Geração integrada de eletricidade como alternativa para melhoria da vazão ecológica no sub-médio e baixo da bacia do Rio São Francisco

Hagen Koch[1]; Ana Lígia C. Silva[2]; José Roberto Azevedo[3]; Werônica Meira de Souza[4]; Johann Köppel[5]; Clecio Barbosa Souza Junior[6], Fred F. Hattermann[7]*

Resumo – Muitas fontes de recursos para a geração de electricidade, como centrais hidroeléctricas e a energia eólica, dependem de factores climáticos. Reservatórios são construídos para superar a natureza estocásticas da vazão e para tornar a produção hidroeléctrica mais confiável. No entanto, reservatórios estão afetando o estado ecológico de ecossistemas fluviais, desencadeando discussões do regime da vazão a jusante dos reservatórios. No nordeste do Brasil a capacidade instalada para geração de energia eólica aumentou acentuadamente nos últimos anos. Neste artigo é analisado se a geração de energia eólica, culminando na estação seca, pode ajudar a alcançar um regime de vazão mais ecológica no sub-médio e baixo do rio São Francisco. Descargas maiores de reservatórios durante a estação chuvosa e descargas menores durante a estação seca, o que representa um regime de fluxo mais natural, estão levando à geração de energia hidrelétrica reduzida na estação seca. Em geral, a demanda da electricidade só pode ser parcialmente coberta pela energia eólica e hidrelétrica. Uma grande parte precisa ser gerada por centrais térmicas ou ser importadas de outras regiões. A adoção da referida abordagem integrada pode contribuir para melhorar o regime da vazão no sub-médio e baixo do rio São Francisco.

Palavras-Chave – rio São Francisco, geração de eletricidade, vazão ecológica

INTRODUCTION

Hydropower and wind are renewable resources for the generation of electric energy. Both types of electricity generation depend on climatic factors. The electricity generation by a hydropower plant is strongly connected to river discharge and hence on precipitation and evapotranspiration, while wind power generation makes direct use of wind. Reservoirs can balance, at least partially, the stochastic occurrence of precipitation and discharge, and increase the reliability of hydropower generation and water supply. For wind power generation up to now there is no technology to reduce the direct dependence on wind. With the construction and operation of dams a discussion on benefits, environmental and social costs emerged (Scudder, 2005; Bergkamp *et al.*, 2000). Impacts of dams include alteration of flow regimes and sediment transport, change of aquatic biodiversity, flooding or falling dry of native vegetation, greenhouse gas emissions, reallocation of water by evaporation and infiltration (Anderson *et al.*, 2006; Fearnside, 2002).

The study area is the sub-middle and lower São Francisco river basin. The São Francisco river basin has an area of approximately 640 000 km^2. The mean discharge at the mouth is 2 846 m^3/s (ANA/MMA, 2013). Due to climatic characteristics with a strong seasonal flow regime in the last century large dams were constructed. The largest dams are Três Marias with a total capacity of 19 528 hm^3 (live capacity of 15 278 hm^3, installed hydropower capacity 396 MW), Sobradinho (34 117 hm^3, 28 669 hm^3, 1 050 MW) and Itaparica (10 782 hm^3, 3 549 hm^3, 1 500 MW). The main uses of these reservoirs are flood protection and hydropower generation, but they also deliver water for agricultural irrigation and to municipalities, and are used to augment streamflow for navigation. Downstream of Itaparica reservoir a number of large hydropower plants, Apolônio Sales (400 MW), Paulo Afonso 1 (180 MW), Paulo Afonso 2 (445 MW), Paulo Afonso 3 (800 MW), Paulo

---

[1]* Potsdam Institute for Climate Impact Research – PIK, P.O. Box. 601 203, D-14412 Potsdam, Germany, hagen.koch@pik-potsdam.de
[2] Doutoranda da Universidade Federal de Pernambuco - UFPE, Recife, Brasil. Bolsista CNPQ. analigiaifpb@hotmail.com
[3] Departamento de Eng. Civil, Universidade Federal de Pernambuco - UFPE, Recife, Brasil, robdosport@hotmail.com
[4] Unidade Acadêmica de Garanhuns, Universidade Federal Rural de Pernambuco - UFRPE, Garanhuns, Brasil. weronicameira@gmail.com
[5] Berlin Institute of Technology, Environmental Assessment and Planning Research Group - TUB, Berlin, Germany, johann.koeppel@tu-berlin.de
[6] Berlin Institute of Technology, Environmental Assessment and Planning Research Group - TUB, Berlin, Germany, junior@campus.tu-berlin.de
[7] Potsdam Institute for Climate Impact Research – PIK, Potsdam, Germany, fred.hattermann@pik-potsdam.de

