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Sisvaznat: Natural Flows Reconstitution System as a Support for Water Resources Management

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I. Introduction

This paper presents a general system for the reconstitution of mean monthly natural flows in watersheds to support the SNIRH (Brazilian acronym for National Water Resources Information System) in charge of the National Water Agency (ANA). The system, called SisVazNat (Natural Flow System), was developed in Delphi platform, because it has a better performance in the implementation of software for desktop environments and provides resources that allow the best graphic designs [1].

The need for system structuring is due to the fact that flows may suffer the influence of human modifications, which affect the natural flow regime impairing the assessment of water availability of a particular reach of a stream. In order to make a reliable assessment, it is essential to determine the so-called "natural flow series".

The reconstitution of natural flow series demands careful analyses and procedures, among which the water balance stands out. In short, the method considers that natural flows are calculated from data of inflows that are turbinated and released from hydropower plants, water traveling time between those power plants and the arrangement of the set of power plants. Losses by evaporation of the flooded areas in each reservoir in relation to conditions that already existed before its implementation, a phenomenon called net evaporation, is also considered in this calculation.

The particular objective of this project was to develop automated tools that facilitate the reconstitution of those natural flows. The software developed also allows the extraction of metric and topological information on the millionth scale.

II. The New Brazilian Model of Water Resources Management

Water resources availability and multiple uses as well as the conflicts that arise from their use, currently represent a major challenge for society. In this context, Brazil is facing the challenge of creating legal and administrative mechanisms to harmonize the use of water resources with sustainable economic and social development.

The new model of water resources management is based on Law nº 9.433/97, which establishes the principle of multiple uses as one of the bases of the National Water Resources Policy to allow different user sectors the right of access to water. In order to establish this policy, the federal government created ANA which is entrusted with implementing the management tools, among which SNIRH stands out. SNIRH development is based on a strategy of joint construction, participatory and decentralized involving the federal and state spheres of the government.

A monitoring network composed of gauging stations to provide continuous data, the so-called historical discharge series, is needed to characterize water supply. On the other hand, demand is obtained from an updated registry of users. The balance between supply and demand, which is called water availability, indicates the scarcity or abundance of water in a watershed. Characterizing water availability and determining its relationship with current and future demands is crucial to define the rules for the allocation of water resources among different users [2].

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Thus, the historical discharge series are essential data for water resources management. However, stream flows are affected by human modifications such as dams, irrigation, withdrawals for human, animal or industrial supply. The consumptive water uses can affect the natural flow regime impairing or even preventing the correct evaluation of water availability. Thus, it is important to determine the “natural flow series” i.e., those that occurred before human actions. This process receives the name of reconstitution of natural flow series.

III. System Structure

The SisVazNat was structured into five modules: SisVAP, SisPEx, SisEL, SisReNat and SisUSO. Fig. 1 shows the interconnection between the SisVazNat modules for the natural flow series reconstitution process.

