International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Impacts of management options on water deficits, losses and livelihoods in the Jaguaribe Basin of North East Brazil

Anthony P. Hurford[a], Ivana Huskova[a], Evgenii S. Matrosov[a], Julien J. Harou[a]
[a] *University College London, Department of Civil, Environmental and Geomatic Engineering*
anthony.hurford.11@ucl.ac.uk

Abstract: The North East of Brazil is the driest region of Brazil; rainfall is seasonal and reservoirs and transfer systems are used such as in the Jaguaribe basin studied here. Reservoir releases from the Jaguaribe's three major reservoirs are decided through bi-annual negotiations involving the local water management authority and water users. This paper investigates impacts of different management options in the Jaguaribe basin using several different system performance measures. We use an 89 year historical hydrological record to investigate the inter-basin transfer options and to investigate changing the current policy requiring at least 30 months of municipal demand to be stored at all times. We apply multi-objective search to the reservoir release rules for one of the drier decades of the time-series to investigate the trade-offs between different storage policies. Analysis of the inter-basin transfer options show benefits could be gained by implementing the São Francisco transfer. We find limited impact of changing the protected municipal demand duration although this may be a result of the limited input flow series and current model limitations. The optimisation analysis shows potential for helping the negotiated release process.

Keywords: Jaguaribe; water management; IRAS-2010; inter-basin transfer

1 INTRODUCTION

1.1 Background

The state of Ceará in the north east of Brazil is the country's driest, with annual average rainfall of between 400mm in the interior to 1200mm on the coast, most of which falls in the period from January to June. Water management is a critical issue as the state not only has such low rainfall coupled with high temperatures and associated high evapotranspiration but also has a large population of rural poor depending on water for their livelihoods. Largely crystalline rocks under thin soils do little to improve the availability of water due to their poor potential for groundwater storage. Reservoirs of all sizes have been installed across the state to store the high flows of the rainy season for use during the dry season. They total more than 4,700 in all with combined capacity of 13,560Mm^3 (Johnsson and Kemper 2005). Losses due to evaporation are significant.

The population of Ceará's largest city, Fortaleza is rapidly expanding along with its municipal and industrial demand for water. Fortaleza does not lie in a water rich basin and lacks large storage reservoirs, so a transfer has been set up from the nearby Jaguaribe basin which has much more plentiful resources. The Jaguaribe basin itself has a history of regular and occasionally devastating droughts however. Where once the main Jaguaribe rivers ran dry outside the wet season and the most devastating droughts killed hundreds of thousands of people, the construction of major reservoirs over time has enabled flow to be maintained throughout the year.

The large (6700Mm^3) Castanhão reservoir was commissioned as recently as 2003 to provide flood control and increased storage capacity in the Jaguaribe basin. The Castanhão reservoir supplies the Fortaleza water transfer scheme. Another premise of Castanhão's construction was that it provides the increased capacity necessary as interim storage for a proposed inter-basin transfer from the large and naturally perennial São Francisco river to the south (Braga, 2005). The basin's other main reservoirs are Orós (1940Mm^3) and Banabuiú (1601Mm^3) (See Figure 1) which in conjunction with Castanhão constitute over 75% of the basin's storage capacity.

A system of negotiated allocation of water for various uses has been implemented in the Jaguaribe basin and others across Ceará. The three major reservoirs considered (Orós, Banabuiú and Castanhão) are managed individually through this participatory process. While the effectiveness of the process for decentralisation and the empowerment of the most vulnerable people is questioned (Taddei 2011, Broad et al. 2007), it is a significant step towards such a goal (Johnsson and Kemper 2005). Each January and June meetings are held to negotiate between different user groups the reservoir releases for the next six month period, based on the current storage in the reservoir. The water resources management company (COGERH - *Companhia de Gestão dos Recursos Hídricos*) presents modelling results representing a number of feasible release scenarios which form the basis of discussion and eventually consensus on release rates (see Taddei, 2005 for more information on this process). The agreed release must not lead to violation of the principal that assuming no reservoir recharge in the next wet season, there will be 18 months of municipal supply, plus the associated volume which will be lost through evaporation, at the end of the next wet season. This amounts to 30 months of municipal supply being guaranteed from the date of negotiation. This is considered a conservative approach but is rooted in the region's history of unpredictable and severe droughts (Sankarasubramanian et al. 2009).

