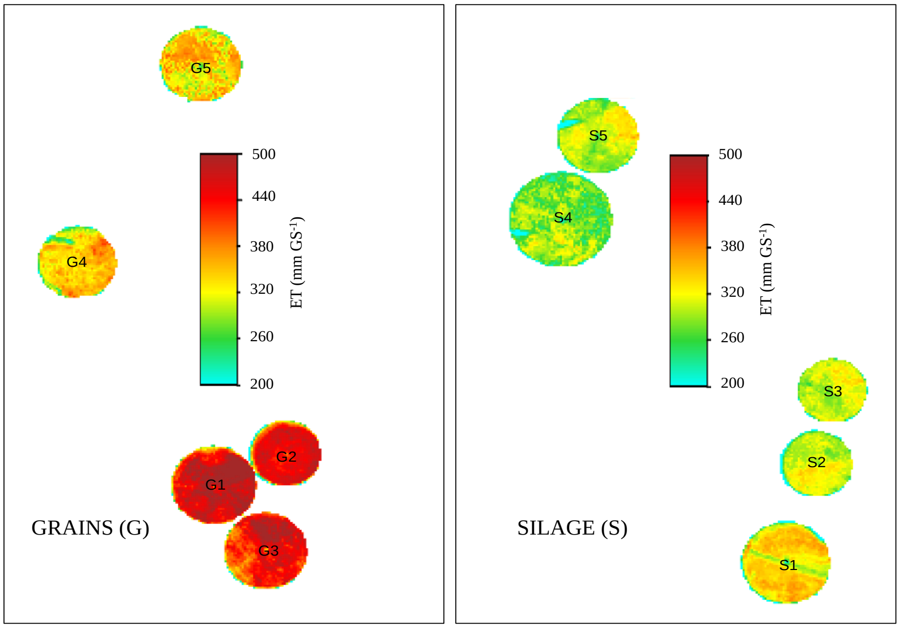

Figure 4. Spatial distribution of actual evapotranspiration (ET) for a growing season (GS) considering both commercial targets, grains (G) and silage (S), in the Northwestern side of São Paulo state, Southeast Brazil.

For both grains (G) and silage (S), the highest ET_{GS} values are for the pivots 1, 2 and 3, however for G1, G2 and G3 several pixels above 450 mm GS^{-1}, while for S1, S2 and S3 most of them are below 400 mm GS^{-1}. The highest water consumption for these pivots are due to the largest atmospheric demands involving periods ranging from DOY from 108 - 285 (mid-April to the first half of October) for grains and DOY from 105 - 241 (mid-April to end-August) for silage. The higher water consumption for grain than for silage, are due to the larger GS lengths, which were in average, respectively 160 and 120 days, what will affect ET depending mainly on the rainfall conditions along the growing seasons.

Equation 11 was applied to the grids of ET_0 in the entire Sao Paulo State (Figure 5), and the corn growing areas extracted for analyses of the WR for a second-harvest corn-growing season (GS).

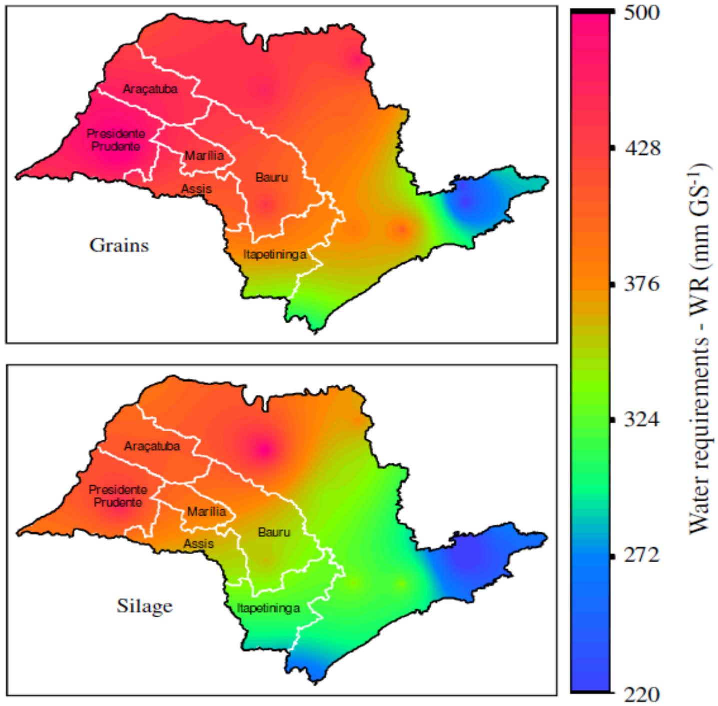

Figure 5. Spatial distribution of water requirements (WR) for a second-harvest corn-growing season (GS), from March to August 2012, in São Paulo state, Southeast Brazil, highlighting the corn growing regions.