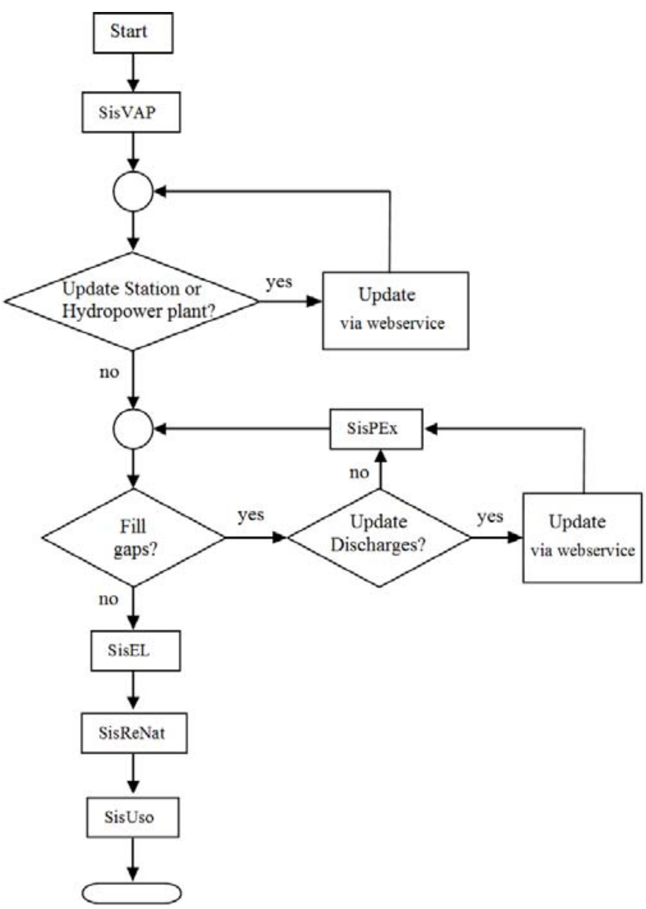

Fig.1 : Interconnection between the SisVazNat modules

SisVAP is a tool for editing and selecting the basin which contributes to the point defined by the user, as well as, from the local database, associating with the existing climate, gauging and raingauge stations and hydropower plants on the selected basin. Its objectives are:

- Interaction with the hydro reference base on a 1:1.000.000 scale.
- Segmentation of incremental basins.
- Identification and location of the contributing basin to the point defined by the user.
- Identification and location of the climate, gauging and raingauge stations and hydropower plants in the contributing basin to the point defined by the user.
- Possibility of edition of the arrangement of the hydropower plants and stations automatically identified by the tool, allowing the user to define which arrangement he/she wishes to use in the reconstitution of the natural flows, as well as recording and restoring, in digital mode, different built arrangements.

Given the huge amount of data, the separation per hydrographical unit was chosen for the incorporation of the integrated hydro reference base on a 1:1.000.000 scale, provided by ANA. Each project corresponds to a basin or sub-basin in national territory, as shown in fig. 2. As an example, fig. 3 presents the Tocantins river basin, located in the Amazon Region. Current and forecasted hydropower plants, climate, gauging and raingauge stations are presented in this figure.