Sankarasubramanian et al. (2009) consider the benefits of using long-term forecasts to better inform the water allocation process and ensure that the system is more efficient by reducing spillage and evaporation losses. It is considered by the authors of this paper that it may be possible to enhance the performance of the demands in the basin more simply by reducing the period of storage required to be stored as standard.

The transfer out of the Jaguaribe basin to Fortaleza is controversial amongst the inhabitants of the basin (Johnsson and Kemper 2005) but any changes are likely to involve increases in the volume transferred due to the expanding urban population and industrial demands. The maximum capacity of the transfer canal is 1.9 Mm3/day, although at present the transfer amounts to 744 thousand m3/day. Conversely, there are plans to transfer water into the Jaguaribe basin from the São Francisco basin. The transfer from the São Francisco is expected to be approximately 700 thousand m^3/day (Braga, 2005). The combination of these transfers will change the water balance of the Jaguaribe basin and potentially thereby impact on various water users in the basin. We investigate this impact.

Multi-objective optimisation has rarely been applied to models where performance measures consider the impacts on the livelihoods of the poorest sectors of a society. We seek to define the trade offs between performance measures, including livelihoods factors such as the fishery quality available in the reservoirs for itinerant fishermen and the amount of land available within the reservoir floodplain which is assigned to the poorest famers.

1.2 Data availability

The following data were obtained from various sources:

- 1911-2000 monthly time series of observed inflows at the three reservoirs – Orós, Banabuiú and Castanhão (as none of the reservoirs were completed in 1911 it is assumed the inflow data are for the locations of the dams' construction)
- Present day demand data for the six reaches and three main reservoirs of the Jaguaribe shown in Figure 1. These data include inter-catchment transfers and all sectors licensed to abstract water from the surface water of the Jaguaribe river. Demands were split into constant demands and monthly demands and stated as an average constant flow.
- Monthly evaporation rates for each of the three reservoirs.
- Negotiated and actual mean flow released between June-January for Orós and Banabuiú reservoirs for each year 1998-2010 including stored volume at the beginning and end of each period at the Q90 outflow (source: COGERH)
- Records of Water level, Volume stored and Area inundated for the three reservoirs: Orós (1978-2011), Banabuiú (1979-1981,1985-2011) and Castanhão (2002-2011)
- Negotiated and actual mean flow released between June-January for Castanhão reservoir for each year 2002-2010 including stored volume at the beginning and end of each period (source: COGERH)
- COGERH Sub-basin management plans for the Upper (Orós), and Middle (Castanhão) sub-basins of the Jaguaribe river basin.

