

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

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Abstract

This paper presents a general system for the reconstitution of natural flows series to support the SNIRH (Brazilian acronym for National Water Resources Information System). There is a need for system structuring due to the fact that streamflows may suffer human modifications which difficult to carry out water resources management. In order to make a reliable assessment, it is essential to determine the so-called "natural flow series" i.e. the flows that would have occurred prior to human action. The SisVazNat system was applied in the Tocantins watershed, located in the Amazon Region, and in order to validate the proposed methodology, the results were compared with those published by the Electric System National Operator (ONS). The mean percent differences obtained in each hydropower plant were, respectively: UHE Serra da Mesa (3.2

Index terms— SisVazNat, water resources, natural flow reconstitution.

1 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.

2 II.

3 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.

43 The new model of water resources management is based on Law n° 9.433/97, which establishes the principle
 44 of multiple uses as one of the bases of the National Water Resources Policy to allow different user sectors the
 45 right of access to water. In order to establish this policy, the federal government created ANA which is entrusted
 46 with implementing the management tools, among which SNIRH stands out. SNIRH development is based on
 47 a strategy of joint construction, participatory and decentralized involving the federal and state spheres of the
 48 government.

49 A monitoring network composed of gauging stations to provide continuous data, the so-called historical
 50 discharge series, is needed to characterize water supply. On the other hand, demand is obtained from an updated
 51 registry of users. The balance between supply and demand, which is called water availability, indicates the scarcity
 52 or abundance of water in a watershed. Characterizing water availability and T determining its relationship with
 53 current and future demands is crucial to define the rules for the allocation of water resources among different
 54 users [2]. Thus, the historical discharge series are essential data for water resources management. However,
 55 stream flows are affected by human modifications such as dams, irrigation, withdrawals for human, animal or
 56 industrial supply. The consumptive water uses can affect the natural flow regime impairing or even preventing
 57 the correct evaluation of water availability. Thus, it is important to determine the "natural flow series" i.e., those
 58 that occurred before human actions. This process receives the name of reconstitution of natural flow series.

59 4 III.

60 5 System Structure

61 The SisVazNat was structured into five modules: SisVAP, SisPEX, SisEL, SisReNat and SisUSO. Fig. 1 shows
 62 the interconnection between the SisVazNat modules for the natural flow series reconstitution process. Given the
 63 huge amount of data, the separation per hydrographical unit was chosen for the incorporation of the integrated
 64 hydro reference base on a 1:1.000.000 scale, provided by ANA. Each project corresponds to a basin or sub-basin
 65 in national territory, as shown in fig. The hydro reference methodology is based on the concept of segmentation
 66 of incremental basins, which is defined from the difference between the surrounding drainage areas of each pair
 67 of successive points of interest located in a certain section of the river, for example, "P1" and "P2" points in fig.
 68 4. The calculation of the surrounding areas of each point of interest was defined from the sum of all basin areas
 69 upstream of the section which contains the point, added of the area directly proportional to the ratio between
 70 the distance from the beginning of the section up to the point and the total length of the section. It allows the
 71 user to visualize the gauging stations, as well as the data availability period within a certain river basin, fig. 6. In
 72 addition, it is possible to select the stations of interest, and import, partially or completely, the discharge series,
 73 being only necessary that the user types the dates of beginning and ending. This option was created to help the
 74 user in deciding which base stations may be used for gap filling and/or series extension. The automatic gap filling
 75 and/or extension may be done through: ? Relationship between drainage areas: Developed to be used, at least,
 76 between 2 stations, one of which serves as a base, located in the same water course or the same basin, and the
 77 other which has its gaps filled and/or extended. ? Multiple correlations: It is a generalization of the relationship
 78 between drainage areas where the user may define the multiplier coefficients of the base stations, and where the
 79 use of more base stations for filling and/or extension of flow gaps is possible. ? Linear regression: Forecasted to
 80 be performed between one or more base stations and that which will be filled and/or extended, as shown in the
 81 example in fig. ??.

82 6 Fig. 9 : Linear regression equation

83 When the user clicks the button "Executar", the values for gap filling and/or extension of the series of the gauging
 84 station shall be automatically calculated. In addition to the tabular output, fig. 10, the SisPEX allows the user to
 85 verify, through a summary board, from the complete series of the station, the number of months that were filled
 86 and/or extended, how many could not be filled ("Valores indeterminados") and the number of The water balance
 87 of the reservoirs formed by the hydropower plants is a function of the net evaporation loss during a period of time
 88 (EL). The net evaporation loss, as defined by [3] is the difference between the evaporation from the reservoir and
 89 the evapotranspiration from the reservoir site (before the reservoir formation). In the scenario prior to the lake
 90 formation, there is ground cover which demands water for its needs, named effective precipitation. According to
 91 [4], the effective precipitation corresponds to the precipitation share stored in the influence zone of the cultivated
 92 roots and available for them to fulfill their demands. In this way, the effective precipitation (Pe) is the share of
 93 total precipitation (P) which does not flow superficially nor runs off below the root zone of said vegetation, and
 94 can be calculated through the USDA method below, according to [5], by the following equations: , for $P > 250$
 95 mm (2) Besides, in this situation, the vegetation transpiration process and soil evaporation in its surroundings,
 96 named real evapotranspiration (ETR), which corresponds to the amount of water the atmosphere can effectively
 97 remove from the soil-plant system must be taken into account. To calculate it, the SisEL allows the user to
 98 choose between the formulation proposed by [6] and the CRAE model from [7]. As the method from [6] is a
 99 function of the potential or referential evapotranspiration (ETo), SisEL allows the user to estimate ETo through
 100 the Penman-Monteith [8], Hargreaves-Samani [9] and Blaney-Cridle [10] methods.