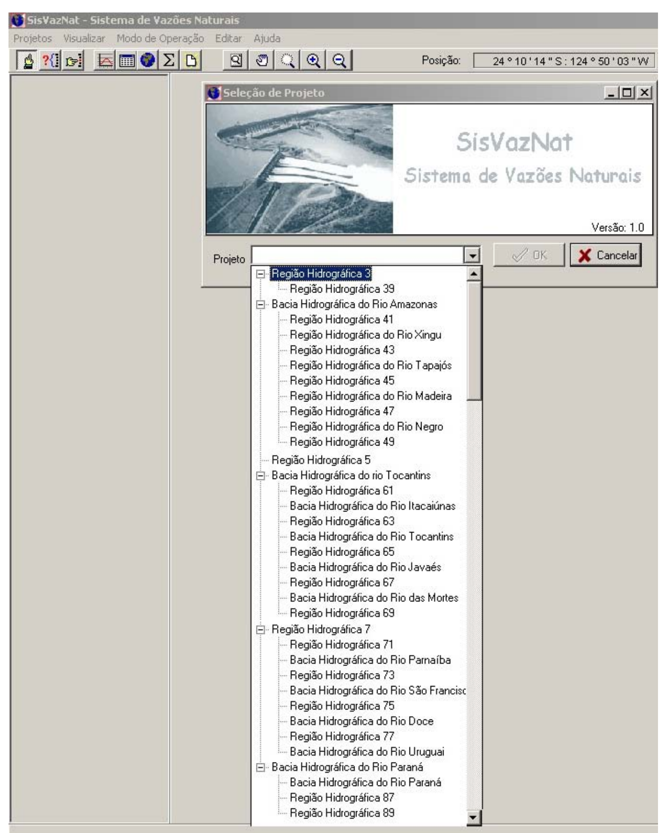

Fig. 2 : SisVazNat start screen

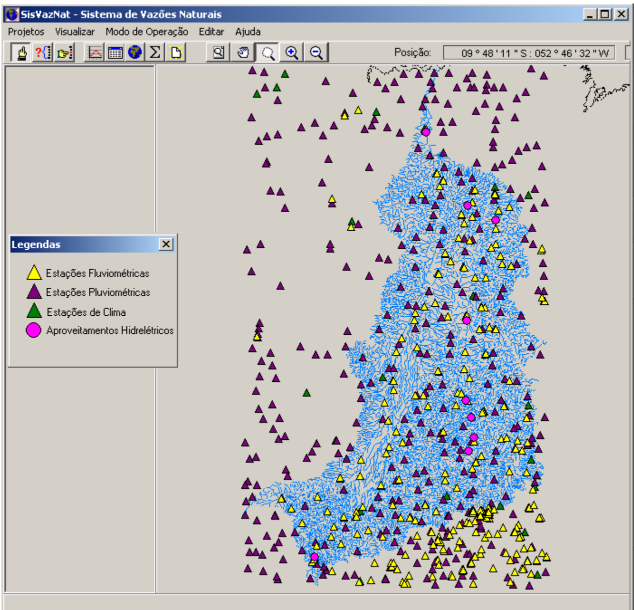

Fig.3 : Tocantins river basin

The hydro reference methodology is based on the concept of segmentation of incremental basins, which is defined from the difference between the surrounding drainage areas of each pair of successive points of interest located in a certain section of the river, for example, "P1" and "P2" points in fig. 4. The calculation of the surrounding areas of each point of interest was defined from the sum of all basin areas upstream of the section which contains the point, added of the area directly proportional to the ratio between the distance from the beginning of the section up to the point and the total length of the section.

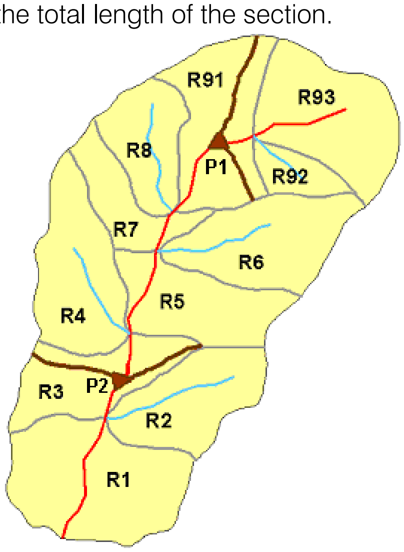

Fig.4 : Incremental areas for P1 and P2 points of interest

The SisVAP allows the user to visualize the contributing basin of the river sections and identify and locate the raingauge, climatic and gauging stations, and the hydropower plants upstream of the selected point. In addition, the lengths of the reaches and the drainage areas to the point selected by the user are provided, as shown in fig. 5.

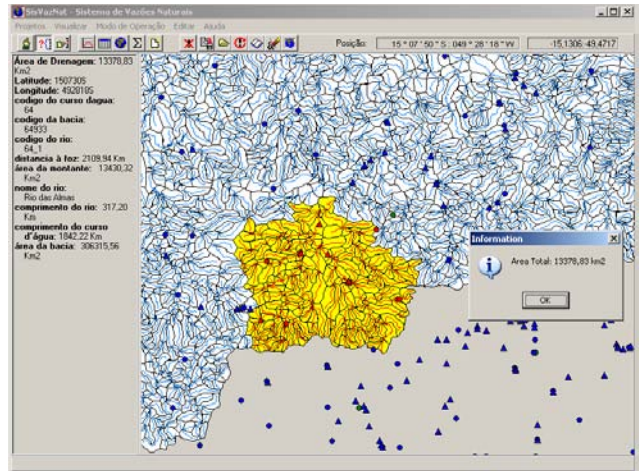

Fig.5 : Incremental basin segmentation located upstream of a point of interest

The second module is SisPEx, which was built for automatic filling and extension of the mean monthly average discharges series in each gauging station. Its main objectives are:

- Allowing the management of gauging station database registries of mean monthly discharges.
- Visualization of the registries (graphs and tables).
- Extension or gap filling the discharge series by linear regression or relationship between drainage areas or multiple correlations.

It allows the user to visualize the gauging stations, as well as the data availability period within a certain river basin, fig. 6. In addition, it is possible to select the stations of interest, and import, partially or completely, the discharge series, being only necessary that the user types the dates of beginning and ending. This option was created to help the user in deciding which base stations may be used for gap filling and/or series extension.

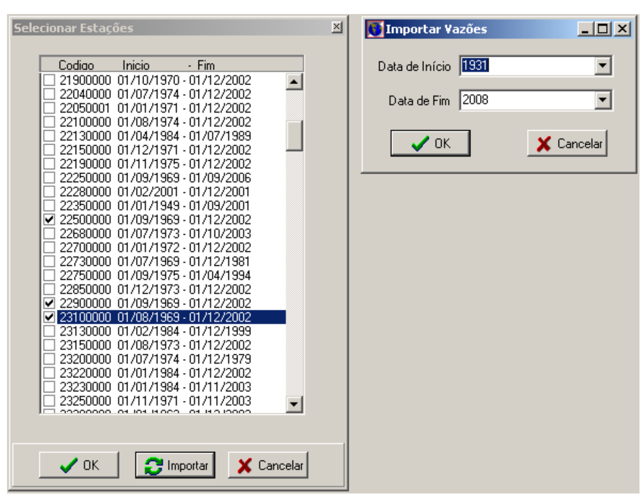

Fig.6 : Station Selection for Filling and/or Extension of Flow Series

The evaluation of the mean monthly discharge series may be done from the visual analysis of the hydrographs generated by SisPEx for one or more selected stations, as shown in fig. 7, or even through tabulated values, fig. 8.