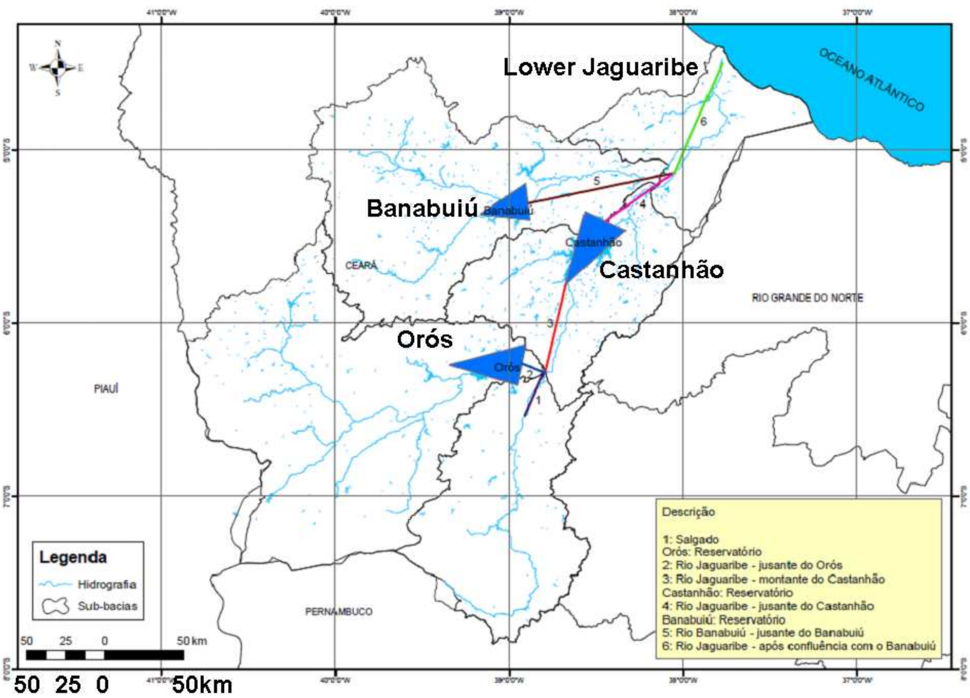


Figure 1. Map of the Jaguaribe basin overlaid with a schematic of the three main reservoirs and river reaches connecting them (source: Mendiondo, pers. comm.)

2 METHODOLOGY

This section describes the modelling approaches taken and then goes on to outline the options modelled and any specifics of this modelling. The final part gives a brief description of the method for optimising release rules.

2.1 Modelling software

The generic IRAS-2010 water resources system model (Matrosov, Harou and Loucks 2011) is used to simulate the water resources system in the basin. A water demand prioritisation feature (not described in original publication) is used. This means that once water is released from a reservoir the water becomes allocated to the various demands downstream by 'earmarking' the water so that it is preserved in the stream for abstraction at a downstream demand rather than being available for abstraction by the furthest upstream abstractors. In this way it is not important to locate the various demands according to their real sequence along the river. Prioritisation ensures that the water supplies the user defined demands in the desired sequence.

In order to use the prioritisation function, each demand was modelled as a node and link branched off from the main river channel composed of links and junction nodes. Each junction node was associated with one demand abstraction to the node and link described above. The model thereby comprised approximately 120 nodes and 120 links.

A monthly (30 day) time step is used. Owing to the length of the river channel and time-step, no flow routing is required as it assumed that flow entering a reach passes through it within each time-step.

2.2 Reservoir releases

Owing to the complex and unpredictable nature of the negotiated allocation procedure which takes place in the Jaguaribe basin every six months, for the non-optimisation part of this study it was necessary to make some approximation for the releases from the reservoir.

A mean monthly release was calculated for each of the three reservoirs, using the daily data of observed reservoir levels, observed inflows and modelled outflows for the period 2002 -2010. Evaporation was accounted for using monthly mean daily evaporation, varying by month and by water surface area in the reservoir. Assuming only the reservoir levels and inflows to be correct in the 2002-2010 data, outflows were calculated by a simple water balance for the three reservoirs. Using the calculated outflows to re-construct reservoir storage volume time-series provided an indication of how good an approximation of the 'real' outflows had been achieved. It was found that the modelled outflow data for the Castanhão reservoir were better than those provided by water balance calculation. For the Orós and Banabuiú reservoirs the water balance calculation was found to best represent the 'real' outflows. The outflow data which provided the best fit with the observed storage time series were used to derive the monthly mean releases. These monthly mean releases were used as standard releases for all subsequent modelling.

The initial stored volume of each reservoir was taken to be the average of the storage at the beginning of January (the start point of the model) over the 2002-2010 period.