Afonso 4 (2 460 MW), and Xingó (3 000 MW), is located (ANA/GEF/PNUMA/OEA, 2004). Due to the huge reservoirs and their storage effects the discharge at the main river has changed dramatically. The natural flow regime with wet and dry seasons no longer exists (Medeiros *et al.*, 2013). Recently, environmental hydrograms (hidrogramas ambientais) were developed within the project "Avaliação dos Impactos Hidrológicos da Implantação do Hidrograma Ambiental, do baixo trecho do rio São Francisco - AIHA". This project provided monthly target values for river discharges for the sub-middle and lower São Francisco river basin. The environmental hydrograms were developed for normal and dry years, and were derived using the Building Block Methodology (see Ferreira, 2014; Medeiros *et al.*, 2013). In the austral winter half year, the dry season in the São Francisco river basin, in north-eastern Brazil the wind speed is high, while in the austral summer, i.e. the rainy season, wind speed is lower. The research topic of this paper is to analyze if wind power generation can help to achieve a more ecological flow regime in the sub-middle and lower São Francisco river basin with higher discharges during the rainy season and lower discharges during the dry season, leading to reduced hydropower generation in the latter.

DATA AND METHODS

Electricity generation in north-east Brazil and in the São Francisco river basin

Data of electricity demand, electricity generation by hydropower, thermal power and wind power plants, and electricity imported to north-eastern Brazil are available from ONS (2016a). The development between 2006 and 2015 is shown in Figure 1. Between 2006 and 2015 the mean annual electricity demand has increased by 38 %, in the years 2013 to 2015 the mean monthly demand was between 10 627 and 12 368 MW. Since 2012, with declining hydropower generation in the São Francisco river basin due to an ongoing drought, the generation by thermal power plants has increased sharply. Also the increased wind power generation, due to the higher installed wind generation capacity, is visible. The values for imported electricity show a high fluctuation.

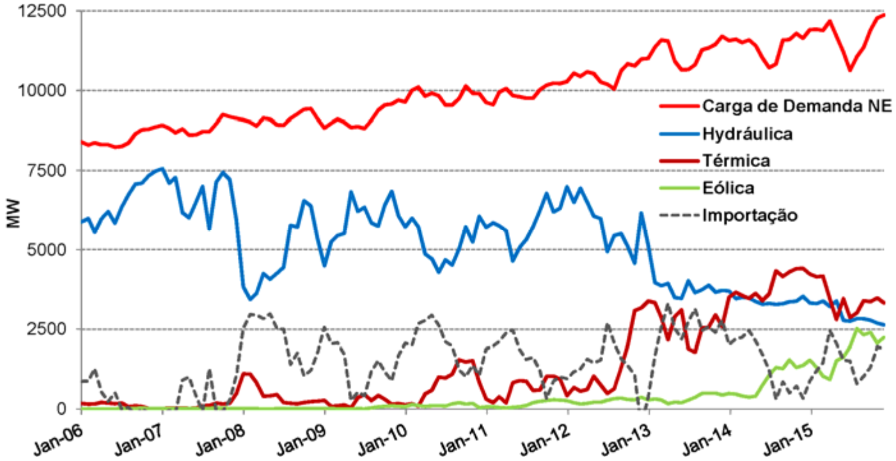

Figure 1 – Development of electricity demand, electricity generation by hydropower plants, thermal power plants and wind power plants, and electricity imported to north-eastern Brazil (ONS, 2016a)