101 The processes which govern the scenario after the lake formation are precipitation and lake evaporation,
 102 once there is no more ground cover nor, consequently, the effective precipitation and actual evapotranspiration
 103 processes. In this case, the phenomenon may be represented by: $ETR - EL_a = EL$ (3)

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

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

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

113 Otherwise, the natural flow is calculated from the transferral of the inflows to a hydropower plant located on
 114 the same river reach or, in case of lack thereof, from the transferral of the gauging station discharges located on
 115 the same river of a nearby basin. In both situations, the transference process is done based on the relationship
 116 between drainage areas. In case of a hydropower plant, the value transferred corresponds to the difference between
 117 the natural flow (estimated through Eq (8)) and the consumptive water use at the location of the plant, and the
 118 result is added of the consumptive water use at the point of interest. In a similar manner, in the case of gauging
 119 stations, the consumptive water uses are added up after the transference of the observed gauging station flows to
 120 the point of interest, Eq (??) and (10). For the calculation process, the system informs which the hydropower
 121 plants (fig. 12) or gauging stations (fig. 13) are on the river reach or basin where the chosen point is located, as
 122 well as the availability of operational data and/or series of historical discharges of the selected period. Finally,
 123 once the hydropower plant or gauging station is selected, the SisVazNat automatically generates the natural flow
 124 at the point of interest defined by the user and presents the natural flow series for the chosen period, as shown
 125 in fig. 14.

126 7 Methodology

127 The method adopted by [13] in the reconstitution of the natural affluent flow of the hydropower plants is the
 128 reservoir water balance. The natural flow of each hydropower plant is obtained from the application of the
 129 following expression: $Q_{inc} Q_{nat} + = (4)$

130 Where: Q_{nat} is the natural flow at the location of the selected hydropower plant; Q_{natp} is the natural flow at
 131 the upstream reservoir(s); Q_{inc} is the natural incremental flow between the selected hydropower plant and the
 132 upstream hydropower plant(s).

133 The flow of the incremental basin related to each hydropower plant (incremental natural flow) is calculated
 134 from: $Q_{div} Q_{evp} Q_{use} Q_{rel} - Q_{inf} Q_{inc} + + + = (5)$

135 Where: Q_{inc} is the incremental natural flow, between the selected hydropower plant and the upstream
 136 hydropower plant(s). Q_{inf} is the inflow to the selected hydropower plant reservoir; Q_{rel} is the released flow
 137 of the upstream reservoir(s); Q_{use} is the flow related to the consumptive uses of the incremental basin; Q_{evp}
 138 is the flow related to the net evaporation; Q_{div} is the flow diverted in the incremental basin, through channels,
 139 tunnels or bombing station. The flow related to net evaporation is expressed by: $+ ? + ? + ? + ? = 33221$
 140 $06hAhA h A A [102,6298 EL Q_{evp} 1000] h A 44 ? ? + (6)$

141 Where: h is the reservoir average stage; $A_{0,1,2,3,4}$ are the coefficients of the stage-reservoir area equation;
 142 $2,6298.106$ is the number of seconds in a month.

143 The value of the diverted flow shall be accounted on the flow related to the consumptive uses of the incremental
 144 basin. Based on this, Eq (6) may be rewritten as follows: $Q_{evp} Q_{use} Q_{rel} - Q_{inf} Q_{inc} + + = (7)$

145 The general equation of the natural flow in a hydropower plant "i" can then be expressed as:
 146 $() + ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? + = = i n 1 j j n 1 j j j i i Q_{use} Q_{use} Q_{rel}$
 147 $inf Q_{inf} Q_{nat} ? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? + = i n 1 j j Q_{evp} Q_{evp} (8)$

148 Where: $() ? ? ? ? ? ? ? ? = n 1 j j j Q_{rel} inf Q$
 149 is the sum of the Sisvaznat: Natural Flows Reconstitution System as a Support for Water Resources
 150 Management difference between the inflows and release flows of the set of hydropower plants located upstream
 151 of the hydropower plant "i" (it corresponds to the "Ret" column in fig. 14); $? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ?$
 152 $? = i n 1 j j Q_{use} Q_{use}$

153 is the sum of the incremental consumptive uses of the set of hydropower plants located upstream of the
 154 hydropower plant "i", including itself; $? ? ? ? ? ? ? ? + ? ? ? ? ? ? ? ? = i n 1 j j Q_{evp} Q_{evp}$

155 is the sum of the net evaporation flows of the hydropower plants reservoirs located upstream of the hydropower
 156 plant "i", including itself.

157 For the generation of the monthly natural flows in streams where there are no hydropower plants, the mean
 158 monthly flow data from the gauging station(s) upstream or downstream from the point of interest is used,
 159 transferred by relationship between drainage areas, added of the consumptive uses accrued up to the point of
 160 interest. The equation for the reconstitution of the monthly natural flow from the observed data is expressed as:
 161 $j i j i Q_{use} A A Q_{nat} + ? ? ? ? ? ? ? ? =$

162 $, i$ downstream from $j J i i j j i Q_{use} A A Q_{nat} + ? ? ? ? ? ? ? ? =$

163 , i upstream from j (10) Where: Q_j is the mean monthly average discharge at the gauging station located at
164 point " j "; A_i is the drainage area surrounding the point of interest " i "; A_j is the drainage area surrounding the
165 gauging station located at point " j "; $Q_{use\ i}$ is the accrued monthly consumptive uses up to the point of interest
166 " i ".

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

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

172 V.

173 8 Results

174 The SisVazNat was applied in the Tocantins basin located in the Amazon Region. The basin has a drainage
175 area of 767,000 km², or about 7.5% of the Brazilian territory. The geographic coordinates used to locate the
176 operating hydropower plants in the basin are shown in Table 1. * UHE is the Brazilian acronym for hydropower
177 plant.

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

182 9 Conclusion

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

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

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

195 1



Figure 1: Fig. 1 :?