2.3 Demands

Aggregated demand data were obtained for each month from abstraction license data, taking into account both fixed and monthly varying demands for each sector. The sectors used were Municipal, Livestock, Irrigation, Aquaculture and Industry. The demands for which data were obtained, listed by supply region and sector, are shown in Table 1.

Table 1. Demands included in the model, by sector and supply region (mean flow demand in thousands m^3/day – where demand is time varying range is stated)

	Orós	**Castanhão**	**Banabuiú**	**Lower Jaguaribe**
Municipal	20.6	15.8	14.6	10.4
Irrigation	116.8 – 625.4	754.0 – 1,031.5	569.7 – 813.2	208.8 – 242.7
Livestock	12.0 – 14.6	10.9	1.7 – 3.4	0 – 1.3
Aqua-culture	8.4	-	-	35.2 – 40.5
Industry	0.05	0.40	60.3	0.55
Transfer	-	743.9	-	45.5

Demands are prioritised as 1) Municipal, 2) Livestock, 3) Irrigation, 4) Aquaculture and 5) Industry. The transfer to Fortaleza was prioritised equally with Municipal demands in the Castanhão and Lower Jaguaribe supply areas, but the Trabalhador transfer canal from the Lower Jaguaribe was not prioritised at all owing to its low capacity and hydraulic gradient which make it ineffective as a transfer to Fortaleza.

2.4 Return flows

Return flows were included in the model based on the information provided by Araujo (pers. comm.) based on work which measured this in a Middle Jaguaribe River reach during the M.Sc. Thesis of Dr. Teresa Rego in 2001.

2.5 Assessment criteria

By applying the 1911-2000 inflow time-series data to the model we investigated the impacts of various management options on a range of seven performance measures:

- Mean annual evaporative loss – this is the sum from all three reservoirs, measured in Mm^3
- Mean annual spill loss – this is the sum of water released uncontrolled from the three reservoirs and is a surrogate for flood protection, measured in Mm^3
- Mean annual transmission loss – the sum of water lost during transmission through the water courses downstream of the reservoirs, measured in Mm^3. Losses were calculated based on work by Araujo et al. (2004)
- Mean annual number of months below 100% hydropower generation
- Mean annual number of months with poor fisheries in all three reservoirs (based on Hardy (1995)
- Mean annual proportion of the maximum land available to the poorest farmers in the growing season (based on van Oel et al. (2008))

- Mean annual number of months where irrigation demands receive less than 30% of their requirement (due to prioritisation, this represents demand deficits in all sectors)

We assume that the 2011-2000 inflow time series represents a sufficiently diverse range of flood and drought conditions to provide a meaningful assessment of the impacts of different management options.

2.6 Management Options

First we assess impacts of various transfers to Fortaleza on annual deficits in the Jaguaribe basin. The canal which transfers water to Fortaleza has a maximum capacity of 1.9 Mm3/day, so we consider the impact of utilising this maximum capacity. We compare this with the present day performance, where demand is reported to average 744 thousand m3/day. We also compare the impacts of the present day transfer with the option where the interbasin transfer from the São Francisco basin is implemented. This transfer is expected to bring 700 thousand m^3/day into the upper Jaguaribe basin (Braga, 2005), flowing into the Castanhão reservoir, so the net balance is a 44 thousand m3/day outflow to Fortaleza. Transferring water in or out of the basin at Castanhão only has direct impacts downstream of the Castanhão reservoir.

Secondly, we assess the deficit reduction potential of less conservative municipal supply policies, i.e. maintaining a reserve of less than 30 months of municipal supply (plus associated evaporation). We investigate this using reservoir release rules, whereby the release from the reservoir is strictly limited to total municipal demand once the reservoir draws down to this protected volume. We consider options where 6 or 0 months of municipal supply is protected. The volumes protected under each policy option are shown in Table 2. It should be noted that the municipal demands in the lowest reach of the river – 6. Jaguaribe – are divided between the Banabuiú and Castanhão reservoirs based on their relative storage capacity.

