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Development of a tool for hydroeletric reservoir operation with multiple uses considering effects of climate changes. Case study of Furnas HPP

Elaboração de uma ferramenta para operação de reservatórios hidrelétricos com usos múltiplos considerando efeitos de mudanças climáticas: Estudo de caso da UHE de Furnas

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ABSTRACT

The possible impact of climate change on the multiple uses that involve the hydro power plant of Furnas was one of the objectives of this study by proposing a methodological approach to mitigate these conflicts. The first stage of the study was to perform a time trend analysis oh hydrologic variables being identified significant increasing trends in some rain gauges not reflected in streamflow data in the study basin. For representation of the future climate the hydrological model (MGB-IPH) was used inputted by the global model HadCM3 and regional Eta model through the A1B scenario of the IPCC. If the climate changes scenarios are verified, the reservoir can be quickly dumped, however the improvement of a methodology that considers the determination of the length and transgression frequency of levels, conflicts over water use can be minimized without damage to power generation.

Keywords: *Reservoirs. MGB-IPH. Nonparametric test. Furnas.*

RESUMO

O possível impacto das mudanças climáticas sobre os usos múltiplos que envolvem a UHE de Furnas foi um dos objetivos deste trabalho, sendo apresentado uma abordagem metodológica para mitigação destes conflitos. A primeira etapa foi realizar análise de tendência temporal das variáveis hidrológicas, sendo identificadas tendências de aumento significativas em alguns postos pluviométricos, não refletidas nos dados fluviométricos na bacia de estudo. Para representação do clima futuro, foi utilizado o modelo hidrológico (MGB-IPH), alimentado pelo modelo global HadCM3 e regional Eta por meio do cenário A1B do IPCC. Caso os cenários de mudanças do climas se verifiquem, o reservatório pode esvaziar-se intensamente; contudo pelo aprimoramento de uma metodologia que considera a fixação da duração e frequência de transgressão de níveis, os conflitos pelo uso da água podem ser minimizados, sem prejuízos a geração de energia.

Palavras Chave: *Reservatórios. MGB-IPH. Testes não Paramétricos. Furnas.*

INTRODUCTION

Water is one of the very important elements for the maintenance of life and of which all living things depend on it to survive. It is worth mentioning that not only the population increase and the acceleration of the economy amplify the multiple uses of water, but also the cultural development makes other needs to be incorporated (TUNDISI, 2003). Thus, in order to ensure the uses in a sustainable manner, it is important to manage water resources through structural and non-structural measures.

However, managing this resource is a challenge because there is an imbalance between availability and demand, either spatial or temporal. Moreover, the water supply is closely related to physical, geographical, occupation and other factors, at the climatic characteristics.

The climate behavior, due to its relevance, has attracted over time numerous studies by the scientific community, so much so that in 1988 was the establishment of the Intergovernmental Panel on Climate Change (IPCC), by the Organization World Meteorological (WMO) and the United Nations Environment Programme (UNEP) to evaluate climate changes on Earth.

After the fourth IPCC evaluation report in 2007, the number of studies on the impacts of climate change is increasing worldwide, especially on the effects of precipitation. This concern is mainly, because rainfall is the main input variable in the hydrologic cycle. Thus, it is important to understand the magnitude of the change, for each climate change scenario (CHIEW et al., 2009).

When it comes to a controversial subject and full of uncertainties such as climate change, divergent opinion heve been generated among the scientists themselves and society as a whole. Doran and Zimmerman (2009) estimate that over 90% of climatologists scientists agree that human activity contributes to a change or intensification of a phenomenon in global or regional climate.

According to Whitmarsh (2011), part of British society, mostly older and traditionalist people do not believe or are indifferent to studies that demonstrate "alleged evidence" of climate change. One of the reasons for their disbelief presented by them and even by some climatologists are uncertainties and ease of tampering of the data used in the predictions of computer models.

In Brazil, some evidence of climate change could be diagnosed with a warming of about 0.7 ° C in the last fifty years, higher value than the best estimate of the global average increase which was 0.64 ° C (IPCC, 2007). As a possible consequence of this event, Marengo et al. (2011) reported that in the period 2005 - 2010 there were two major droughts and one of the worst floods ever seen in the Amazon, and there was a record level of rivers in Manaus in 2009, and the following year, a record low.

Thus, climate changes can produce significant economic impacts. Among these, the power generation from hydroelectric power plants, which has significant share in the national energy matrix, could suffer from the electricity supply in the event of a reduction in rainfall, or imply the thermal power plant operation which generation costs are higher apart from greater pollution effect.

Among the main hydropower undertaking, there is the hydropower plant –Furnas HPP, located in the middle reaches of the Grande river, built in the early 60, flooding pastoral farmland, the main economic source of the time, forcing the surrounding population to adapt to new conditions imposed by initiating the development of other activities, especially the tourism around the lake

The Furnas HPP has wide reservoir, and the exposure to intense and lasting emptying represent instability in socio-economic activities dependent on the water slide. This uncertainty resulted in the organization of users and election by a minimum quota of Lake operation: 762 meters.

Therefore, further study of the hydrological components is necessary for better management of water infrastructure among these the hydroelectricity. Thus, based on historical data of precipitation and flow rate is possible do perform a study of time trends through statistical analysis based on non-parametric tests (not conditioned by any probability distribution of the data in analysis).

Blain, Picoli e Lulu (2009) justifies the adoption of parametric and nonparametric investigations based on statements of Dale's (1968) and Sansigolo and Nery (2000) for the greater statistical basement of climate description when theoretical models are used.

Among the research related to the better understanding of hydrologic variables, Santana, Silva e Santos (2011) analyzed the flow behavior in HPP Furnas basin, using the Mann-Kendall test, Sneyers (1975), and concluded that the basin of the Sapucai River was the one that recorded the highest number of stations with increasing trend of average flows rates. The same test was applied by Fechine and Galvíncio (2010) to analyze the variation in annual rainfall data in El Niño years fifteen stations located in the basin of Pontal river in Pernambuco, being observed slight reduction however not significant of data precipitation.

As in all planning activity in which the estimate of the future scenario may produce better results, the ideal condition is to obtain the prediction of flow to make a best projection of the operation of a hydraulic structure.

However, this kind of prediction, made by several research centers, does not identify patterns of climate change in which can occur over a few decades, due to natural or human activity variability.

In order to evaluate which climate changes would occur due to greenhouse effect, global climate models have been developed, they are three-dimensional mathematical model in space considering the main movements processes of the atmosphere and of the oceans, through a series of equations that describe the energy flow, momentum, mass conservation and gas laws, Ribeiro Junior (2013).

The models representing the global climate use global average values, but do not consider the temporal and spatial variability of the process (IPCC, 2012).

This study used four climate scenarios generated by HadCM3 global model (Hadley Centre Coupled Model, version 3) from Met Office weather centre (UK) although they have a spatial resolution of about 300 km, which makes them poorly suited to watershed scale.