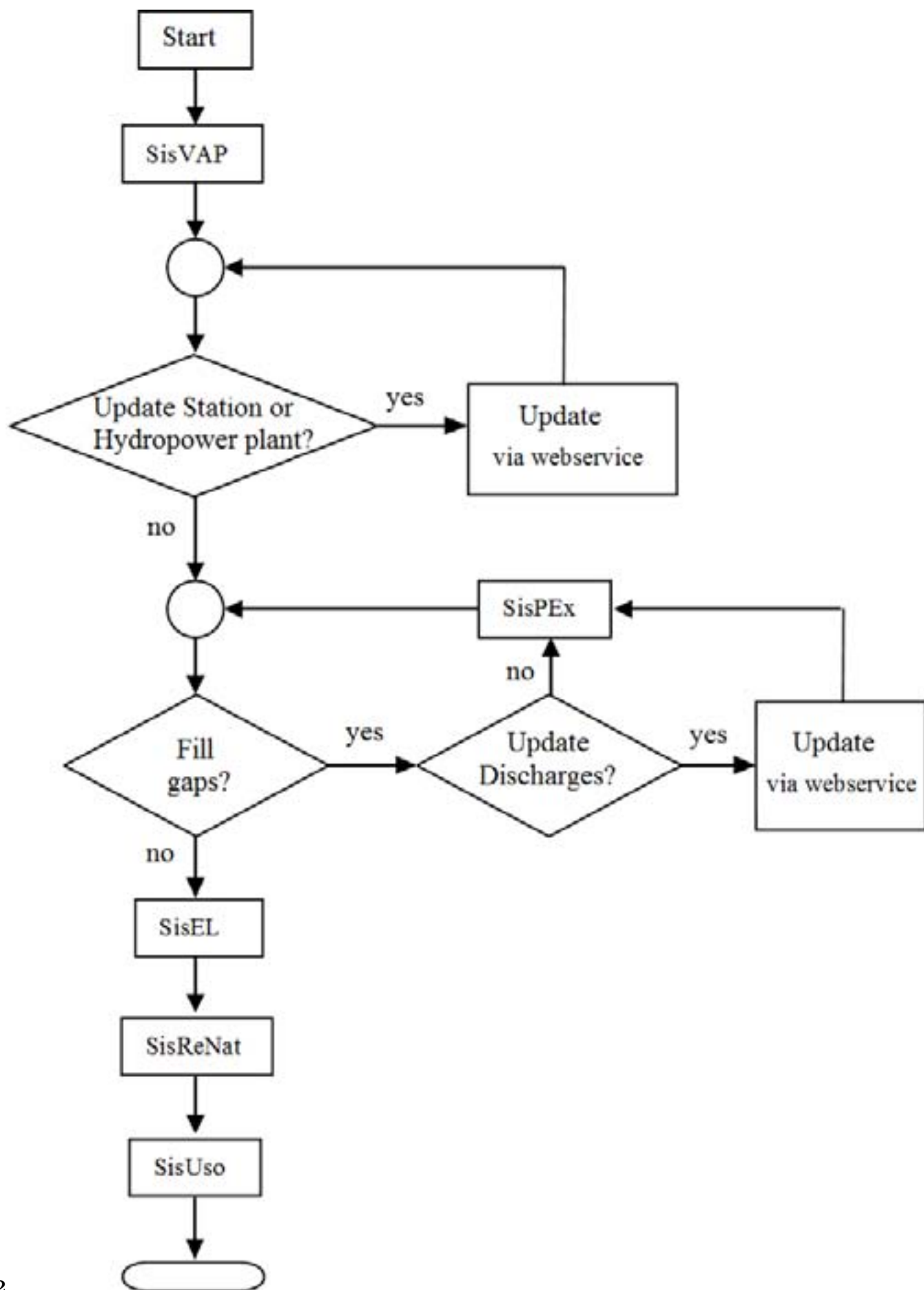
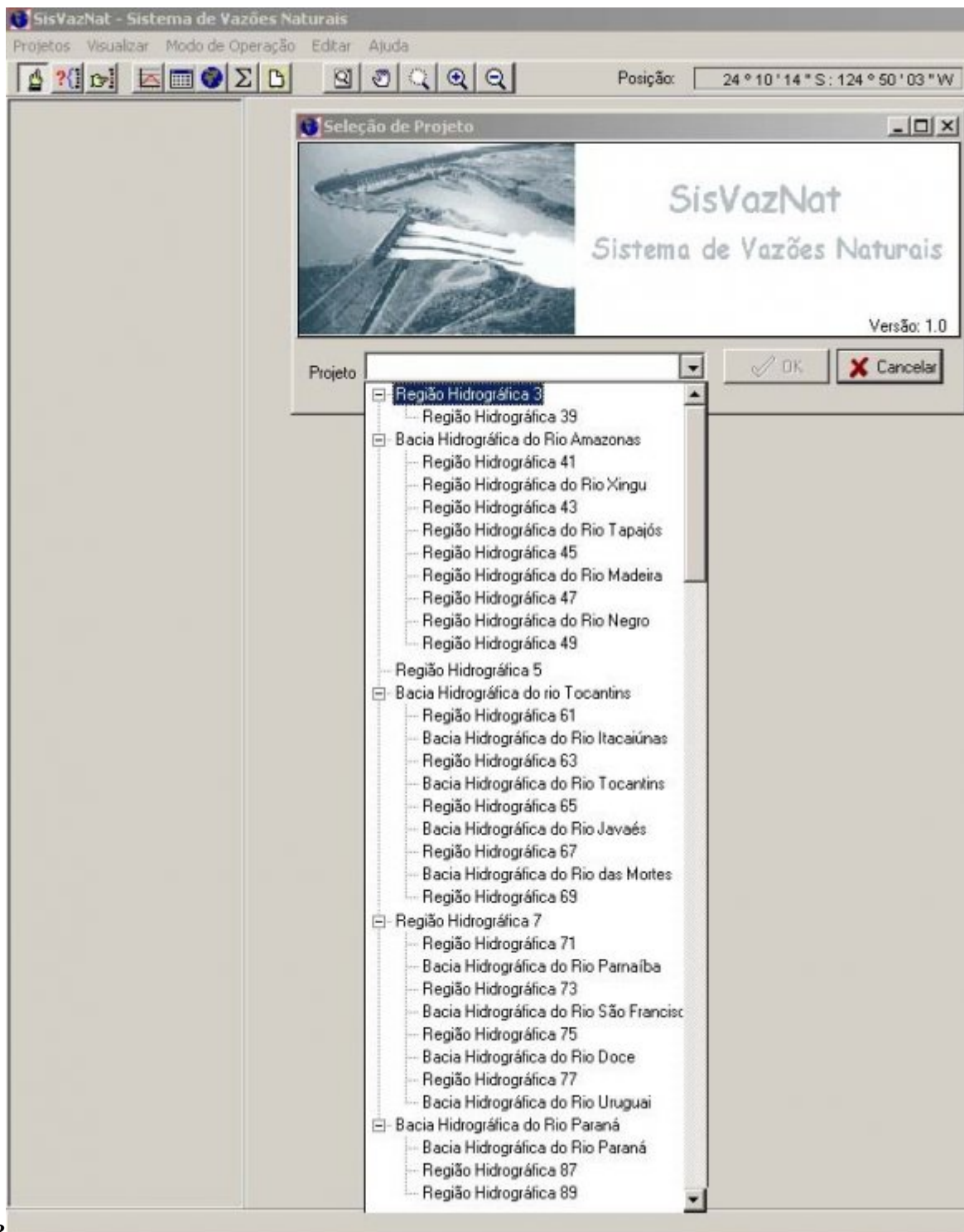