Wind power generation

Data from climate observation stations Petrolina/PE (PCD 32475; 05/2001 to 12/2015), Irecê/BA (PCD 32546; 01/2001 to 12/2015), Floresta/PE (PCD 32026; 05/2002 to 12/2014) and Belem de Sao Francisco/PE (PCD 31935; 08/2005 to 12/2015) were used in this study (3-hourly mean wind speed at height of 10 m; INPE, 2016). There are many more climate observation stations with 3-hourly mean wind speed data in the region, however, often the time periods are very short or the time series have many gaps. According to data of CEPEL (2005) in the surroundings of the cities of

Petrolina and Irecê mean annual wind speed is 5.4 m/s and 5.9 m/s, respectively. In the greater region there are locations with mean annual wind speed of 4.01 to 5.00 m/s and 8.01 to 9.00 m/s. However, the majority of cells are in the same class as Petrolina and Irecê, and in the class 6.01 to 7.00 m/s. Therefore, the wind speed at climate observation stations Petrolina (32475) and Irecê (32546) can be seen as representatives of wind speed in this region.

In the estimation of the wind power generation annual and daily fluctuations of wind speed need to be considered. Furthermore, generation power curves and an extrapolation to the hub-height of the wind mills are necessary. In the calculations of wind power generation a power curve as described in Akdag & Güler (2011) or Koch *et al.* (2015) is applied: a horizontal-axis wind turbine with a hub-height of 100 m and blades of 50 m length. The wind speed data were extrapolated to hub-height of 100 m above ground using the logarithmic wind profile (Hoogwijk *et al.*, 2004):

$$VH = VM \left(\ln(H/z0) / \ln(M/z0)\right) \tag{1}$$

where H is the hub-height (m), VH is the wind speed at H (m/s), M is the anemometer height, and z0 is the roughness length of the surface (m). In this function no thermal effects on wind speed are included. The anemometer height is 10m. Roughness lengths of the surface (z0) of 0.02 and 0.15 were used for Petrolina (32475) and Irecê (32546), respectively.

Table 1 – Wind speed (mean for 3-hourly intervals in m/s) for Petrolina/PE (PCD 32475), Floresta/PE (PCD 32026), Belem de Sao Francisco/PE (PCD 31935) and Irecê/BA (PCD 32546); date: 24-07-2006

PCD	0:00 h	3:00 h	6:00 h	9:00 h	12:00 h	15:00 h	18:00 h	21:00 h
32475	7,5	5,1	5,4	7,4	12,4	13,2	11,1	8,2
32026	10,4	5,9	5,1	4,2	10,1	10,1	10,4	9,2
31935	11,1	8,1	8,1	7,1	11,8	12,6	10,8	8,3
32546	3,5	3,9	2,7	7,8	0,1	12,5	11,8	7,1

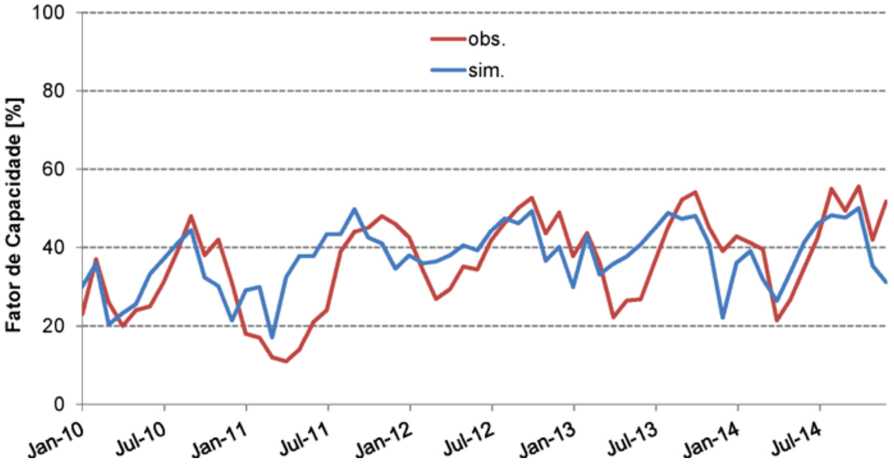

Figure 2 – Observed and simulated mean monthly utilization of wind power plants for north-eastern Brazil (MME, 2012; ONS, 2016b, own simulation)

In Table 1 examples for data used (3-hourly mean wind speed) are given for the day 24-07-2006. The values given for 9:00 h and 15:00 h have the same magnitude, while at 12:00 h the value for Irecê (32546) is significantly lower than those for the three other stations. However, a revision of the time series was beyond the means of this study. Gaps in the time series for Petrolina (32475) and Irecê (32546) were filled with data of Floresta (32026) and Belem de Sao Francisco (31935), if none of the station had data for a certain time interval data from preceding days were used.