Table 2. Protected volumes (Mm^3) in each reservoir for each option

	30 month	6 month	No protected volume	Maximum storage of reservoir
Orós	168	41	0	1940
Banabuiú	400	210	0	1601
Castanhão	637	295	0	6700

Note: These storage volumes are in addition to dead storage

Finally, to give an indication of the sensitivity to release rates, we applied two reservoir release rate increases. The release rates for all three reservoirs and every month were increased by a factor of 1.5, applied cumulatively to the second increase.

2.7 Optimisation of release rules

The IRAS-2010 model is linked via a Python wrapper to the Epsilon Dominance Non-dominated Sorted Genetic Algorithm-II (ε-NSGAII) to provide optimisation functionality. Owing to the negotiation procedure in the basin and general data scarcity, release rules were one of the greatest sources of uncertainty in this modelling study, when trying both to simulate the past and to predict the future. Optimisation of these rules offers the potential to assess the water efficiency of past decisions and to improve the efficiency achieved by future decision making.

For the purposes of this study, the rules were limited to two release rules for each of two (wet and dry) seasons and for each reservoir. The first release rate was associated with a hedging point which was also optimised for the storage level at which it was placed, while the second release rate was associated with the reservoir at its storage capacity (see Figure 2 for illustration).

We utilised the optimisation system described above to define the Pareto-optimal trade-off curves between the performance measures described above and suggest how this approach could be used to enhance the negotiation process in future. For the purposes of this initial study, one of the drier 10-year periods of the time-series was selected.

The optimisation formulation was to minimise all performance measures described above, except for the availability of land for poor farmers, which was to be maximised.

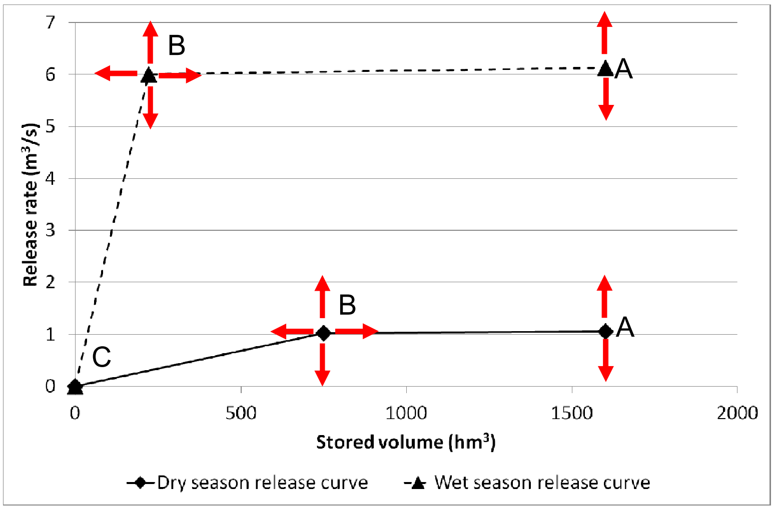


Figure 2. Illustration of optimisation constraints - ‘A’ points are fixed at the maximum stored volume so only the release rate can vary and must be equal to or higher than ‘B’ points release rates for same season, ‘B’ points can vary along both axes, ‘C’ points are fixed at (0,0) Red arrows show directions of possible variation