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To solve this issue, the HadCM3 scenarios were detailed by CPTEC/INPE - Centro de Previsão de Tempo e Estudos Climáticos do Instituto Nacional de Pesquisas Espaciais (Weather Prediction and Climate Studies Center of the National Institute for Space Research) using the dynamical downscaling technique, generating projections with spatial resolution of 40 km (CHOU et al., 2012). The scenarios are projections of climatic variables covering the period 2010-2099 in addition to the 1960-1990 verification period at the interval of 6 hours.

For transformation of climatic variables scenarios flows the MGB-IPH – Modelo Hidrológico de Grandes bacias (hydrological model of large basins), developed by IPH – Instituto de Pesquisas Hidráulica (Institute of Hydraulic Research) of the Federal University of Rio Grande do Sul was used (COLLISCHONN, 2001) the MGB-IPH has been successfully apllied to identify possible impacts of climate change in the Grande river basin as the work of Nobrega et al. (2011), as well as the labor of Collischonn et al. (2007) for the application of hydrologic model for prediction using rainfall provided by the Eta model for energy studies at the Parnaíba river basin. Before the flow scenarios for 2099, a mechanism has been enhanced so that search a better management of water resources in order to mitigate the competing uses in Furnas plant, through the formulation of an operation rule to consider both the downstream interests as the amount by fixing the duration parameters and frequency of the level of the lake so that restrictions are incorporated in lowering the reservoir to dimension 762 m, also considering the energy supply, using the methodology of adaptation developed in Ribeiro Junior (2004) work.

MATERIALS E METHODS

The study area is inserted in the Grande river basin (sub-basin 61),

Figure **1**, which belongs to the Paraná River basin, located in southeastern Brazil, in the states of Minas Gerais and São Paulo. The drainage area is approximately 52,000 km^2 and is located in the section called "Furnas rapids", between the cities of São João da Barra and São João Batista do Glória

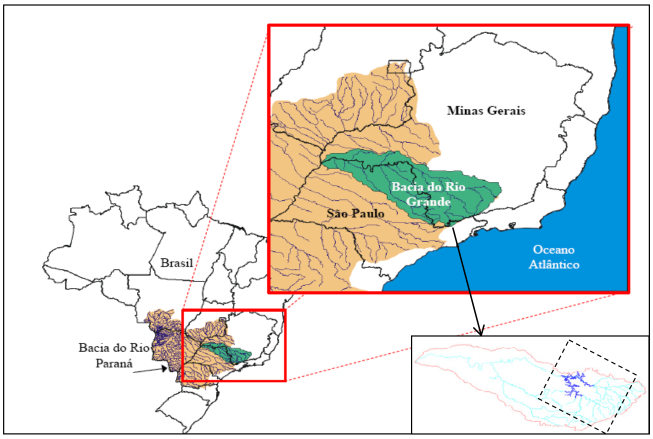

Figure 1 - Delimitation of the study area

in Minas Gerais.

Furnas Hydropower plant had the first unit operating in September 1963. In the early 70s, the expansion was started for installation of seventh and eighth units totaling 1,216 MW (FURNAS, 2012).

The reservoir has about 1,440 km² flooded area, four times the Guanabara Bay. It is one of the largest artificial lakes in Latin America, known as the "Sea of Minas" and perimeter of 3500 km; bathes 34 cities with a population of approximately 850,000 inhabitants.

The project foresees a quota of variation between 750 m and 768 m (minimum and maximum operating level). Between 1963 and 2011, the reservoir remained 75% of the time with a dimension greater than or equal to 762 m, Furnas (2012). However, between 1998 and 2000, the time of greatest crisis in the electricity sector, this same level was present only 30% of the time, a fact that according to Engel (2003) resulted in significant losses for users of water from the lake, which now claim a minimum quota operation (762 m), on the grounds that all tourist developments have been built based on this quota. Data from the Association of Furnas Lake Users Alago (ALAGO, 2012) show that the main impact of the reduction in the level were reduced movement of tourists by 70%; 40% decrease in agricultural production; disorder in the bordering properties for animal watering and reduction in the quality and quantity of fish.

TREND ANALYSIS

After determining the study area, the next step was to analyze the behavior of climate variables, starting with the precipitation which is the main hydrologic variable input of the hydrological cycle. The screening process of information is a key step to support the research, it is also necessary to evaluate the availability, consistency, completeness and failures, that is quantitative and qualitative aspects related to the historical series. However, this analysis should not incur errors that may distort the data, or intervene in other information. Thus, in order to avoid possible trends to the collected data, it was not carried out the gap filling process.

Thus, they were selected for analysis the rainfall stations that were contemplated in the basin where Furnas HPP is located (total of 143). Of these, 45 do not have data available, restricting to 98 the amount of stations to be studied.

For hydrologic analysis, two important factors must be considered: the consistency of information and availability of data which must be longer than 30 years, a fact that limited to 81 the sample space and most of these stations have data up to 2000.

As one of the objectives is to make a flow forecasting based on the IPCC projections (2012), it is important to analyze the behavior of data, covering the validation period of climate models (1960-1990) so that the number stations decreased to 45.

The last filter for selection of stations was to pick the stations that do not have a significant number of failures, and have a common data period, resulting in 22 stations with data between 1948 and 1998 (Figure **2**).

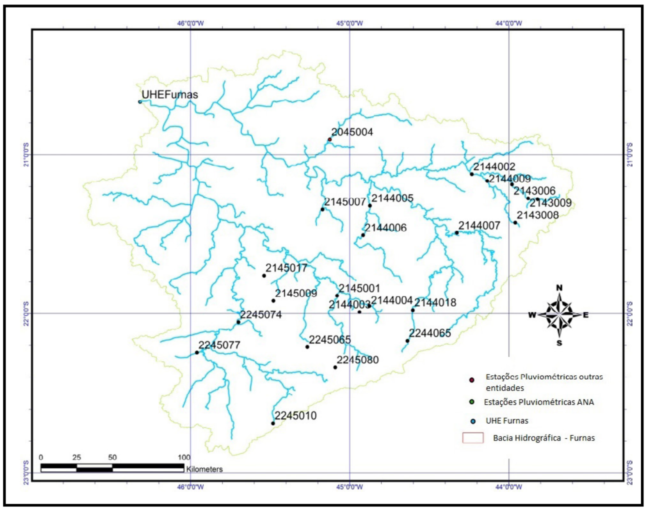

Figure 2 – Selected rainfall stations for analysis

The next step was to apply statistical tests used in research which aims to compare experimental conditions and provide support so that they are valid and are accepted in scientific community. These tests can be divided into parametric and non-parametric.

In parametric tests, the values of the variables studied should have normal distribuition or normal approximation. The non-parametric tests, also known as free distribution tests, have no requirements as to the knowledge of the variable distribution in the population.