In Figure 2 the observed mean monthly utilization of wind power plants for north-eastern Brazil is shown for the years 2010 to 2014 (data for 2010 and 2011 from MME, 2012; data for 2012 to 2014 from ONS, 2016b). Also shown is the simulated mean monthly utilization using the observed wind speed data for Petrolina (32475) and Irecê (32546). Although there are some deviations between observation and simulation, the annual cycle, i.e. lower utilization in the austral summer and higher utilization in the austral winter, can be reproduced. For north-eastern Brazil an installed capacity of 6 200 MW for wind power is assumed in this study.

Hydropower generation

Daily inflow and outflow time series, and volumes for the reservoirs Sobradinho and Itaparica up to the year 2014 were delivered from Operador Nacional do Sistema Elétrico (ONS) to the Brazilian-German INNOVATE project. The reservoir module of the eco-hydrological model SWIM developed by Koch *et al.* (2013) was used in this study. In order to exclude deviations between observed and simulated discharges the reservoir module was applied outside of SWIM, i.e. the observed daily inflow time series were used as input for the reservoir module. Daily climate data, e.g. temperatures, precipitation, wind speed, solar radiation, were available from the WATCH-project until 2010 (http://www.eu-watch.org/; Weedon *et al.*, 2011). These data were used to calculate the potential evaporation using the TURC-IVANOV methodology (see Wendling & Schellin, 1986). Using the observed inflow time series, precipitation and the potential evaporation rates, the reservoir module was used to simulate the management of the reservoirs Sobradinho and Itaparica and the electricity generation by these reservoirs and the hydropower plants downstream. The hydropower plants included in this study, i.e. all hydropower plants listed in the Introduction except Três Marias, have an installed capacity of 9 835 MW.

Electricity demand

The monthly electricity demands for north-eastern Brazil for the years 2013 to 2015 can be seen as variations of the present state and therefore are used in this study. To calculate the electricity demand for wind power and hydropower generation from these values the electricity imported is subtracted as initial condition. An installed capacity of 4 400 MW for thermal power plants is used. In the long term a utilization of 60 % for hydropower plants (mean generation of 5 900 MW), of 40 % for wind power plants (mean generation of 2 480 MW) and of 70 % for thermal power plants (mean generation of 3 080 MW) is assumed. Therefore, in the long term 73 % of the electricity demand should be covered by wind and hydropower generation. Because for wind power generation there is no technology to reduce the direct dependence on wind, while reservoirs can be used to store and release water when needed, first wind power generation is simulated, and in the second step, depending on electricity demand, hydropower generation is simulated to fill the gap between electricity demand and generation. The remaining gap not covered by hydropower generation then needs to be covered by thermal power plants and/or electricity imported. If wind power generation and hydropower generation, the latter having a base generation as reservoirs need to release a minimum discharge, are higher than the electricity demand to be covered by wind power and hydropower, thermal power plants generation and/or electricity import can be reduced.

For the simulation of wind power and hydropower generation climate data are needed. Wind speed data were available from 2001 to 2015. Because precipitation data and climate data needed for the calculation of potential evaporation were available until 2010 only, the time period 2001 to 2010 was used in this study. As the electricity demand during this time period was much lower than the demand of the last years, scenarios with electricity demands representing the present state were applied. In scenario “Demanda 1” the observed electricity demand of 2013 is used for the year 2001, the observed demand of 2014 is used for the year 2002 etc. Scenario “Demanda 2” uses the observed demand of 2014 for the year 2001 and of 2015 for the year 2002 etc. In this way the uncertainty about electricity demand can be included at least partially (see Table 2).