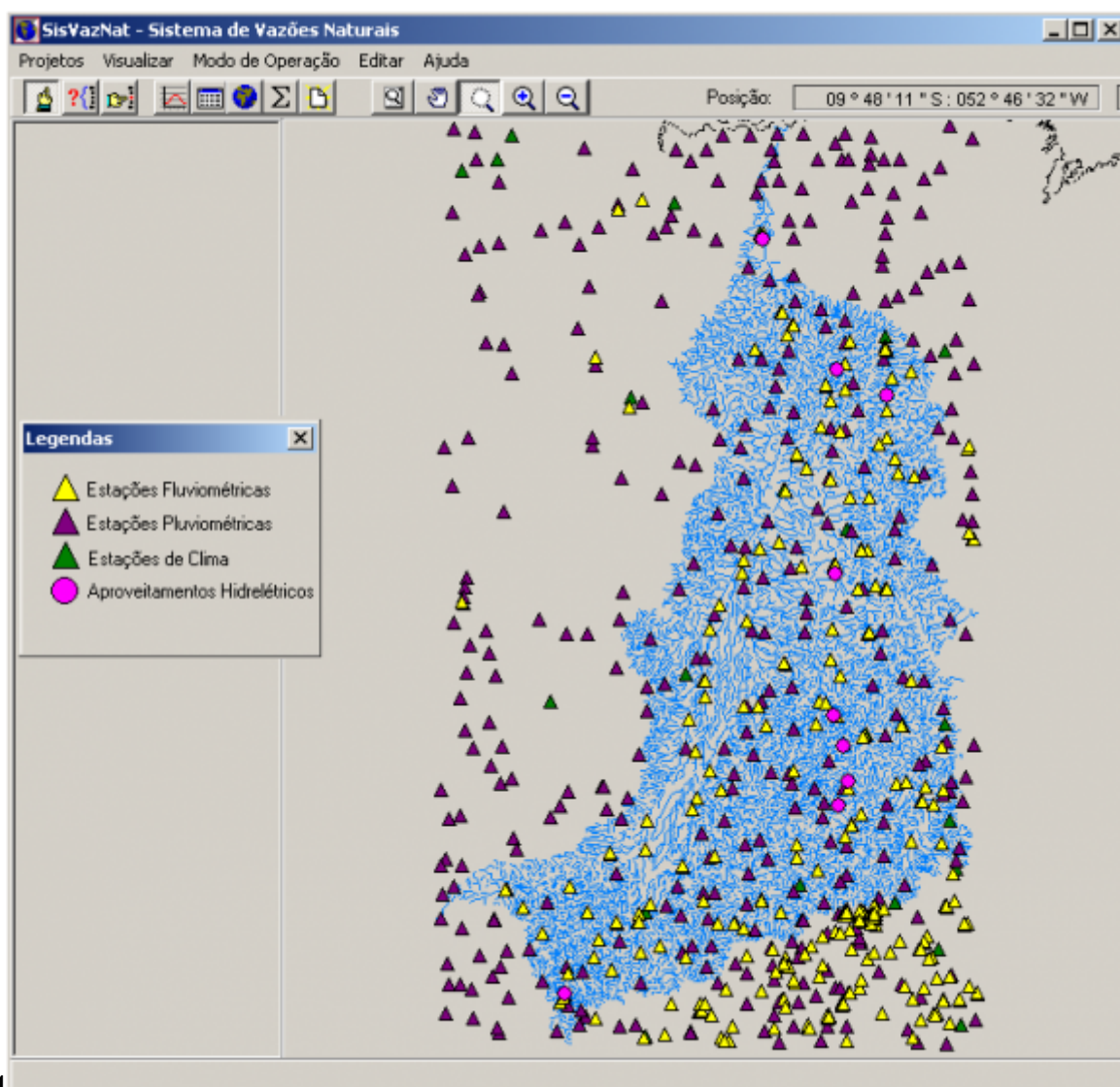