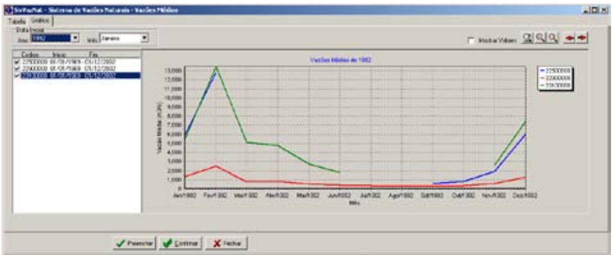

Fig. 7 : Mean discharge hydrograph

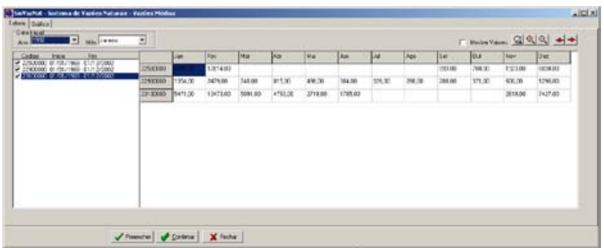

Fig. 8 : Mean monthly discharge tabulated values

The automatic gap filling and/or extension may be done through:

- Relationship between drainage areas: Developed to be used, at least, between 2 stations, one of which serves as a base, located in the same water course or the same basin, and the other which has its gaps filled and/or extended.
- Multiple correlations: It is a generalization of the relationship between drainage areas where the user may define the multiplier coefficients of the base stations, and where the use of more base stations for filling and/or extension of flow gaps is possible.
- Linear regression: Forecasted to be performed between one or more base stations and that which will be filled and/or extended, as shown in the example in fig. 9.

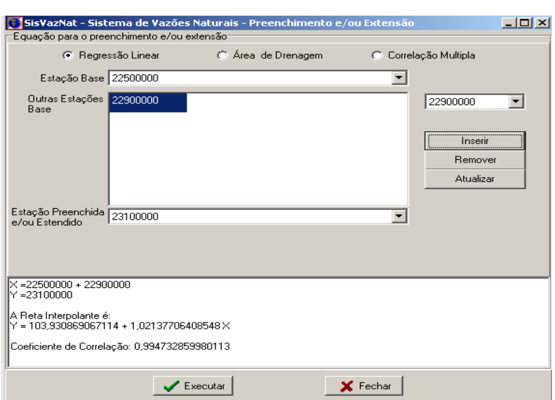

Fig. 9 : Linear regression equation

When the user clicks the button "*Executar*", the values for gap filling and/or extension of the series of the gauging station shall be automatically calculated. In addition to the tabular output, fig. 10, the SisPEx allows the user to verify, through a summary board, from the complete series of the station, the number of months that were filled and/or extended, how many could not be filled ("*Valores indeterminados*") and the number of months of observation for a certain station ("*Valores consolidados*"), fig. 11.

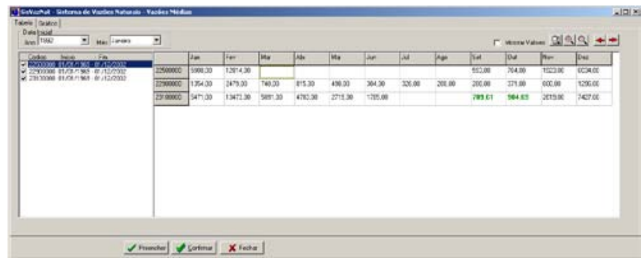

Fig. 10 : Filling results tabulated values

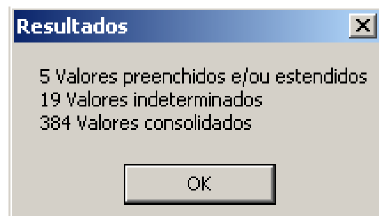

Fig. 11 : Filling results summary board

The third module is the SisEL, which allows visualization of climatic data (temperature, wind velocity, evaporation, rain, sun exposure and humidity) and the insertion of new information. It calculates the climatic variables involved in the natural flow series generation process (reservoir water balance).