Table 2 – Data used for the simulation of wind power and hydropower generation, and three scenarios for electricity demand (see text for explanation)

ano	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Geração eólica, velocidade de vento, intervalos de 3 horas	observação	observação	observação	observação	observação	observação	observação	observação	observação	observação
Geração hidráulica, vazão e dados climaticos, diario	observação; Watch	observação; Watch	observação; Watch	observação; Watch	observação; Watch	observação; Watch	observação; Watch	observação; Watch	observação; Watch	observação; Watch
Demanda 1; demanda por mês	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013
Demanda 2; demanda por mês	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014
Demanda 3; demanda por mês	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015

RESULTS

The interconnection of wind and hydropower generation leads to strong variations in the demand on hydropower generation. In Figure 3 volumes of Sobradinho reservoir observed and simulated are shown.

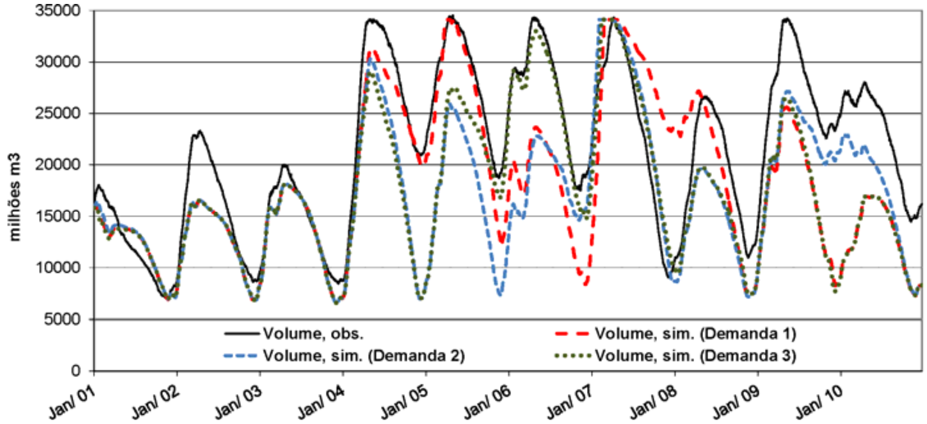

Figure 3 – Observed and simulated volume for Sobradinho reservoir

As the electricity demand in the scenarios is higher compared to the observations, most of the time the volumes are lower in the simulations. Only for the wet year 2007 and electricity demand of 2013 (“Demanda 1”) the volume is considerably higher than the observed volume. The simulated wind and hydropower generation, the demand on wind and hydropower generation, and the total electricity demand for north-eastern Brazil for scenario "Demanda 1" are shown in Figure 4. For the very dry year 2001 and until the end of 2003, as a consequence of this drought, the generation of wind and hydropower plants is almost always lower than the demand on wind and hydropower generation, i.e. generation by thermal power plants generation and/or electricity import need to be increased. In the wet years 2004 to 2008 the generation of wind and hydropower plants is almost always higher than the demand on wind and hydropower generation, i.e. generation by thermal power plants generation and/or electricity import can be reduced. In March 2007 the generation of wind and hydropower plants is even higher than the total demand, i.e. electricity can be exported.

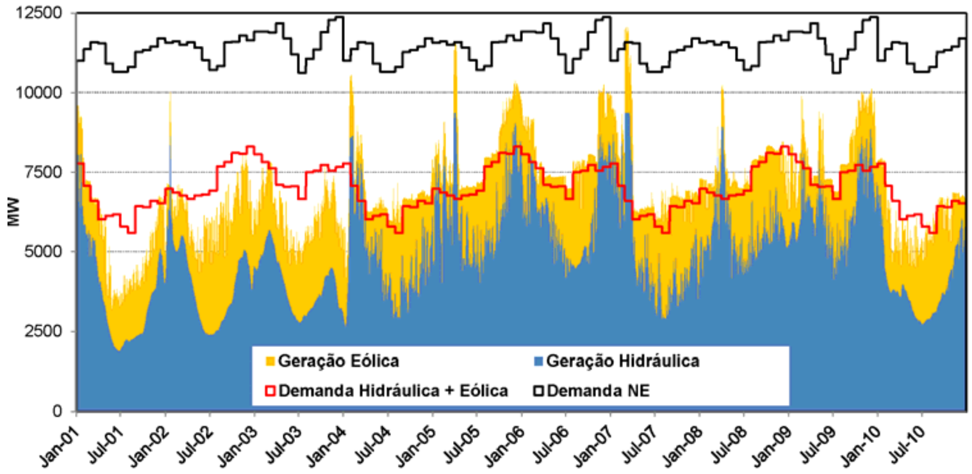

Figure 4 – Simulated wind and hydropower generation, demand on wind and hydropower generation, and total electricity demand for north-eastern Brazil for scenario “Demanda 1”