Barnett and Turkman (1997) conducted intensive bibliographic research and report that 65% of the tests conducted on environmental data are simple tests of significance, 25% of data processing are performed with multivariate data analysis and only 10% of data processing are developed with other mathematical tools such as temporal trends tests, which reinforces the importance of this work.

Since the objective of this study is to evaluate the behavior of hydrologic series, it is more appropriate to use nonparametric tests.

Among the most recommended methods for checking the behavior of climate data, there is the evaluation by non-parametric analysis, using Mann-Kendall test and Pettitt, according to Blain (2010), being that some authors also recommend applying Run test (BACK, 2001). Thus, these methods have been applied to check the orientation of the data in the study area. In addition to these non-parametric methods, linear regression tests are applied, mobile window and annual fluctuation, which allow better visualization of the hydrological behavior, such as the Spearman test, Alexandre, Baptista e Naghettini (2010), designed to measure the correlation between the data.

The Mann-Kendall test, initially proposed by Sneyers (1975), regards that in the event of stability of a time series, the succession of values occurs independently and the probability distribution must always remain the same (simple random number). Blain (2010) describes the method considering a time series X_i of N terms ($1 \leq i \leq N$); The test consists of the sum t_n of the number of terms m_i of the serie, related to the X_i value which above terms ($j < i$) are lower than the same ($X_j < X_i$).

The null hypothesis is that there is no climate change considering a α level of probability of 5% between sample values and the population of this, that is, the absolute value of statistics of the normal distribution pattern Z should be greater than $Z_{1-\alpha / 2}$, ie $Z > 1.96$. If this occurs, it means that there is a significant trend in the series, and the signal will indicate whether the trend is positive ($S > 0$) or negative ($S < 0$). However, the author states that the presence of positive autocorrelation may represent a false upward trend, and the same can happen for negative values. Also according to Blain (2010), this test is useful because it takes into account the fact that there may be seasonal variations in the data, but is not considered the value of this variation.

The work of Blain (2010) applied the Mann-Kendall test, in order to detect climate trends in rainfall monthly series in eight cities in the state of São Paulo, in the period 1948-2007, and in Monte Alegre do Sul was observed the presence of elevation trends in the monthly series of September and May. The stations of Campinas and Ribeirão Preto indicated the existence of elevation trends in the series for the month of May. In the serie of Jundiaí was observed upward trend only when the annual totals were analyzed. In the cities of Cordeirópolis and Pindorama no significant trend was observed. As for the town of Ubatuba there was detected a small downward trend in August.

The major repercussion of climate change forecast studies led Hamed (2008), to propose an adaptation to the Mann-Kendall test (changes in the expression of variance), and apply to 57 series of global runoff data centre at Koblenz Germany, indicating that the evidences of the real trends in hydrological data is weaker than suggested by the original test, also indicating that the proposed adjustment helps to reduce the discrepancy found in previous studies.

The Pettitt test (PETTITT, 1979) uses a version of the Mann-Whitney test proposed by Wilcoxon (1945) and Mann and Whitney (1947), where it is verified whether two samples X1, ... Xt and Xt + 1, ..., XT are the same population. The statistical Ut, T makes a count of the number of times a member of the first sample is greater than the second member. This test allows the location of the point at which the abrupt change occurs (break) in a time series besides of calculate the level of statistical significance without prior knowledge of the point in time where it occurs.

The run test is a nonparametric test used to assess whether a serie is randomly. Consists of performing counting the number of oscillations above and below the median values in a naturally ordered series of data. The number of oscillations is called Run and must test if the observed value is within the range considered normal distribution. A high Run value indicates many oscillations, and lower values indicate a deviation from the average during the period of records

Regression analysis may be used to indicate climate change through the angular coefficient significance test. Considering the line equation: $Y = aX + b$, the test is to determine the confidence interval of the coefficient"a", and that this range

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does not include the value zero, the trend is significant.

The moving average is a technique used to analyze the average value of a sample in a given period. The term "moving average" refers to the arithmetic average of a certain number (n) of the most recent observations. As new observations are performed the older observations are abandoned.

The method of annual fluctuation is based on the the sum of the difference of all measures compared to the average, and the resulting value is zero. In this case, the highest values of the accumulated deviations indicate how far, in general, values are to the average value.

But the Spearman test allows to evaluate the correlation coefficient r between two variables X and Y and measures the degree of association, which must be in the range $-1 < r < 1$. In this study, which is intended to assess the existing trend in the series of hydrological data, the variable "X" represents the hydrologic data set in its natural sequence, and the variable "Y" is the order of the data in ascending order.

These methods have been applied to several studies to check climate precipitation trends, flow, temperature and minimal grass, among other variables, in various regions and in daily series, monthly, annual, quarterly, annual maximum daily, etc. as the focus of research.

HYDROLOGICAL MODEL

For the transformation of rain in flow, the MGB-IPH model were used, it incorporates information from physical characteristics of the basin, such as topography and soil types and land uses.

In advance to use of the model there is a need to generate maps of the study region, for example, relief maps of the studied region, the drain bowl and the length of the river. For Furnas basin, these maps were generated by the MGB-GIS routines with SRTM relief maps available for almost all of Brazil according to EMBRAPA (2012), with a resolution of approximately 90 x 90m.

Complementarily, were obtained soil and vegetation maps of the region, the first obtained by the IGA (2012), and the second obtained by supervised classification of satellite images with different capture bands made by Collischonn et al. (2007).

The development of this step is intended to provide information to the model to calculate the water balance within each pixel and thus estimate runoff responsible for generating flow in the pipelinechannel.

Finally the basin was divided into sub-basins for the calibration of the model to take into smaller areas, prioritizing the precision and the possibility of observing variations in setting parameters between sub-basins. The division was established by the existence of streamflow stations, with consistent data series, being the outfall of each sub-basin. At this stage, there was again a check of the direction of flow of the cells as the area of each sub-basin should be close to that reported for the fluviometric stations by the ANA – Agência Naciona de Águas (National Water Agency) which in this study was 20 seasons.

The information about the soil was obtained from IGA (2012), in order to estimate the infiltration capacity and may be able to provide an estimate of runoff and infiltration in each cell.

To use and occupation was used the supervised classification performed by Collischonn et al. (2007), in which a separation of water, pasture and exposed soil, agriculture and forest was carried out.

Using the information presented it is possible to run the MGB-IPH model to estimate the flow and calibrate the required parameters. Thus it should be set the time interval of data used for calibration and the interval for checking. The range from 1968 to 1990, in which the availability of data is quite comprehensive in the basin and includes the IPCC validation period was divided into two series. The first series includes the years 1968 to 1980, used for calibration, and the second series from 1981 to 1990, to validate the calibration performed.

The calibration parameters for the quality check are: volume error (ΔV), Nash-Sutcliffe coefficient (NS that represents the proximity of hydrograms generated with the readings in fluviometric stations, especially in flow peaks) and also the coefficient logarithm of NS (NSLog, which resembles the last, but with special attention to low flow).