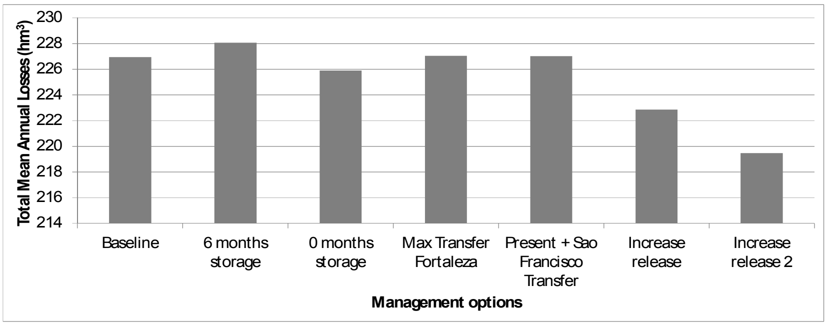
3 RESULTS AND DISCUSSION

3.1 Management options analysis

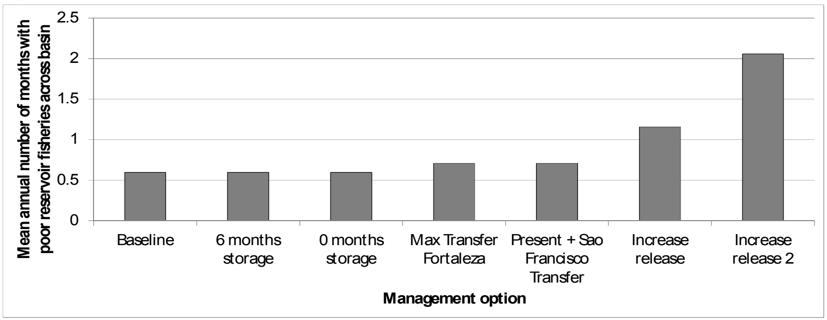
The results in Figure 3 show that the management options relating to both the period of municipal demand protection and the transfers into and out of the Jaguaribe basin make little difference to performance measure values, except where demand deficits are considered. The results for the irrigation demand deficit demonstrate that there are impacts on irrigation (and other sector) demand deficits from varying the inter-basin transfer option and therefore the basin water balance. The other performance measures vary primarily with the release rate from the reservoirs, which it was necessary to fix for this modelling study. The increased release rate options prove this dependence on release rate by their much greater variation in resulting performance values.

The combined impacts of municipal demand protection, inter-basin transfers and release rates could be used for a multi-criteria search, taking into account the performance measures developed as part of this study. It may be possible to validate the water allocation efficiency of the negotiated process or suggest improvements for future management.

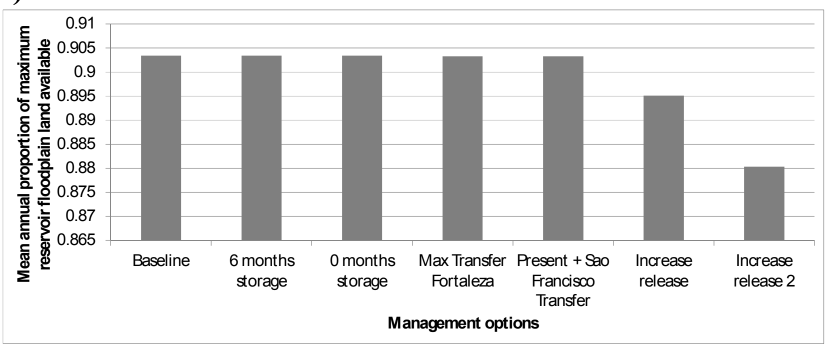
a)



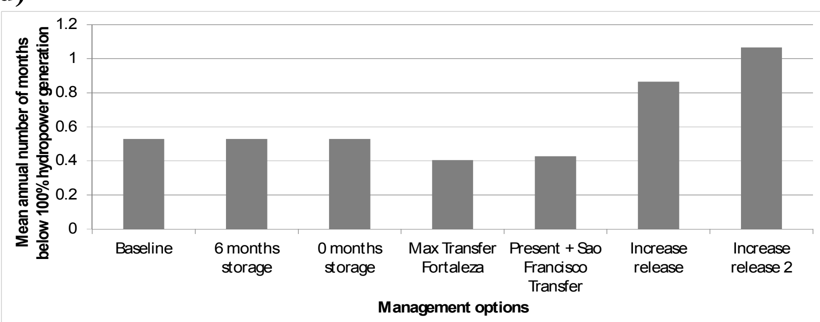
b)



c)



d)



e)