The water balance of the reservoirs formed by the hydropower plants is a function of the net evaporation loss during a period of time (EL). The net evaporation loss, as defined by [3] is the difference between the evaporation from the reservoir and the evapotranspiration from the reservoir site (before the reservoir formation). In the scenario prior to the lake formation, there is ground cover which demands water for its needs, named effective precipitation. According to [4], the effective precipitation corresponds to the precipitation share stored in the influence zone of the cultivated roots and available for them to fulfill their demands. In this way, the effective precipitation (Pe) is the share of total precipitation (P) which does not flow superficially nor runs off below the root zone of said vegetation, and can be calculated through the USDA method below, according to [5], by the following equations:

$$Pe = \frac{P \cdot (125 - 0{,}2 \cdot P)}{125}\text{, for } P < 250 \text{ mm} \quad (1)$$

$$Pe = 125 + 0{,}1 \cdot P\text{, for } P > 250 \text{ mm} \quad (2)$$

Besides, in this situation, the vegetation transpiration process and soil evaporation in its surroundings, named real evapotranspiration (ETR), which corresponds to the amount of water the atmosphere can effectively remove from the soil-plant system must be taken into account. To calculate it, the SisEL allows the user to choose between the formulation proposed by [6] and the CRAE model from [7]. As the method from [6] is a function of the potential or referential evapotranspiration (ETo), SisEL allows the user to estimate ETo through the Penman-Monteith [8], Hargreaves-Samani [9] and Blaney-Cridle [10] methods.

The processes which govern the scenario after the lake formation are precipitation and lake evaporation, once there is no more ground cover nor, consequently, the effective precipitation and actual evapotranspiration processes. In this case, the phenomenon may be represented by:

$$EL = ELa - ETR \quad (3)$$

Where: ELa is the lake evaporation; and ETR the real evapotranspiration before the implementation of the reservoir. The lake evaporation may be calculated through the Linacre [11], Kohler et al [12] and Morton CRLE model methods, or yet through class A tank.

The fourth module is the SisReNat, which allows automatic generation of the monthly natural flow series from a particular point of interest located in a certain river reach. The calculation of the monthly natural flow series for any point in the hydrographic network may be performed in three different ways: entering the name of the hydropower plant, clicking on the hydrography or entering the coordinates of the point of interest.

If the point of interest defined by the user is a hydropower plant, the system will use Eq (8) for calculating the natural flow series.

Otherwise, the natural flow is calculated from the transferral of the inflows to a hydropower plant located on the same river reach or, in case of lack thereof, from the transferral of the gauging station discharges located on the same river of a nearby basin. In both situations, the transference process is done based on the relationship between drainage areas. In case of a hydropower plant, the value transferred corresponds to the difference between the natural flow (estimated through Eq (8)) and the consumptive water use at the location of the plant, and the result is added of the consumptive water use at the point of interest. In a similar manner, in the case of gauging stations, the consumptive water uses are added up after the transference of the observed gauging station flows to the point of interest, Eq (9) and (10). For the calculation process, the system informs which the hydropower plants (fig. 12) or gauging stations (fig. 13) are on the river reach or basin where the chosen point is located, as well as the availability of operational data and/or series of historical discharges of the selected period.

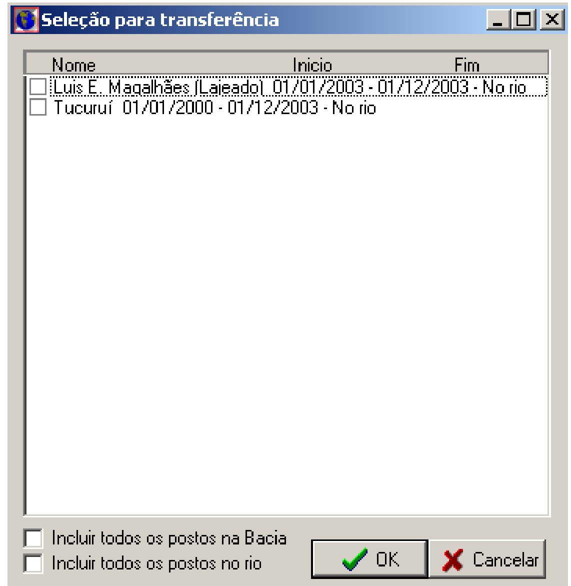

Fig. 12 : List of hydropower plants located within the same river reach of a point of interest