NSLog values greater than 0.6 can be considered good values, that is, the calibration was good, being tolerable values around 0.5.

CLIMATE MODELS

The next step was the application of climate scenarios of the Eta model for representations of the present and future climate, represented by numerical projections of climate models. However most of the time the models are not able to represent perfectly all phenomena and climate processes due to the influence of the spatial discretization of the models so that the representation of climate appears distorted in related to the measured data.

In general, these differences are caused by systematic errors which must be removed so that misunderstandings do not spread in projections of streamflow. Thus, the six climatological variables designed by Eta model will be corrected in the periods: 1961-1990, 2011-2040, 2041-2070 and 2071-2099, for the four climatic members.

After the consistency of climate data, these will be the basis to feed the MGB-IPH hydrological model, resulting in series of Furnas flows under the effect of the present and future climate. The regional climate can be controlled by physical factors that may have much smaller spatial scale. Physical characteristics such as topography, vegetation type, land/ water distribution can cause significant influence on regional climate, such as the Mar and Mantiqueira ridges which are important geological formations and can go "unnoticed" or model can not represent these mountains, depending on the Global model grid scale.

As a solution to this obstacle was applied the technique of "downscaling" which consists in densification technique that uses a higher resolution atmospheric model (regional model) supplied by border conditions produced by the global model.

In the process of downscaling the regional model uses the conditions of frontier of the global model cells to generate a simulation with a higher resolution which produces a more detailed and closer representation of the observed or actual of that region

In order to improve the representation of climate and physical processes for a particular region the regional models have been developing increasingly using different methodologies.

The Eta model has been used by the INPE as weather prediction model and the seasonal climate. The seasonal climate version of this model has been adapted to run integrations with decadal time intervals, with the focus on the study of climate change scenarios. The Eta model was adjusted to the HadCM3 global model, with a 40 km horizontal resolution and 38 layers vertically, as Chou et al. (2012).

For the preparation of future climate projections model, the CO_2 concentration was kept constant within the A1B scenario parameters of the IPCC. This scenario is representingt the closest future development of what we experience ie with conditions "average" not so pessimistic (rapid increase in the consumption of fossil fuels and destruction no or very little environmental concern, etc.) and it is not so optimistic (only use renewable energy to have an exaggerated concern for the environment, etc.).

From this definition of greenhouse gas emissions scenario, disturbances have been made in some model parameters in order to generate scenarios or different members within the Eta model, resulting in the generation of hundreds of members, among which were chosen only three members who had high, medium and low sensitivity in response to future global average temperature. Together, a member without any disturbance characterized as control was done. These four members provide future boundary conditions for driving multiple achievements of the Eta model. To connect or check with the observed data were simulated data for the period 01/01/1961 to 30/12/1990, representing the present climate, according to the methodology presented by Chou et al. (2012).

Whereas climate models can not perfectly represent the current climate and that its results have errors it's becomes necessary to remove these systematic errors (bias) for each of the climate variables of the projections generated by the Eta-40 model using different methodologies, which were based the errors behavior analysis and also due to the spatial discretization and temporal data.

The methodology used to remove errors in precipitation was presented by Bárdossy and Pegram (2011) and is called by Quantile-Quantile mapping. This method is based on comparison of cumulative probability curves (curves showing the probability of the variable is less than or equal to a given value) of the observed variable and the variable estimated by a weather model the current and future period.

For bias removal for precipitation identified in the Eta model of the current climate is identified in the cumulative probability curve for each daily value belonging to the month of the year for which they were estimated, the value of the cumulative probability. Subsequently, the fixed daily amount is equal to the observed value which has the same amount of cumulative probability of the observed data (Figure 3).

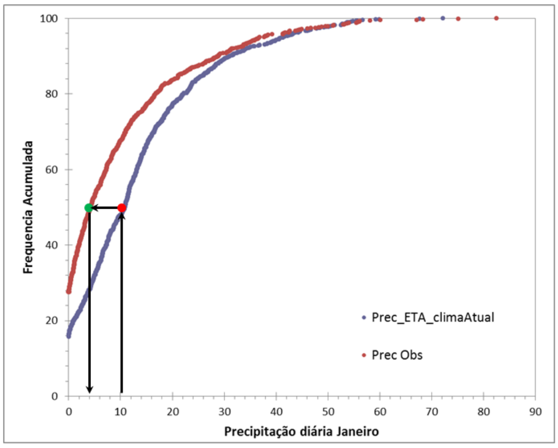

Figure 3 - Bias removal procedure in the current period

In this example, the daily rainfall of 20 mm recorded by the Eta global model in January shows a cumulative probability of 76% (24% of the values were greater than or equal to 20 mm in January). This same cumulative probability (76%) equivalent to 14 mm of precipitation observed. Thus, it can be verified that there was a overestimated deviation of 6 mm of rainfall value.

For the future period, the procedure adopted was similar,that is, for each daily value of future variable series analyzed belonging to the month of the year for which the curves of accumulated probability were estimated is identified the value of the cumulative probability in the current range of climate model. Subsequently, the daily value corrected in the future period is equal to the observed value that has the same amount of cumulative probability

The method was applied using the precipitation time series estimate in the center of each of the existing cells in the studied region. The removal procedure of systematic errors was applied independently to the precipitation values estimated by different members of the Eta-40 model (CTRL, LOW, MID and HIGH).

For correction of systematic errors present in other climatological variables of the Eta model (wind to 10 m, temperature at 2 m, atmospheric pressure, relative humidity and solar radiation), we used the bias removal methodology called linear scaling by Lenderink, Buishand and Van Deursen (2007). This methodology is based on the calculation of a correction coefficient from the differences between the climatological normals observed and estimated by climate models in the current period. The same coefficient is used later in the removal of systematic errors in future periods correction. If the physical limits were exceeded, the variable value that day is limited to the amount of physical limit.

After interpolation of the Eta model data to solve the hydrological model, the next step is to verify that the model simulates the seasonality of the current climate. in order to describe the hydrological cycles, ie, humid periods (flood) and dry (drought) and verify if these are coincident.

After the calibration and verification of the calibration of the hydrological model, the next step is to generate the series of flows based on future projections of the Eta model. The flow files were divided into monthly average flow rates (average

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30 days) and daily flow remembering that each month of the Eta model has 30 days, totaling 360 days each year. The files were divided for each period (1961-1990, 2011-2040, 2041-2070 and 2071-2099) and for each model Eta member (M1-control, M2-Low, Medium M3-M4 and-High).

RESERVOIRS OPERATING MODEL

Through research on climate change linked to projections of the EPE – Empresa de Pesquisa Energética (Energy Research Company) that demonstrate the importance of the water to the interconnected system, a factor which may imply greater reliance on reservoirs and consequently greater emptying the lake to meet the energy demand there is the need to develop a model that reconciles the multiple uses of water, as required by law 9.433/97, taking into account the interests of downstream populations (with interest in regulating flows) and upstream (interested in maintaining the levels of the reservoirs), in contrast the current model that saved some restrictions has the only purpose of generating energy.