Figure 2: 2 .



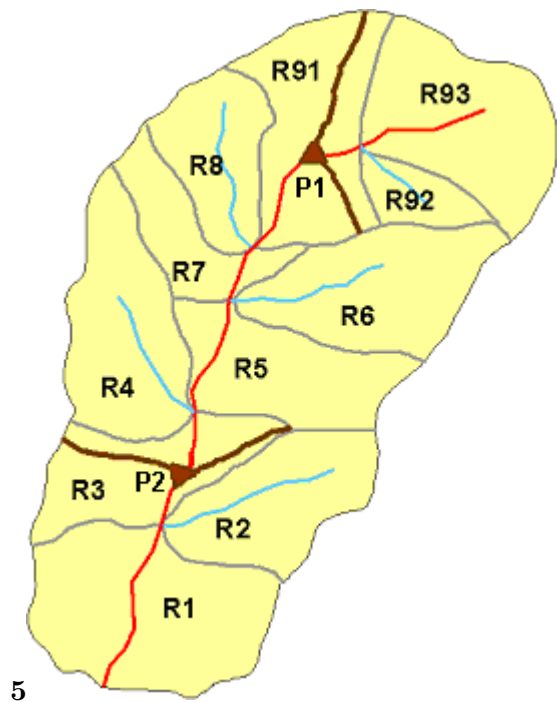
23

Figure 3: Fig. 2 :Fig. 3 :



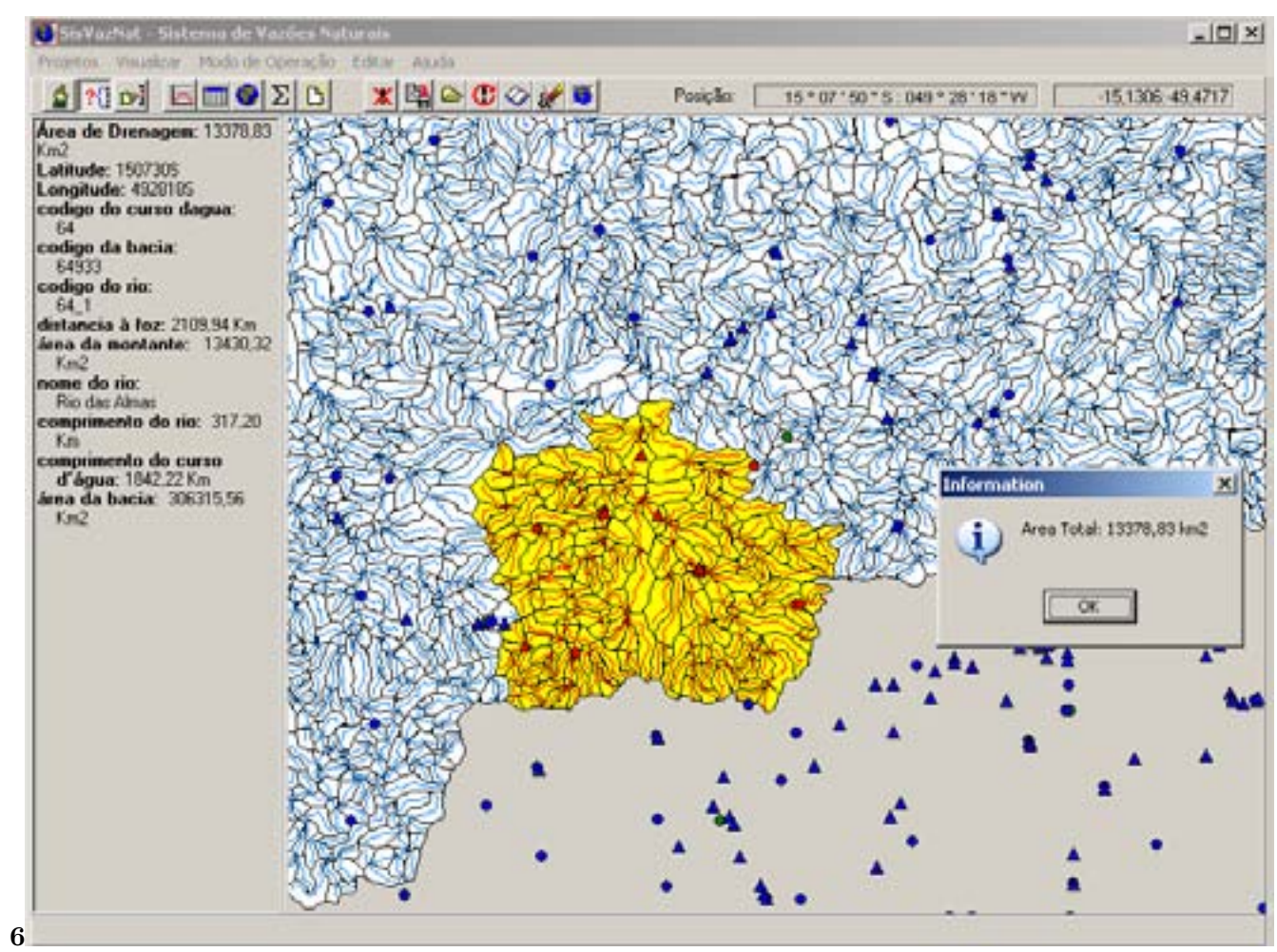
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Figure 4: Fig. 4 :



5

Figure 5: Fig. 5 :



6

Figure 6: Fig. 6 :