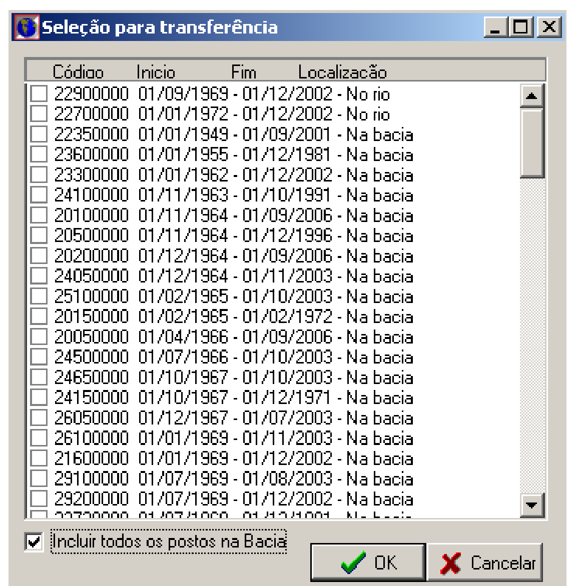

Fig. 13 : Gauging stations located on the river reach or basin of a point of interest

The fifth and last module is the SisUSO, which was developed to allow automatic water consumption flow estimate (water consumptive use). The calculation takes into account the sum of the various types of

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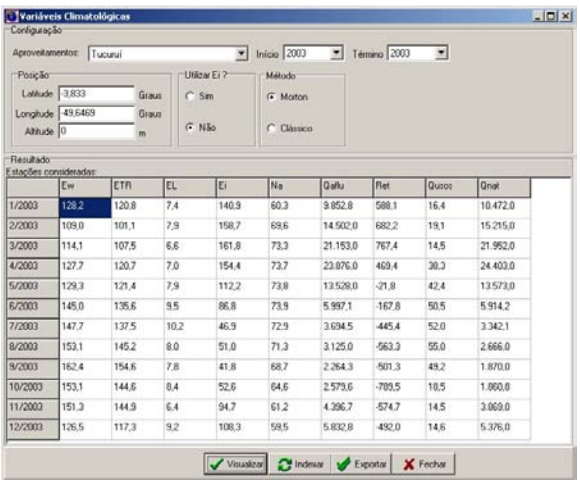
identified water uses in the basins upstream of the section which contains the point of interest, added of the sum of the sections where the point is inserted. The definition of consumptive water uses per basin was done by ANA and transferred to SisVazNat database.

Finally, once the hydropower plant or gauging station is selected, the SisVazNat automatically generates the natural flow at the point of interest defined by the user and presents the natural flow series for the chosen period, as shown in fig. 14.



	Ew	ETR	EL	Ei	Na	Qaflu	Ret	Qusos	Qnat
1/2003	128,2	120,8	7,4	140,9	60,3	9.852,8	588,1	16,4	10.472,0
2/2003	109,0	101,1	7,9	158,7	69,6	14.502,0	682,2	19,1	15.215,0
3/2003	114,1	107,5	6,6	161,8	73,3	21.153,0	767,4	14,5	21.952,0
4/2003	127,7	120,7	7,0	154,4	73,7	23.876,0	469,4	38,3	24.403,0
5/2003	129,3	121,4	7,9	112,2	73,8	13.528,0	-21,8	42,4	13.573,0
6/2003	145,0	135,6	9,5	86,8	73,9	5.997,1	-167,8	50,5	5.914,2
7/2003	147,7	137,5	10,2	46,9	72,9	3.694,5	-445,4	52,0	3.342,1
8/2003	153,1	145,2	8,0	51,0	71,3	3.125,0	-563,3	55,0	2.666,0
9/2003	162,4	154,6	7,8	41,8	68,7	2.264,3	-501,3	49,2	1.870,0
10/2003	153,1	144,6	8,4	52,6	64,6	2.579,6	-789,5	10,5	1.860,8
11/2003	151,3	144,9	6,4	94,7	61,2	4.396,7	-574,7	14,5	3.869,0
12/2003	126,5	117,3	9,2	108,3	59,5	5.832,8	-492,0	14,6	5.376,0

Fig. 14 : Natural flow series generated at a hydropower plant location

IV. Methodology

The method adopted by [13] in the reconstitution of the natural affluent flow of the hydropower plants is the reservoir water balance. The natural flow of each hydropower plant is obtained from the application of the following expression:

$$Qnat = Qnatp + Qinc \qquad (4)$$

Where: Qnat is the natural flow at the location of the selected hydropower plant; Qnatp is the natural flow at the upstream reservoir(s); Qinc is the natural incremental flow between the selected hydropower plant and the upstream hydropower plant(s).