This study is proposed a method of operation using an adaptation of Ribeiro Junior study (2004) who considers an operational rule that includes the time and number of times, attention cycle, at a determined distance (reservoir level) so that not only meets the power generation but could also ensure the sustainability of multiple uses; to do so it is necessary to the definition of the following concepts:

Duration *(d)*: represents the number of times (months) coordinates that occur below the reference level at a specific period;

Frequency (*f*): represents the number of cycles (periods) that are existing below a reference level at a specific period;

Transgression duration (*dt*) is the relationship the duration (*d*) and frequency (*f*);

$$dt = \frac{d}{f} \qquad (1)$$

Transgression frequency ($\overline{ft}$): relantionship between the frequency (f) and the sample size (*n*);

$$\overline{ft} = \frac{f}{n} \qquad (2)$$

Taking as reference that a litigation for a minimum quota of the lake occurred after 1997 was considered in the previous period (1963-1997) the plant had an operating cycle in order to meet the interests of all users. Thus are calculated for this period (1963 - 1997), the duration (*dt*) and frequency (*ft*) of transgression to the 762 m quota (reference for users of the Lake) that will serve as a parameter for future projections.

Thereby:

Duration (d): = 99 months;

Frequency (f): = 13 cycles;

Transgression duration (dt): is the relationship the duration (*d*) and frequency (*f*);

$dt = \frac{d}{f}$ = 99/13 = 7.62 (months/period)

Transgression frequency:

$\overline{ft} = \frac{f}{n}$ = 13/412 = 0.032

Considerind the five-year planning horizont (60 months), the duration is determined (d_d) and the frequency (f_d) desired for this period based on $\overline{ft}$ e *dt* estimated values.

$\overline{ft} = \frac{f}{n}$ => f = 0.032 x 60 = 1.89 (cycles)

Thus, in a period of five years will be allowed to transgress below the dimension 762 m in only two cycles.

For the transgression duration (*dt*):

$dt = \frac{d}{f}$ => d= 7.62 x 1.89= 14.4 (months)

Thus, in order to balance the interests of users of the lake, the ideal is that the reservoir is only two cycles (f_d) and a maximum of 15 months (d_d) below the 762 m quota in an interval of five years.

If the desired frequency and duration conditions are not met within the specified period (five years), or $d_c \geq d_d$ or $f_c \geq f_d$, will be adopted an operation rule so the reservoir reaches desired levels through the storage of 15% of the influent flow whenever the projected level is below the 762 m quota, so that the reservoir can achieve the desired levels. After storage of this quantity of water is calculated again duration and frequency for the last five years.

The accumulation of water greater than planned will continue until the calculated time is less than or equal to the desired within five years. When this happens, that is, $d_c \leq d_d$, one should check if the frequency was answered.

If so, from next month outflow should be planned flow itself. But if not, ie, whether the imposed condition is met for the duration but not to the frequency it is not necessary to continue accumulating water in a quantity greater than the planned; thus, the proposal is that the reservoir level is kept constant until the desired frequency is achieved by maintaining the outflow to be the same as the inflow.

For comparative purposes the Table 1 presents a comparison between the design developed by Ribeiro Junior (2004) original of the methodology and the adjustment made.

This methodology will be used considering the inflow data designed by MGB-IPH taking as input the information provided by the Eta model, considering the A1B scenario of IPCC for the period 2011-2099, according to the following assumptions:

The first hypothesis considered for the future period that Furnas HPP will try to maintain the average monthly history of energy production between 1963 and 2011, ie outflows and the level of the reservoir will be determined on the basis of energy production and inflow .

In the second hypothesis, Furnas will have to reconcile the interests of upstream and downstream users, meeting

Table 1 - Comparison between frequency and duration models

Item	Original Model	Adapted Model
Inflow projection	through stochastic method	Throught hidrological model
Reservoir operation rules	main focus on the reconciliation of the interests of upstream and downstream users	besides the interest of users consider the power generation
Restriction levels	Compliance with the frequency and duration conditions, considering the quotas 761m, 766 m and 767 m.	compliance with the frequency and duration conditions, considering the 762 m quota
Planning horizon	30 years	100 years (IPCC projection)
Time to meet the frequency and duration conditions	10 years	5 years
Outflow storage	10%, 15%, 20% and 30%	Not applicable
Inflow storage	10%, 15%, 20% and 30%	15%
When not meet the duration frequency conditions	stores a percentage of inflow and outflow	stores a percentage of the influent flow only when the inflow exceeds planned outflow

the frequency conditions for desired duration. In this case, depending on the affluent and defluent flow series scheduled, the production of energy will be designed.

RESULTS AND DISCUSSION

TREND ANALYSIS

For analysis of the hydrological behavior of the study area were used statistical tests for the period 1948-1998 for the 22 selected rainfall stations, as shown in figure 2. For the Mann Kendal test (adopting the significance level of 5%) the pluviometric stations that did not obtain the Z value contained in the range [-1.96: +1.96], ie which have suffered some kind of significant change are shown in Table 2.

Table 2 –Mann-Kendall test results

Station	Z	Station	Z	Station	Z
2143006	2.31	2144018	2.30	2144004	3.82
2143008	3.84	2145001	2.52	2245065	2.66
2145009	3.46	2245080	2.92		

In the same manner as in Mann-Kendall test, for the Pettitt test was adopted a level of significance of 5%. For selected rain gauges stations, whereas the series have 51 years data, the critical value is 288.37, i.e., when the Ut value is greater than this value indicates the breakpoint of the series, as shown in Table 3.

Table 3 –Pettit test results

Station	U(t)	Breakpoint	Station	U(t)	Breakpoint
2143006	316	1971	2145001	312	1963
2143008	560	1970	2145009	462	1964
2144004	478	1971	2245065	289	1965
2144018	342	1975	2245080	506	1963

As shown, the stations that showed upward trend are the same identified in the Mann-Kendall method, which reinforces the trend of increasing rainfall data in 1948 to 1988 these posts. However, this method makes it possible to assess the extent of trend change, in this case ranged between 1965 and 1975.

As in other tests applied, in the Run test was also admitted a significance of 5% and the results were as shown in Table 4.

Table 4 – Run test application

Station	T	Station	T	Station	T
2143008	-4.39	2145009	-2.97	2245080	-5.23
2144004	-4.39	2245074	-2.97		

Throught the Run test, only five stations showed upward trend and only one of these stations (2245074) had not shown this trend compared to previous tests.

The Spearman test allows to evaluate the correlation coefficient r between two variables X and Y and measures the degree of association. In this study, which is intended to assess what the existing trend in the hydrological data serie, the variable X is the set of hydrological data in its natural sequence and the variable Y is the order of the data in ascending order. Table 5 shows the results for this test.