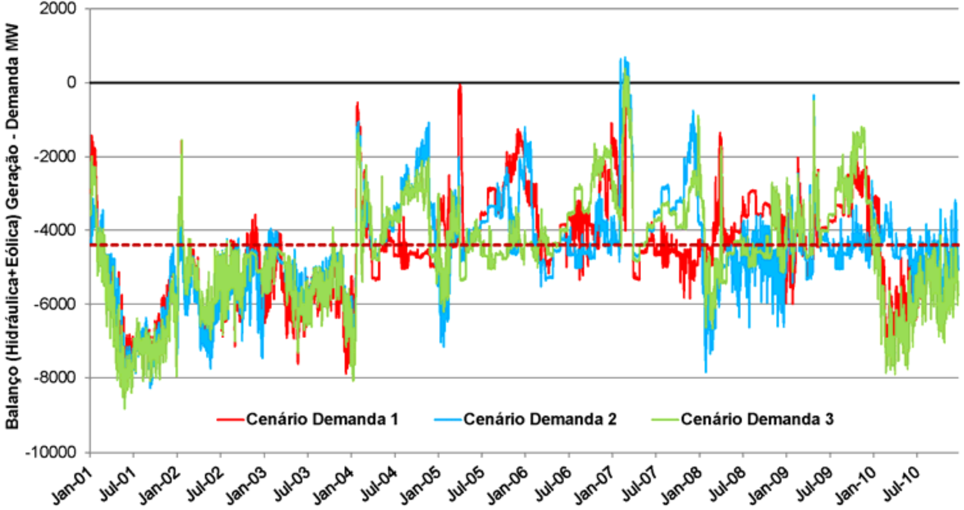

Figure 5 – Balance between simulated wind and hydropower generation and demand on wind and hydropower generation, dotted brownish line: installed capacity of 4 400 MW for thermal power plants

The balance between simulated wind and hydropower generation and the demand on wind and hydropower generation is shown in Figure 5. Also shown is the installed capacity of 4 400 MW for thermal power plants. As long as the balance is lower than minus 4 400 MW the gap can be filled by thermal power generation in north-eastern Brazil theoretically. As the electricity generation by hydropower plants in other regions of Brazil usually is cheaper than the generation of thermal power plants, the gap would be filled partially by electricity import. If the gap is larger than 4 400 MW, i.e. values below the dotted brownish line, electricity needs to be imported. Finally the question if wind power generation can help to achieve a more ecological flow regime is discussed. The mean monthly discharges for the years 2001 to 2010 from Sobradinho reservoir observed and simulated are shown in Figure 6. Also shown are the Hidrogramas Ambientais for normal and dry years. The interconnection of wind and hydropower generation enables a more dynamic flow regime in the sub-middle and lower São Francisco river basin, i.e. higher discharges in the rainy season and lower discharges in the dry season. However, in comparison to the Hidrogramas Ambientais the simulated flows at the end of the rainy season are declining early (April) and are already increasing before the end of the dry season (August).