9 CONCLUSION

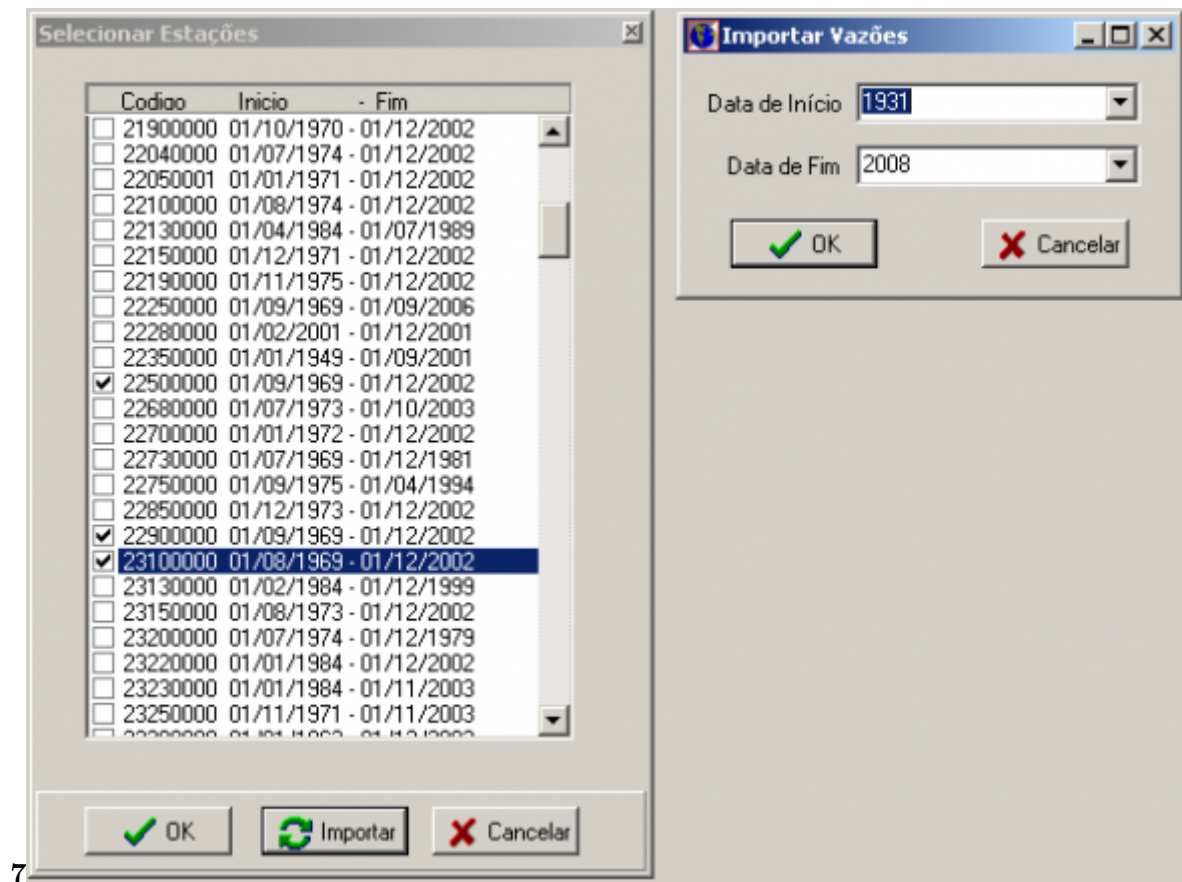


Figure 7: Fig. 7 :