Table 5 – Spearman test aplication

Station	T	Station	T	Station	T
2143006	2.43	2144018	2.63	2244065	1.45
2143008	4.89	2145001	2.66	2245074	2.02
2144004	5.04	2145009	3.91	2245080	3.68

This test identified the growth trend in those posts already identified by earlier tests applied.

The tests of the Moving Average, Annual Fluctuation and Linear Regression allow a better graphical visualization of the behavior of hydrologic variables. Results for Moving Average and Linear Regression tests confirmed the results presented above. But the annual fluctuation test allows you to view the point where the time series is replaced by a change of behavior. Figure 4 illustrates what happened and you can see that for the city of Baependi there was a decay of rainfall until the beginning of the 70s, and after this period, the total annual precipitate was higher than the annual average for the study site.

Overall, the rainfall of the studied stations have a decay trend in the 1948 period to the beginning of the 70's and from this point the records of rainfall rates have returned to an upward trend, with reference to the average data of the annual total.

Figure 5 represents the arrangement of stations that

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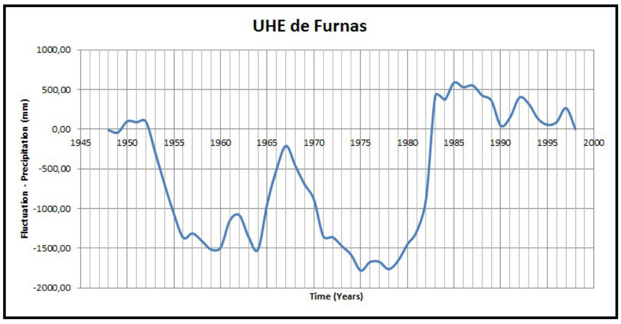

Figure 4 – Accumulated rainfall variation for the city of Baependi

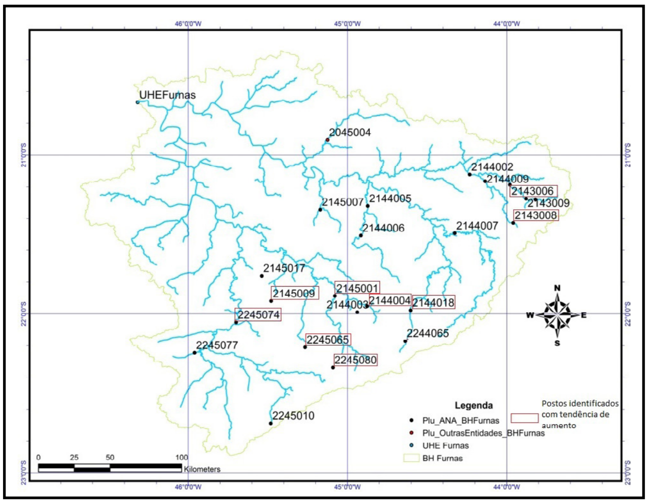

Figure 5 – pluviometric stations identified trend of increasing rainfall indices in 1948-1998 period

have been analyzed as well as those that have been identified as having a tendency of increase of the historical data of rainfall records.

In this case, it may be noted that only part of the rain gauge stations showed upward trend which may represent a clue that the phenomenon is of regional scale. Moreover, the fact that they are concentrated in the higher parts of the basin, in regions where urbanization rate is still not as high indicates that the existing phenomenon may be evidence of climate change and not just an effect of urbanization.

As the objective of this study is to analyze the effect that these changes can bring to the operation of Furnas HPP, the same statistical analysis was performed considering the data of the natural series of reconstructed flow by ONS and the fluviometric stations of the study basin, and found that the behavior of the average annual flow for the period 1948-1998 showed a slight upward trend, a fact that may be related to increased rainfall. Table 6 presents the results for the flow series of Furnas plant.

Table 6 – Statistical results for Furnas HPP

Mann-Kendall	Pettit	Run	Spearman
1.10	204	-0.988	0.962

The results of statistical tests indicate that the series of annual average flow rates for the period 1948-1998 show an increasing trend, but not significantly. This increased "water supply" is an indication that other basins may also be experiencing changes, a fact that can become even more relevant in the face of scenarios and studies that show possible changes in climate, but the theme is still very controversial.

The evaluation of trend of increasing rainfall and flow are important; however another factor to be considered is how this event occurs. A decrease in the distribution period can increase the flood and reduced minimum peaks, and therefore reduce the water availability and also affect other sectors such as agriculture where rain has a critical climate role for plants, since water is essential for growth and plays an important role in photosynthesis, so in production.

However a more specific analysis for the rain gauges stations indicate that the number of days of rain each year did not change significantly.

HYDROLOGICAL MODEL

As one of the objectives is to evaluate the hydrological behavior by the IPCC projections, the next part proceeded to the hydrologic modeling. To this were generated relief maps with high and low resolution being that much of the basin is concentrated between the altitudes from 700 to 900 meters.

Finally, manual adjustments of the parameters for the 20 sub-basins were performed. After this step, the model advances for automatic calibration in the direction from upstream to downstream basins, comparing the values observed in streamflow stations and performing NS calculations, NSLog and ΔV, and noted the value of NS log close to 0,83 for Furnas sub-basin which shows that the MGB-IPH was well adjusted to the study basin.

Figure 6, represents a comparison between the calibration and verification in the "Furnas sub-basin". Note that in this is the case, the model represents well the hydrological behavior.

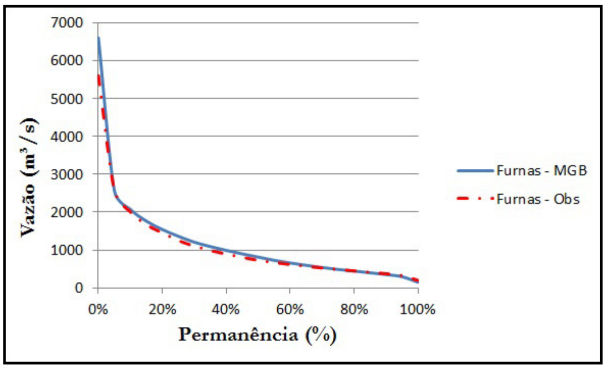

Figure 6 – Permanence curve of calculated and observed streamflow for Furnas basin

CLIMATE MODELS

The next step was the realization of the projected flow for the period January 2011 to the end of November 2099. To feed the rain – flow model was used six climatological variables designed by Eta model within the A1B scenario parameters of IPCC.

From the definition of the greenhouse gas scenario have been made disturbances in some model parameters resulting in the generation of hundreds of members of which only three were chosen, who had a high, medium and low sensitivity in the response of the future global average temperature as well as the use of a member without any disorder characterized as Control.

Figure 7, the average monthly flow is represented in which is located the Furnas plant, outfall basin for the four scenarios of the Eta model and the flow rates observed from 1961 to 1990.