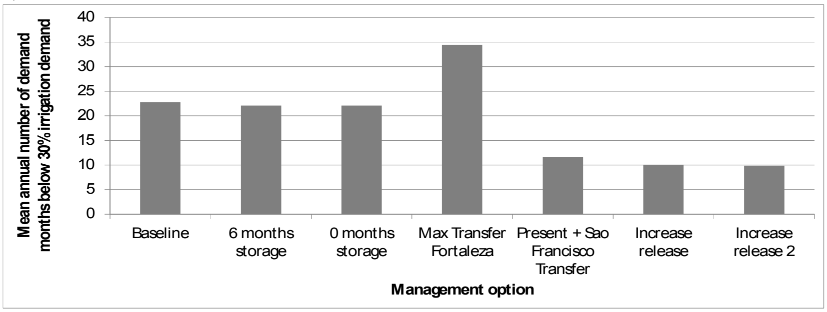
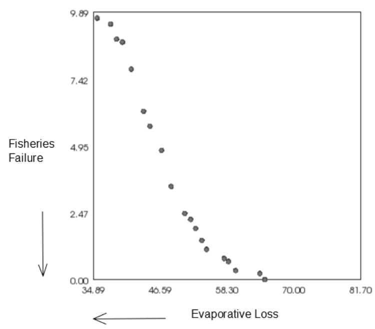


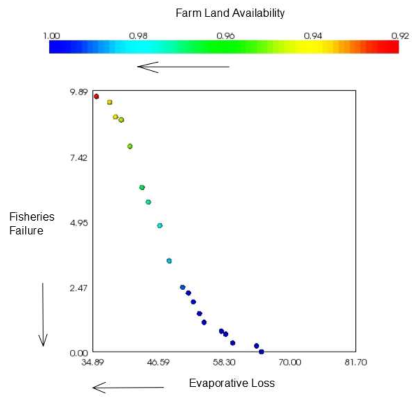
Figure 3. Results of management options analysis for different performance measures: a) Total losses (inc. spills, evaporation and transmission), b) Fisheries degradation, c) Land availability for poor farmers, d) Hydropower inefficiency, and e) Demand deficits (irrigation)

3.2 Optimisation analysis

The many objective optimisation (Kollat and Reed 2007) analysis allowed us to define the Pareto-optimal trade off curves between two or more of the performance measures, based on the results from the IRAS-2010 model. Figure 4a shows an example of a trade off curve between fisheries degradation (failure) and evaporative loss. In the case shown in Figure 4 there is a trade-off decision to be made between reducing evaporative losses and increasing fisheries degradation. We are able to select a trade-off point along the curve based on a management decision and find out which release rules would provide the corresponding levels of performance. Figure 4b shows an expanded 3-dimensional level of trade-off.



a)



b)

Figure 4. Trade-off curve between a) fisheries degradation (failure) and evaporative loss, b) fisheries degradation, evaporative loss and availability of farm land (arrows indicate the direction of optimisation)

3.3 Model limitations and proposed improvements

The implications of the negotiated release process in the Jaguaribe basin are that releases are determined on the basis of stored volume at only two points in the year – January and June. Release rules in IRAS-2010 can determine releases on the basis of current time-step storage, but we propose to extend this to allow releases determined by the stored volume in a previous time-step. Also monthly time steps are currently modelled as a fixed 30 day period; monthly time management capability could be added.

4 CONCLUSIONS AND FUTURE WORK

The modelling demonstrates that reductions in demand deficits could be achieved by implementing the interbasin transfer from the São Francisco river. However, whether these benefits outweigh transfer costs and whether technical difficulties – including en route evaporation – can be overcome as a further 'cost' is an important question. To assess the benefits for the Jaguaribe basin it would be necessary to obtain extensive economic information on marginal benefits of increasing water supplies.