Considering the entire Sao Paulo State, there is a WR gradient, with the low values from the coastal side, bellow 250 mm GS^{-1} to the west side of the State, where the values are higher than 400 mm GS^{-1}, for both, grains and silage productions. The highest values in the Northeastern side found for irrigated corn crop in the commercial "Bonança" farm agreed only in three pivots for grains from Figure 4, what could be an indication that the water applied though irrigation did not satisfied the corn water requirements, mainly in the case of silage.

The corn crop production growing regions were extracted from Sao Paulo State and the WR mean values together with standard deviations analyzed (Figure 6).

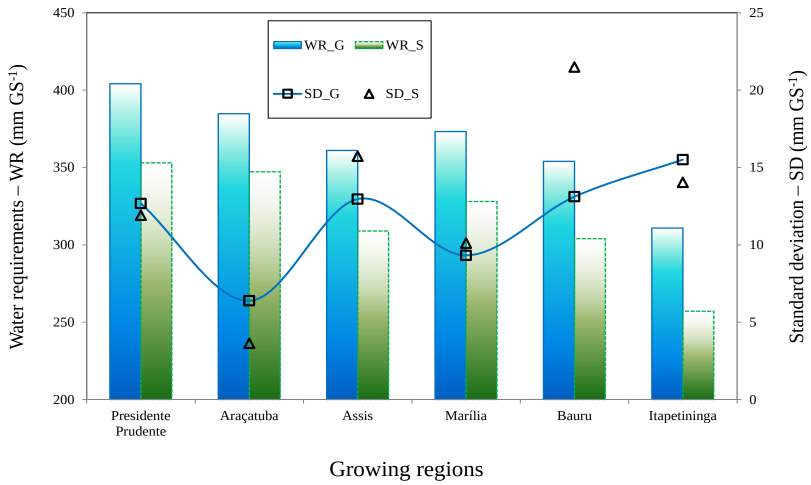

Figure 6. Water requirements (WR) together with the standard deviations (SD), for a growing season (GS) of the second-harvest corn crop in the growing regions of São Paulo state, Southeast Brazil.

It can be seen from Figure 6, that “Presidente Prudente” is highlighted with the highest water demand, with mean WR_{GS} pixel values of 404 ± 13 mm GS^{-1}, while the lowest ones go to “Itapeninga”, 311 ± 16 mm GS^{-1}. The corresponding values for silage production were 353 and 257 ± 16 mm GS^{-1} for respectively, the first and the second corn growing regions. Considering all growing regions inside Sao Paulo State, the water requirements for silage represented 87% from those for grain productions, what is important to be considered when analyzing the physical and economic values of corn water productivity.

From the one hand, there is a direct relation between water consumption and yield (Steduto et al., 2005), thus, from this point of view corn crop should be stimulated in the growing region “President Prudente” to attain high production levels. From the other hand, as recently São Paulo state has experienced severe water scarcity, the yield levels from growing regions with lower WR such as “Itapetininga” should have more attention aiming the better use of the water resources. In this last case, more research for improving corn water productivity (WP) should be carried out, because the WP variability is also due to crop and water management practices (Molden et al., 2007).

Conclusion

Models resulting from the coupled use of satellite images and agrometeorological data, based on the relation between the actual to the reference evapotranspiration and the accumulated degree-days, allowed the determination of corn water requirements in São Paulo, for both grains and silage productions. Differences of water demands among growing regions were observed, with the highest values for Presidente Prudente, while the lowest happened in Itapetinga. The results of the modelling are useful for improving corn water productivity, according with the commercial interest, for both, irrigation and rainfed conditions.

Acknowledgements

To National Council for Scientific and Technological Development (CNPq) and the Brazilian Ministry of Agriculture (MAPA) for the financial support to the project on water productivity. The National Meteorological Institute (INMET) is also acknowledge for providing the weather data.

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