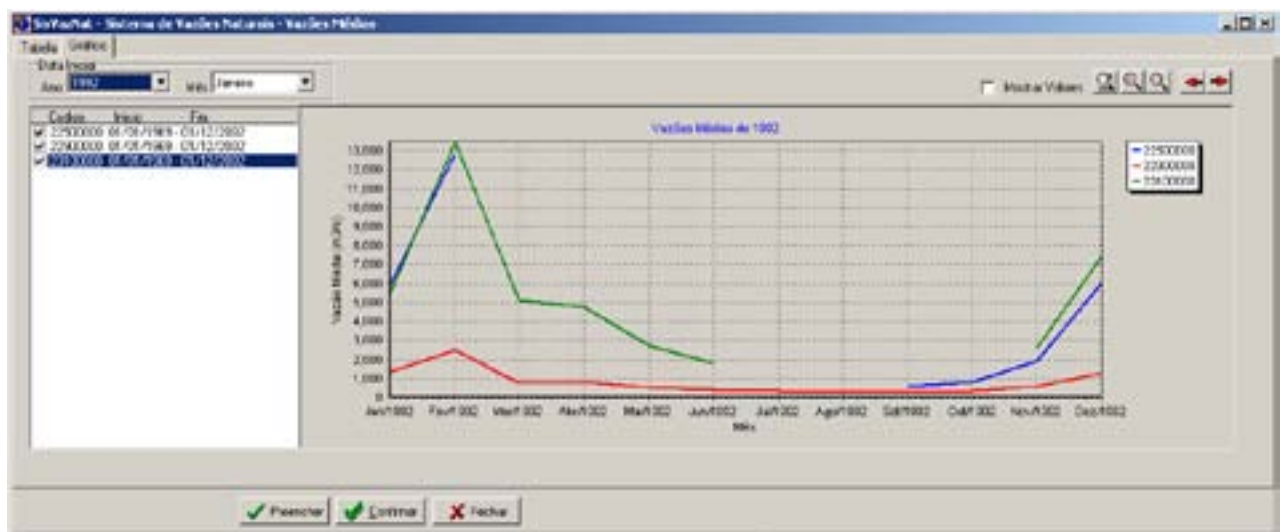
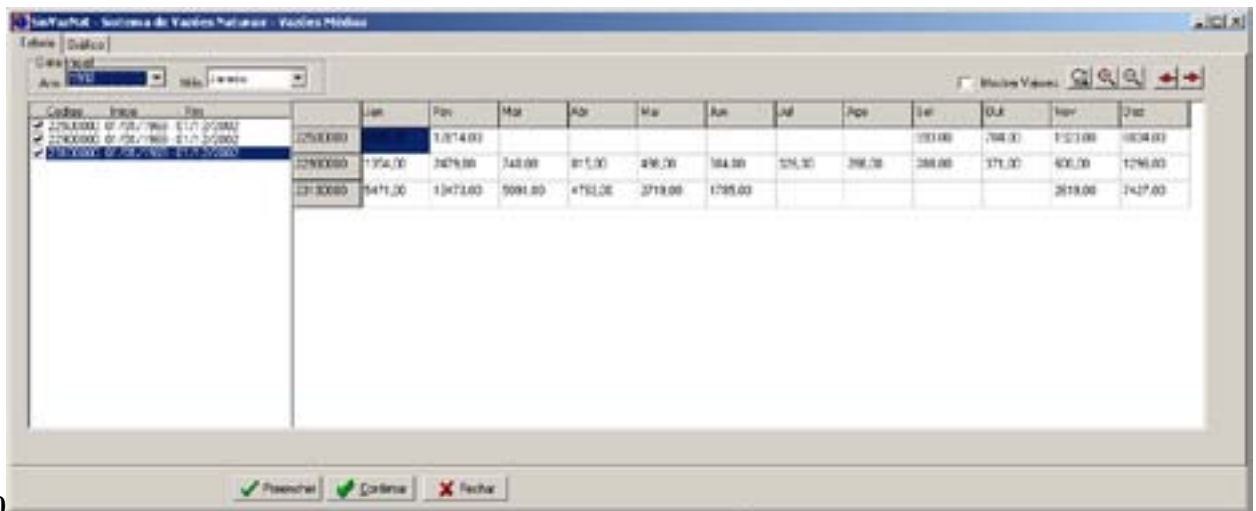
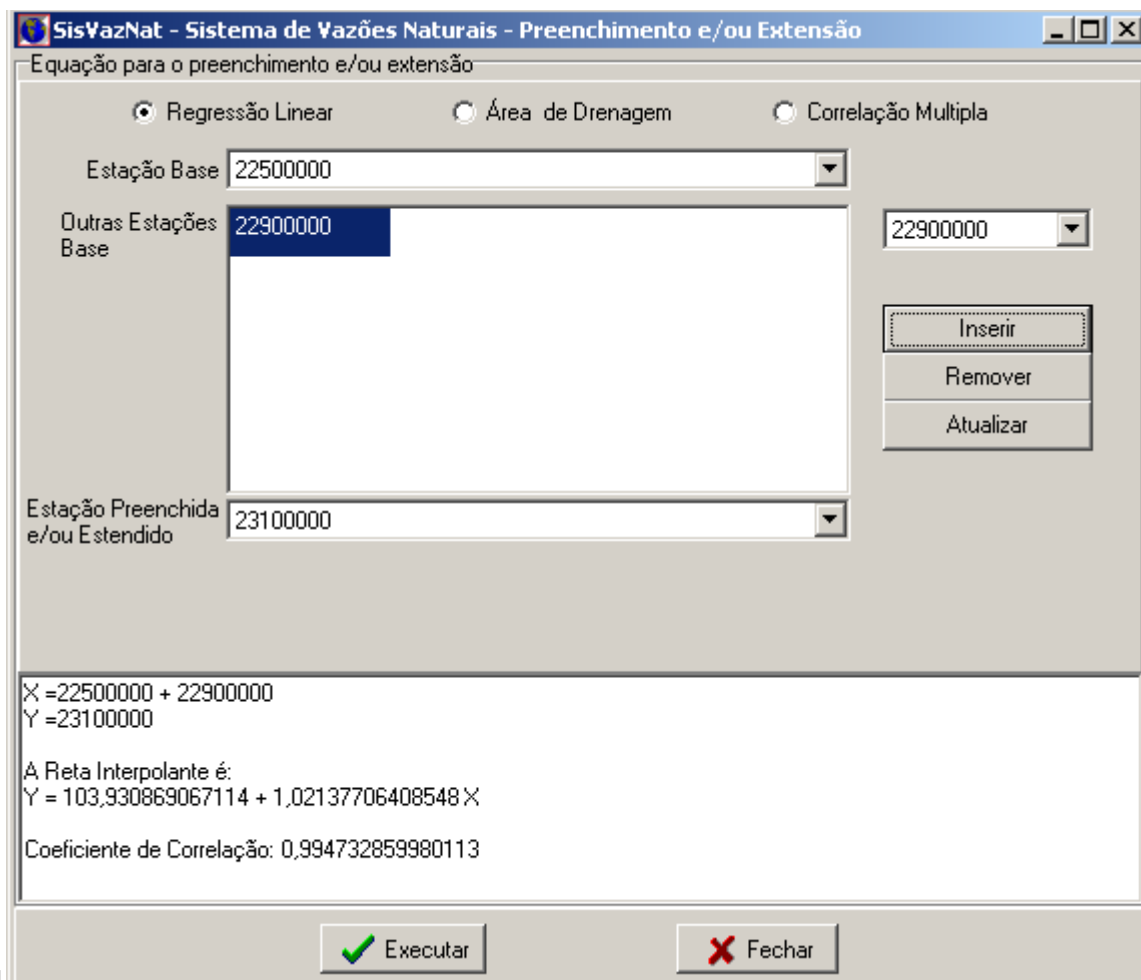


Figure 8:



10

Figure 9: Fig. 10 :



11

Figure 10: Fig. 11 :

9 CONCLUSION

Table: [Seleção]

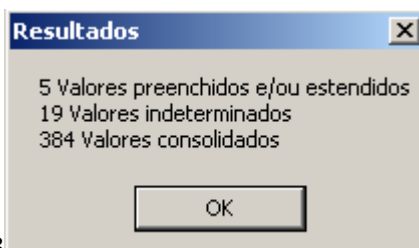
Data: [Ano] 1992 Mes: [Janeiro]

Local	Início	Fim	Jan	Fev	Mar	Abr	Mai	Jun	Jul	Ago	Sep	Out	Nov	Dez	
22500000	01/01/2003	01/12/2003	598.00	12814.30								552.00	704.00	1022.00	6034.00
22900000	01/01/1989	01/12/2002	1354.00	2479.00	748.00	815.30	498.00	364.30	326.00	208.00	200.00	371.00	600.00	1290.00	
23100000	01/01/1989	01/12/2002	5471.00	13471.30	5891.30	4782.30	2713.30	1785.00			789.61	584.83	2019.00	7427.00	

Buttons: [Preencher] [Confirmar] [Fechar]