The flow of the incremental basin related to each hydropower plant (incremental natural flow) is calculated from:

$$Qinc = Qinf - Qrel + Quse + Qevp + Qdiv \qquad (5)$$

Where: Qinc is the incremental natural flow, between the selected hydropower plant and the upstream hydropower plant(s). Qinf is the inflow to the selected hydropower plant reservoir; Qrel is the released flow of the upstream reservoir(s); Quse is the flow related to the consumptive uses of the incremental basin; Qevp is the flow related to the net evaporation; Qdiv is the flow diverted in the incremental basin, through channels, tunnels or bombing station.

The flow related to net evaporation is expressed by:

$$Qevp = \frac{EL}{2{,}6298 \cdot 10^6} \cdot [A_0 + A_1 \cdot h + A_2 \cdot h^2 + A_3 \cdot h^3 + \\ + A_4 \cdot h^4] \cdot 1000 \qquad (6)$$

Where: h is the reservoir average stage; $A_{0,1,2,3,4}$ are the coefficients of the stage-reservoir area equation; $2{,}6298.10^6$ is the number of seconds in a month.

The value of the diverted flow shall be accounted on the flow related to the consumptive uses of the incremental basin. Based on this, Eq (6) may be rewritten as follows:

$$Qinc = Qinf - Qrel + Quse + Qevp \qquad (7)$$

The general equation of the natural flow in a hydropower plant "i" can then be expressed as:

$$Qnat_i = Qinf_i + \left[\sum_{j=1}^{n}\left(Qinf_j - Qrel_j\right)\right] + \left[\left(\sum_{j=1}^{n} Quse_j\right) + Quse_i\right] + \\ + \left[\left(\sum_{j=1}^{n} Qevp_j\right) + Qevp_i\right] \qquad (8)$$

Where: $\left[\sum_{j=1}^{n}\left(Qinf_j - Qrel_j\right)\right]$ is the sum of the difference between the inflows and release flows of the set of hydropower plants located upstream of the hydropower plant "i" (it corresponds to the "Ret" column in fig. 14); $\left[\left(\sum_{j=1}^{n} Quse_j\right) + Quse_i\right]$ is the sum of the incremental consumptive uses of the set of hydropower plants located upstream of the hydropower plant "i", including itself; $\left[\left(\sum_{j=1}^{n} Qevp_j\right) + Qevp_i\right]$ is the sum of the net evaporation flows of the hydropower plants reservoirs located upstream of the hydropower plant "i", including itself.

For the generation of the monthly natural flows in streams where there are no hydropower plants, the mean monthly flow data from the gauging station(s) upstream or downstream from the point of interest is used, transferred by relationship between drainage areas, added of the consumptive uses accrued up to the point of interest. The equation for the reconstitution of the monthly natural flow from the observed data is expressed as:

$$Qnat_i = Q_j \cdot \left(\frac{A_i}{A_j}\right) + Quse_i \text{, i downstream from j} \qquad (9)$$

$$Qnat_i = Q_j \cdot \left(\frac{A_j}{A_i}\right) + Quse_i \text{, i upstream from j} \qquad (10)$$

Where: Q_j is the mean monthly average discharge at the gauging station located at point "j"; A_i is the drainage area surrounding the point of interest "i"; A_j is the drainage area surrounding the gauging station located at point "j"; $Quse_i$ is the accrued monthly consumptive uses up to the point of interest "i".

In case of lack of gauging stations on the river reach, in which the point of interest "i" is located, the option of transference is granted to the user, through the relationship between drainage areas, from the gauging station(s) located on nearby basin(s).

In case the hydropower plant does not possess operational data, it shall be considered by the SisVazNat as a point of interest and the monthly natural flow is estimated from Eq (9) or (10).

V. Results

The SisVazNat was applied in the Tocantins basin located in the Amazon Region. The basin has a drainage area of 767,000 km^2, or about 7.5% of the Brazilian territory. The geographic coordinates used to locate the operating hydropower plants in the basin are shown in Table 1.