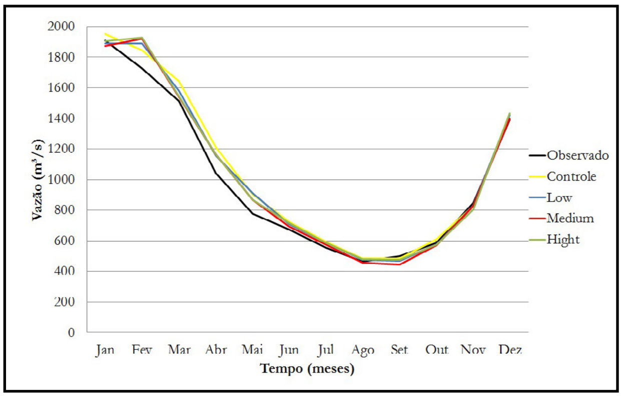

Figure 7 - observed streamflow and the four scenarios of the Eta model for the period between 1961 and 1990

Thus, it can be verified that the Eta model is well adjusted; however suffer small relative deviation from the observed data, which are justified by the difficulty in representing the peaks of the full data of the observed events.

Figure **8**, represents the average monthly hydrograph for the four A1B scenarios of the Eta model for the period 2011-2099.

The medium scenario is the most conservative in regard to inflows projected to Furnas (even compared to historical data) based on the A1B scenario of IPCC, which is why it was used as a reference for inflows (input) in the reservoir operation simulation.

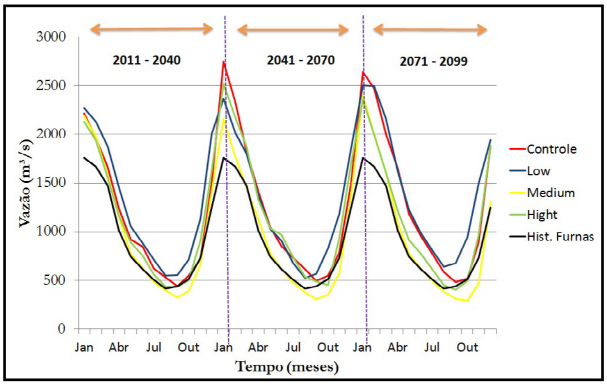

Figure 8 – Flow projection using the MGB-IPH, fed by ETA model, considering the A1B scenario parameters of IPCC

RESERVOIR OPERATION MODEL

For the development of simulations the following characteristics of Furnas HPP were respected:

Maximum level of storage: 768 m;

Minimum operating level: 750 m;

Useful volume: 17.217 billion m³;

Dead volume: 5.73 billion m³.

To estimate / projections of reservoir levels were considered two premises.

The first is that the historical average power generation between 1963 and 2011 for Furnas HPP will be kept constant for future scenarios. Thus if the scenarios of the Eta model are verified, the reservoir tends to remain full, compared to previous records, mainly because of the climate model to project higher water intake in the wet period. However, for the period 2041 - 2070, due to a prolonged drought, the reservoir can be emptied completely so that the energy demand is met, which should be avoided as it will certainly affect the other activities that depend on water resources available in the lake, as shown in Table 7.

Table 7 – Permanence projection of the Furnas reservoir level, considering the maintenance of the historical average generation

Percentil	2012–2040	2041 - 2070	2071-2099	Furnas Historic
0%	768.0	768.0	768.0	768.0
10%	768.0	768.0	768.0	767.7
20%	768.0	768.0	768.0	767.2
30%	768.0	768.0	768.0	766.5
40%	768.0	768.0	768.0	765.9
50%	768.0	767.8	767.9	765.1
60%	767.7	767.3	767.5	764.1
70%	767.2	766.7	766.8	762.8
80%	766.8	765.8	766.0	761.2
90%	766.0	763.8	764.9	758.4
100%	763.5	750.0	758.7	751.5

From the energy point of view due to greater water availability, Furnas HPP power generation will be higher (Table 8), but it was not considered the effect on the SIN - Sistema Interligado Nacional (National Interconnected System)

Table 8 - Projection for Furnas power generation

	2012 - 2040	2041– 2070	2071 – 2099	Furnas Historic
Energy (GWh)	579.4	554.8	544.8	424.3
Total generation capacity (%)	65.3	62.5	61.4	47.8

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Case the projections of A1B model are verified, the Furnas HPP may have an increase in generation by 32% while maintaining the fullest tank. However, downstream population will have to live with the variation of the inflow.

The second premise considers the need to address the interests of users, who in addition to maintaining the level of the reservoir should include the flow regulation to meet the downstream population needs. Thus, we used the outflow series determined by the "trade off" negotiating tool used for balancing of interests, according to Ribeiro Junior (2004). In this case, downstream flow (outflow) will remain more than 40% between 800 and 1100 m³ / s, providing greater security for the activities due to the minimization of seasonality.

By projections of inflows by the MGB-IPH and outflow determines the power generation and consequent variation of the quota on the lake. Thus, it is projected that the reservoir remains most of the time below the level desired by the upstream population (762 m), for example, the period of nearly a decade between August 2057 and January 2066, as shown in Figure 9.

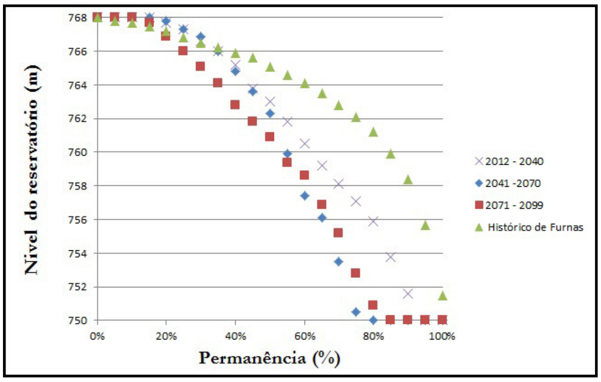

Figure 9 - Levels permanence curves designed to Furnas

From the energy point of view as one of the objectives is to reduce downstream flow seasonality, the plant could use more than 70% of its power generation capacity (Table 9).

Table 9 - Projection for Furnas power generation

	2012 - 2040	2041 - 2070	2071 – 2099	Furnas historic
Energy (GWh)	659.6	620.8	608.4	424.3
Total generation capacity (%)	74.3	69.9	68.5	47.8

In these simulations, the energy analysis was focused only on Furnas plant, not being analyzed the impact on the SIN.

As this scenario is the most restrictive, for the consideration of the interests of all users, this simulation will be used as the basis for application of frequency and duration concepts.

For application of these concepts, the first step is to check the preconditions (stay only two cycles distributed in 15 months below the quota 762 m) in the last five years.

Thus, to meet a full annual cycle and compatibility of the IPCC scenarios, simulations will contemplate the period January 2012 to December 2099.

If the Eta projections are confirmed, Furnas HPP can program generation without restrictions, until the month of October 2018 (Table 10).