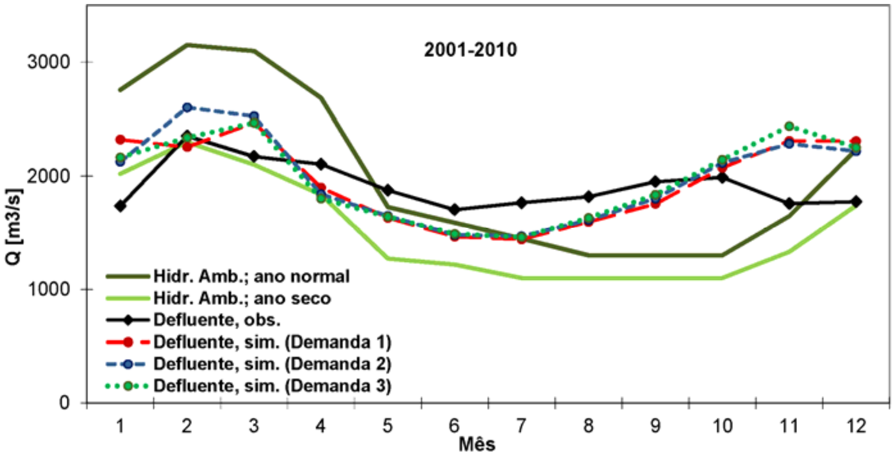

Figure 6 – Observed and simulated discharge for Sobradinho reservoir and Hidrogramas Ambientais

DISCUSSION

In this paper an approach to integrate electricity generation by wind power, hydropower and thermal power plants is presented. The electricity demand can only be covered partially by wind and hydropower plants. A large share needs to be generated by thermal power plants or to be imported. According to the results the flow regime in the sub-middle and lower São Francisco river basin can be changed to reach a better ecological status. However, the ecosystems of reservoirs themselves are not considered here. Water level variations lead to the displacement of shorelines affect the aquatic ecosystem in various ways (Hirsch *et al.*, 2014; Hofmann *et al.*, 2008). Large areas are getting inundated with rising and desiccated with declining water level. During strong short-term water level variations aquatic and riparian organisms are physically stressed (Hofman *et al.*, 2008). At the same time, also wind power can come along with some unintended side-effects on ecosystem functions and services and needs to be sensitively developed (Huesca-Pérez *et al.*, 2016, Köppel *et al.*, 2012). For a discussion on the consideration of ecosystems of reservoirs in reservoir management the reader is referred to Koch *et al.* (2015b). Future studies should include scenarios with increased electricity demand, increased wind power generation capacities and climate change.

Acknowledgements

This work was supported by the BMBF (Germany), the CNPq, the MCTI, and the UFPE Recife (Brazil).

REFERENCES

AKDAGk, S.A., GÜLER, O. (2011). A Comparison of Wind Turbine Power Curve Models. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 33, pp. 2257-2263.

ANA/GEF/PNUMA/OEA (2004). *Projeto de Gerenciamento Integrado das Atividades Desenvolvidas em Terra na Bacia do São Francisco*. Estudo Técnico de Apoio ao PBHSF Nº 09 - Aproveitamento do Potencial Hidráulico para geração de energia elétrica. Brasília-DF.

ANA/MMA (2013). *Conjuntura Recursos Hidricos Brasil*. Agência Nacional de Águas / Ministério do Meio Ambiente. Brasília-DF.

ANDERSON, E.P.; FREEMAN, M.C.; PRINGLE, C.M. (2006). Ecological consequences of hydropower development in central america: Impacts of small dams and water diversion on neotropical stream fish assemblages. *River Research and Applications* 22, pp. 397-411.

BERGKAMP, G.; McCARTNEY, M; DUGAN, P.; McNEELY, J.; ACREMAN, M. (2000). *Dams, Ecosystem Functions and Environmental Restoration*. Thematic Review II.1 prepared as an input to the World Commission on Dams, Cape Town, 186p.

CBHSF (2004). *Plano Decenal de Recursos Hídricos da Bacia Hidrográfica do Rio São Francisco - Resumo Executivo*. Comitê da Bacia Hidrográfica do Rio São Francisco, Salvador, 337p.

CEPEL (2005). *Brazil Wind Data* (10km) - Annual average of the aeolic potential at 50m. Electric Energy Research Center/Federal University of Rio de Janeiro - Brazil. (available at http://www.cepel.br).

FEARNSIDE, P.M. (2002). Greenhouse gas emissions from hydroelectric reservoirs (Brazil's Tucuruí dam) and the energy policy implications. *Water, Air and Soil Pollution* 133, pp. 69-96.

FERREIRA, T.V.B. (2014). *Hidrogramas ambientais para o Baixo Rio São Francisco: avaliação de impactos sobre a geração hidrelétrica*. Rio de Janeiro: UFRJ/COPPE. 304p. Dissertação (mestrado).