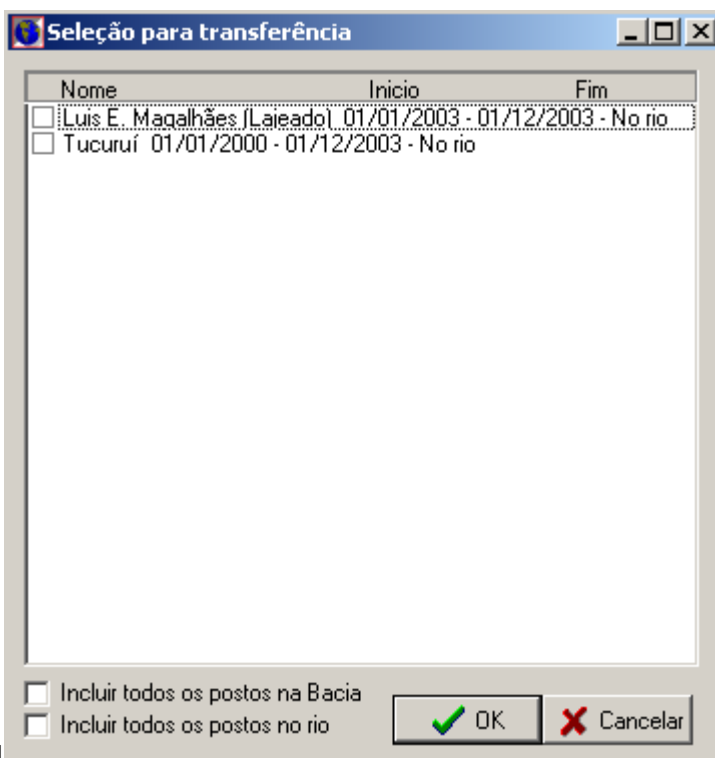
12

Figure 11: Fig. 12 :



13

Figure 12: Fig. 13 :



14

Figure 13: Fig. 14 :

1

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

Figure 14: Table 1 :

2

Date	Natural Flow (m ³ /s)	ONS SisVazNat	Difference (%)
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

Figure 15: Table 2 :

3

Date	Natural Flow (m ³ /s)	ONS SisVazNat	Difference (%)
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Figure 16: Table 3 :

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- 196 [Hora and Hora] , A F Hora , Hora .
- 197 [Hora ()] *Compatibilização da geração de energia em aproveitamentos hidrelétricos com os demais usos dos*
198 *recursos hídricos*, M A G Hora . 2012. p. 112. (Editora da UFF, 2ª edição)
- 199 [Smith ()] ‘CROPWAT. A computer program for irrigation planning and management’. M Smith . *Irrigation and*
200 *Drainage*, 1992. FAO -Food and Agriculture Organization of the United Nations. (Paper nº 46. 126p)
- 201 [Linacre ()] ‘Data-sparse estimation of lake evaporation using a simplified Penman equation’. E Linacre .
202 *Agricultural and Forest Meteorology* 1993. Elsevier. 64 p. .
- 203 [Hargreaves and Samani ()] ‘Estimation of potential evapotranspiration’. G H Hargreaves , Z A Samani . *Journal*
204 *of Irrigation and Drainage Division ASCE* 1982. 108 p. .
- 205 [Kohler et al. ()] *Evaporation from pans and lakes*, M A Kohler , T J Noredenson , W E Fox . 1955. U. S. Weather
206 Bureau Research. p. 21. (Paper 38)
- 207 [FAO "Crop Evapotranspiration (guidelines for computing crop water requirements)". In: Irrigation and Drainage ()]
208 <<<http://www.fao.org/docrep/x0490e/x0490e00.htm>>> *FAO "Crop Evapotranspiration*
209 *(guidelines for computing crop water requirements)". In: Irrigation and Drainage*, 1998. FAO -Food
210 and Agriculture Organization of the United Nations. (Paper nº 56. Available at)
- 211 [FAO "Irrigation Water Management: Irrigation Water Needs". In: Irrigation Water Management -Training manual nº ()]
212 <<<http://www.fao.org/docrep/S2022E/S2022E00.htm>>> *FAO "Irrigation Water Management:*
213 *Irrigation Water Needs". In: Irrigation Water Management -Training manual nº*, 1996. FAO -Food and
214 Agriculture Organization of the United Nations. 3. (Paper nº 24. Available at)
- 215 [Módulo 23 -Critérios para Estudos -Submódulo 23.5 -Critérios para Estudos de Hidrologia Operacional ONS]
216 ‘Módulo 23 -Critérios para Estudos -Submódulo 23.5 -Critérios para Estudos de Hidrologia Operacional’.
217 ONS ONS -Operador Nacional do Sistema. 11p. Julho de
- 218 [Morton ()] ‘Operational Estimates of Lake Evaporation’. F I Morton . *Journal of Hydrology* Oct. 1983, v.66. 114
219 p. .
- 220 [References Références Referencias] *References Références Referencias*,
- 221 [Macmahon and Mein ()] *Reservoir Capacity and Yield*, T Macmahon , R G Mein . 1978. Elsevier Scientific
222 Publishing Company. p. 213.
- 223 [Marques ()] *SisVazNat 1.0: Sistema de Reconstituição de Séries de Vazões Naturais*, M A G M Marques , E .
224 2010. p. 75. (1ª edição)
- 225 [Sisvaznat: Natural Flows Reconstitution System as a Support for Water Resources Management (Jun-03)]
226 *Sisvaznat: Natural Flows Reconstitution System as a Support for Water Resources Management*, Jun-03.
- 227 [Usda-Scs ()] *Soil Conservation Service, United States Department of Agriculture. Part 623: National Engineer-*
228 *ing Handbook*, Usda-Scs . <[ftp://ftp.wcc.nrcs.usda.gov/wntsc/waterMgt/irrigation/NEH15/](ftp://ftp.wcc.nrcs.usda.gov/wntsc/waterMgt/irrigation/NEH15/ch2.pdf)
229 [ch2.pdf](ftp://ftp.wcc.nrcs.usda.gov/wntsc/waterMgt/irrigation/NEH15/ch2.pdf)> 1993. p. . (Chapter 2: Irrigation Water Requirements)
- 230 [Table 5 : Results obtained in UHE Tucuruí Date Natural Flow (m³/s)] *Table 5 : Results obtained in UHE*
231 *Tucuruí Date Natural Flow (m³/s)*,
- 232 [Thorntwaite and Mather ()] ‘The water balance’. C W Thorntwaite , J R Mather . *Publications in Climatology*,
233 (Centerton, NJ) 1955. p. 104. Drexel Institute of Technology -Laboratory of Climatology