Table 10 – Quota projection (m) for Furnas HPP between November 2013 and October 2018

	J	F	M	A	M	J	J	A	S	O	N	D
2013											764	766
2014	768	768	768	768	768	768	768	767	767	767	768	768
2015	768	768	768	768	767	766	765	764	762	**760**	**760**	762
2016	766	768	768	768	768	768	768	767	767	766	766	767
2017	768	768	768	768	767	766	765	763	**761**	**760**	**758**	**757**
2018	**757**	**759**	**758**	**758**	**755**	**752**	**750**	**750**	**750**	**750**		

As methodology, for the last five years (November 2013 to October 2018), there were observed in 16 months levels below the quota 762 m, recorded in both periods. In this situation, as the objective is to prevent the reservoir to continue emptying or to remain at such a low level, 15% of the influent flow planned for the month will be stored. Thus, there is:

Reservoir level in October 2018= 750 m

Inflow planned for November 2018 = 290.43 m³/s

Outflow planned for November 2018 = 727. 96 m³/s

However, as the frequency and duration conditions were not met and the reservoir is in its minimum operating level, the planned outflow will be:

$290.43 \times 0.85 = 246.87$ m³/s

In this case, the reservoir level scheduled for November 2018 will be 750.21 m.

This monthly plan runs until December 2099, considering a moving window of five years, keeping the storage rule 15% of the influent flow whenever the frequency and duration conditions are not met.

In comparison, for the period between 2012 and 2099 were recorded 516 months below the dimension 762 m, and after the application of the methodology, there was a decline to 239 months in addition to the reduction of 23 cycles (periods) to 16, below the 762 m quota.

From the energy point of view, it can be verified that the methodological application does not affect the energy production (Table 11).

Table 11 – Projection for Furnas HPP power generation

	2012 – 2040	2041 - 2070	2071- 2099	Furnas historic
Energy (GWh)	642.1	619.9	620.2	424.3
Generation capacity em (%)	72.3%	69.8%	69.9%	47.8

Considering the outflows projections, the average flow of 930 m³/s, remains 45% of the time in the watercourse, very important factor for ensuring the activities developed downstream..

The conception of a method to examine the downstream and upstream interests due to penalty for significant variations in elevation and flow, continuing to fixation duration and frequency, seems to be a mechanism that can aid in deliberation of interest not only of directly related users the activities of the lake, but also the collective as well as power generation.

Thus it was possible to show that it is possible to operate hydroelectric projects as already established the Water Code (Decree No. 24.643 of 1934, replaced by the current National Water Resources Policy the "Water Law", Law 9433/97), which in its Article 143, instituted that all hydraulic power exploitations should meet the cautionary requirements of the general interest such as food and needs of coastal populations, public health, irrigation, flood protection, conservation and free movement of fish, the flow and rejection of water.

CONCLUSIONS

The use and proper management of water resources are of great importance to sustainable development of terrestrial life and much of the socio-economic activities, and power generation one of the most important, especially in Brazil, where the largest installed capacity comes from the hydroelectricity.

The Furnas HPP due to relevance in the energy scenario and conflicts over water use in the reservoir, was adopted as a case study, being necessary to the improvement of management tools for multiple uses of the lake, which become even more important if the changes climate materialize.

Such relevance of the issue resulted in the creation of the Intergovernmental Panel on Climate Change (IPCC), whose reports are the fifth edition and propose scenarios or overall future development scenarios, in order to describe and predict possible climate change through global models which were analyzed and used in this study.

However, it is noteworthy that future climate scenarios are only projections of likely changes that may occur with the combination of factors such as greenhouse gases and climate change, demographic, economic and technological.

To represent the climatology and the seasonality of the study area, there were used the HadCM3 global model data used and regional Eta model that managed to represent satisfactorily the observed climatology (the period between 1960 to 1990) for the study area. However, for future research, it is recommended to use other atmospheric models and smaller grid resolution.

For climate behavior analysis (past data) there were verified evidence of changes in hydrological variables precipitation and flow, through seven nonparametric tests. However, due to the unavailability of data, inconsistencies, failures, reduced sample space and the need for coverage of the validation period of climate models between 1960 and 1990, the number of posts was restricted to 15% of the total, located in the most upstream part of the basin, which shows the need to improve the collection and management of hydrometric network system.

The test results converged to the posts showing increasing trend of rain rates, a fact satisfactory because in many researches there was no convergence on the results of the statistical tests, which in 40% of the staitons this increase was significant. Regarding runoff data, increasing trend have been identified, but not significant.

In the adjustment and calibration step of the MGB-IPH were defined 20 sub-basins for the period 1968-1990, which showed good correlation to the observed data.

To supply the rainfall-flow rate model was used two climatological variables designed by Eta model through four members (Hight, Medium, Low and Control) within the A1B scenario parameters of the IPCC, which were well adjusted to predict future conditions, for the period from January 2011 to late November 2099, and has been found that the predictions made by medium scenario are the most restrictive with regard to water supply, and if confirmed should require greater attention by supply decreased grievance and risk of major conflicts over water use.

For the electrical system it is important that these elements are considered in the planning, so that it can reduce the risk of failure in electricity supply, since the current model works based on stochastic models and do not incorporate possible changes that may occur in climate .

Thus, it sought to improve a methodology so that the plants work in order to meet both energy production and the need of the riverside community. Based on historical data of the operation proceeded to the determination of the duration and frequency reference transgression, based on the 762 m quota and is stipulated as an ideal condition for a period of five years, the reservoir may be only two cycles spread over 15 months below this level, which can be achieved by adopting an operative rule required by the grant or other legal means.

To achieve this objective was proposed 15% storage inflow planned for the month when the conditions are not met in the last five years.

If the scenarios of the Eta model are verified and the Furnas HPP continue to meet the same historical energy demand the reservoir tends to remain full for the period 2011 - 2099. However, for the period 2041-2070, due to a prolonged period of drought, the reservoir can be emptied completely. This effect can be mitigated by the methodological application of frequency and duration concepts being possible for Furnas achieve higher power generation, emptying the tank at a lower intensity.

In this study, was not analyzed the effect on the SIN, however due to the risks presented, it is recommended that the operation of the plants is enhanced through the incorporation of streamflow prediction system in all basins.

It is important to occur strengthening and training of sectorial agents who work with river basin committees and regulators of water resources, which are suitable agents for assistance to technical issues presented here, to meet sustainable development and reconcile possible future conflicts over water use.

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Contribuição dos autores:

Leopoldo Uberto Ribeiro Junior - Apresentação da problemática envolvida, ou seja, mostrar que é possível realizar a operação das usinas hidrelétricas ponderando os usos múltiplos da água, considerando os cenários de mudanças do clima. Para o desenvolvimento deste trabalho, foi o responsável pela aplicação das metodologias, adaptação do modelo de operação de reservatórios e elaboração do texto.

Antonio Carlos Zuffo - Foi orientador deste trabalho, contribuindo principalmente para a escolha dos métodos estatísticos para a definição de tendência climáticas, participando também da análise dos resultados e revisão do texto do artigo

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