HIRSCH, P.E.; SCHILLINGER, S.; WEIGT, H.; BURKHARDT-HOLM, P. A. (2014). Hydro-Economic Model for Water Level Fluctuations: Combining Limnology with Economics for Sustainable Development of Hydropower. *PLoS ONE* 9(12), e114889.

HOFMANN, H.; LORKE, A.; PEETERS, F. (2008). Temporal scales of water-level fluctuations in lakes and their ecological implications. *Hydrobiologia* 613, pp. 85- 96.

HOOGWIJK, M.; De VRIES, B.; TURKENBURG, W. (2004). Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. *Energy Economics* 26, pp. 889-919.

HUESCA-PÉREZ, M.E.; SHEINBAUM-PARDO, C.; KÖPPEL, J. (2016). Social implications of siting wind energy in a disadvantaged region – The case of the Isthmus of Tehuantepec, Mexico. *Renewable and Sustainable Energy Reviews* 58, pp. 952–965.

INPE (2016). *Dados históricos*. Instituto Nacional de Pesquisas Espaciais. http://www.cptec.inpe.br/

KOCH, H.; LIERSCH, S.; HATTERMANN, F.F. (2013). Integrating water resources management in eco-hydrological modelling. *Water Science & Technology* 67, pp. 1525 – 1533.

KOCH, H.; VÖGELE, S.; HATTERMANN, F.F.; HUANG, S. (2015a). The impact of climate change and variability on the generation of electrical power. *Meteorol. Z.* 24, pp. 173-188.

KOCH, H.; SELGE, F.; DE AZEVEDO, J.R.G.; DA SILVA, G.S.; SIEGMUND-SCHULTZE, M.; HATTERMANN, F.F. (2015). Incluindo aspectos ecológicos na gestão de reservatórios: opções de gestão no Sub-médio e Baixo do rio São Francisco. *XXI SIMPOSIO BRASILIERO DE RECURSOS HIDRICOS*; 22.-27.11.2015; Brasília/Brazil.

KÖPPEL, J.; DAHMEN, M.; HELFRICH, J.; SCHUSTER, E.; BULLING, L. (2012). Cautious but Committed: Moving Toward Adaptive Planning and Operation Strategies for Renewable Energy’s Wildlife Implications. *Environmental Management* 54 (4), pp. 744–755.

MEDEIROS, Y.D.P.; FREITAS, I.M.P.; STIFELMAN, G.M.; FREIRE, R.R.; O´KEEFE, J. (2013).Social Participation In The Environmental Flow Assessment: The São Francisco River Case Study. *Gesta - Revista Eletrônica de Gestão e Tecnologias Ambientais* 1, pp. 122-130.

MME (2012). *Boletim Mensal de Monitoramento do Sistema Elétrico Brasileiro – Janeiro/2012*. MINISTÉRIO DE MINAS E ENERGIA, SECRETARIA DE ENERGIA ELÉTRICA, DEPARTAMENTO DE MONITORAMENTO DO SISTEMA ELÉTRICO.

ONS (2016a). *Histórico da Operação. Operador Nacional do Sistema Elétrico*. http://www.ons.org.br/home/index.aspx

ONS (2016b). GERAÇÃO EÓLICA VERIFICADA NO SUBSISTEMA NORDESTE 2015 - NT 0024/2016. Operador Nacional do Sistema Elétrico, Rio de Janeiro.

SCUDDER, T. (2005). *The Future of Large Dams: dealing with social, environmental, institutional and political costs*. London: Earthscan. 408p.

WEEDON, G.P.; GOMES, S.; VITERBO, P.; SHUTTLEWORTH, W. J.; BLYTH, E.; ÖSTERLE, H.; ADAM, J.C.; BELLOUIN, N.; BOUCHER, O.; BEST, M. (2011). Creation of the WATCH Forcing Data and Its Use to Assess Global and Regional Reference Crop Evaporation over Land during the Twentieth Century. *Journal of Hydrometeorology* 12, pp. 823–848.

WENDLING, U.; SCHELLIN, H. (1986). Neue Ergebnisse zur Berechnung der potentiellen Evapotranspiration. *Zeitschrift für Meteorologie* 36, pp.214-217.