There is little difference between the options for protecting a volume of municipal supply water. It is likely that available water could be better managed by increasing the use of hedging in the reservoir release rules and varying the release rates. This ignores the negotiation process for defining release rates however. The many objective optimisation of release rules explicitly accounts for their impacts on a number of different user groups and finds the optimal trade offs between them. This would provide a 'head start' in the negotiation process and facilitate more transparent decision-making, and potentially reducing negative impacts on the most vulnerable people in the basin.

Future work will consider optimisation of the municipal supply protection period and look at the impacts of climate change on optimised release rules. Where further data become available benefit functions will be enhanced to more realistically represent stakeholder preferences. Further information relating to the impacts of releases on the environment and ecosystem services would allow these to be incorporated into the design problem.

ACKNOWLEDGEMENTS

We are grateful for data and advice from Dr. Pieter van Oel, Professor José Carlos de Araújo from the Universidade Federal de Ceará in Fortaleza, Cybelle Frazao, Robson Vieira Da Silva and Eduardo Martins from FUNCEME. Joe Kasprzyk and Dr. Patrick Reed provided valuable assistance in the early stage optimisation work described above. The authors bear responsibility for any errors.

REFERENCES

de Araujo, J. C., P. Doll, A. Guntner, M. Krol, C. B. R. Abreu, M. Hauschild & E. M. Mendiondo (2004) Water scarcity under scenarios for global climate change and regional development in semiarid northeastern Brazil. *Water International,* 29**,** 209-220.

Braga, B.P.F. (2005) Water Infrastucture and Institutional Development in Semi-arid Brazil, Presentation to World WaterWeek, Washington DC, March 1-5, 2005

Broad, K., A. Pfaff, R. Taddei, A. Sankarasubramanian, U. Lall & F. d. A. de Souza Filho (2007) Climate, stream flow prediction and water management in northeast Brazil: societal trends and forecast value. *Climatic Change,* 84, 217-239.

Hardy, T. B. (1995) Assessing Environmental Effects of Severe Sustainaed Drought. *Water Resources Bulletin,* 31**,** 867-875.

Hsu, N. S., W. C. Cheng, W. M. Cheng, C. C. Wei & W. W. G. Yeh (2008) Optimization and capacity expansion of a water distribution system. *Advances in Water Resources,* 31, 776-786.

Johnsson, R. M. F. & K. E. Kemper. 2005. Institutional and policy analysis of river basin management: the Jaguaribe basin, Ceará, Brazil. In Report no. WPS3649. New York, USA: The World Bank.

Kollat, J. B. & P. M. Reed (2007) A computational scaling analysis of multiobjective evolutionary algorithms in long-term groundwater monitoring applications. *Advances in Water Resources*, 30, 408-419.

Matrosov, E. S., J. J. Harou & D. P. Loucks (2011) A computationally efficient open-source water resource system simulator - Application to London and the Thames Basin. *Environmental Modelling & Software*, 26, 1599-1610.

Sankarasubramanian, A., U. Lall, F. A. Souza & A. Sharma (2009) Improved water allocation utilizing probabilistic climate forecasts: Short-term water contracts in a risk management framework. *Water Resources Research*, 45.

Taddei, R.R. (2005) Of Clouds and Streams, Prophets and Profits: The Political Semiotics of Climate and Water in the Brazilian Northeast, Dissertation submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy, Colombia University, USA

Taddei, R. (2011) Watered-down democratization: modernization versus social participation in water management in Northeast Brazil. *Agriculture and Human Values*, 28, 109-121.

Van Oel, P. R., M. S. Krol, A. Y. Hoekstra & J. C. de Araujo (2008) The impact of upstream water abstractions on reservoir yield: the case of the Orós Reservoir in Brazil. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, 53, 857-867.