Table 1 : Hydropower plants code and location

Hydropower Plant*	Lat	Long	Drainage Area (km^2)
UHE Serra da Mesa	-13.827	-48.307	51,233
UHE Cana Brava	-13.407	-48.142	58,022
UHE Lajeado	-9.756	-48.374	183,718
UHE Tucuruí	-3.833	-49.647	757,577

** UHE is the Brazilian acronym for hydropower plant.*

In order to validate the proposed methodology we considered the year of 2003 (January to December) for the simulations using the Morton model, and the results found were compared to the series of natural flows published by ONS. The choice of the Morton model sought to match the simulation of the SisVazNat to the criteria adopted by ONS regarding the generation of natural flows. The differences are shown in Tables 2 to 5.

Table 2 : Results obtained in UHE Serra da Mesa

Date	Natural Flow (m³/s)		Difference
	ONS	SisVazNat	(%)
Jan-03	1,197.0	1,142.4	4.6
Feb-03	1,056.0	1,068.9	1.2
Mar-03	1,140.0	1,138.9	0.1
Apr-03	919.0	917.4	0.2
May-03	425.0	415.6	2.2
Jun-03	293.0	272.8	6.9
Jul-03	206.0	196.6	4.6
Aug-03	135.0	130.1	3.6
Sep-03	167.0	164.2	1.7
Oct-03	139.0	134.9	2.9
Nov-03	283.0	289.6	2.3
Dec-03	340.0	369.1	8.6

Table 3 : Results obtained in UHE Cana Brava

Date	Natural Flow (m³/s)		Difference
	ONS	SisVazNat	(%)
Jan-03	1,319.0	1,293.8	1.9
Feb-03	1,188.0	1,173.1	1.3
Mar-03	1,276.0	1,281.1	0.4
Apr-03	1,095.0	1,028.2	6.1
May-03	485.0	453.3	6.5
Jun-03	330.0	297.1	10.0
Jul-03	231.0	205.4	11.1
Aug-03	154.0	135.2	12.2
Sep-03	185.0	180.8	2.3
Oct-03	158.0	165.8	4.9
Nov-03	311.0	328.6	5.7
Dec-03	381.0	399.9	5.0

Table 4 : Results obtained in UHE Lajeado

Date	Natural Flow (m³/s)		Difference
	ONS	SisVazNat	(%)
Jan-03	3,365.0	3,280.2	2.5
Feb-03	3,322.0	3,329.5	0.2
Mar-03	3,621.0	3,667.1	1.3
Apr-03	3,961.0	3,859.8	2.6
May-03	1,467.0	1,441.0	1.8
Jun-03	898.0	861.4	4.1
Jul-03	597.0	520.4	12.8
Aug-03	422.0	422.9	0.2
Sep-03	424.0	432.7	2.1
Oct-03	451.0	402.8	10.7
Nov-03	780.0	871.3	11.7
Dec-03	1.029.0	1.029.2	0.0

Table 5 : Results obtained in UHE Tucuruí

Date	Natural Flow (m³/s)		Difference
	ONS	SisVazNat	(%)
Jan-03	10,368.0	10,472.0	1.0
Feb-03	16,389.0	15,215.0	7.2
Mar-03	22,076.0	21,952.0	0.6
Apr-03	24,13.0	24,403.0	0.9
May-03	13,714.0	13,.573.0	1.0
Jun-03	5,853.0	5,914.2	1.0
Jul-03	3,231.0	3,342.1	3.4
Aug-03	2,279.0	2,666.0	17.0
Sep-03	1,759.0	1,870.0	6.3
Oct-03	1,796.0	1,860.8	3.6
Nov-03	3,525.0	3,869.0	9.8
Dec-03	5,404.0	5,376.0	0.5

VI. CONCLUSION

The mean percent differences between the results obtained with the SisVazNat and the monthly natural flow series consolidated by ONS in each hydropower plant were, respectively: UHE Serra da Mesa (3.2%); UHE Cana Brava (5.6%); UHE Lajeado (4.2%) and UHE Tucuruí (4.4%). These small differences allowed the validation of the tool.

The application of the system to the case study was successful generating natural flows similar to those established by the electrical sector in Tocantins river basin. Thus, it is possible to infer that SisVazNat meets the proposed objectives, since it operates in an interactive way with the user, allowing frequent data updating, generating natural flows in any point of a watercourse in the Brazilian territory. The system may be used as a supporting tool that can help Governmental agencies, because it supplies an adequate representation of the water availability in a scenario that existed prior to human modifications in the basin allowing the water resources manager to use the natural flow series to define the criteria for a better allocation of water among multiple users.

The application of the SisVazNat to other Brazilian watersheds is recommended for future developments.

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