

RE-MODULATING WATER ALLOCATION IN A COMPLEX MULTI-RESERVOIR SYSTEM UNDER CURRENT AND CLIMATE CHANGE SCENARIOS

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ABSTRACT

Water resource planning and management at watershed scale should be aimed at guaranteeing soil and water conservation, together with the organization, use and management of water resources for protecting the environment and for the economic and social development. Nevertheless, often appropriate approaches and tools for identifying the most efficient solutions are not adopted, and water resource is allocated for fulfilling water demands from different stakeholders with no clear rules and aims, especially when complex water supply systems are managed.

In this study irrigation and hydropower water demands are analyzed in a large-scale complex system located in Eastern Calabria (Southern Italy), i.e. the Neto-Tacina Rivers System involving 2 watersheds (total area about 1500 km²), 3 irrigation systems (about 235 km² of irrigable fields, more than 70 km² actually irrigated), 9 reservoirs, 3 intakes and a system of three consecutive hydropower plants. Specifically, current configuration is analyzed considering water concessions presently awarded to the companies managing the hydropower plants. Then, by means of: 1) statistical tools, 2) a GIS-based distributed hydrological model and, 3) software tools for integrated water resources planning, an alternative and more efficient water resources allocation is proposed. Furthermore, the reliability of the new system is tested by considering two future water availability scenarios, derived from the most recent high resolution climate change data for the analyzed region, provided by regional downscaling experiments with grid resolutions finer than 20 km.

1 INTRODUCTION

Water resources planning and management is going to face difficult challenges, due both to growing water demand from increasingly populated and complex societies, which requires a shift towards an integrated approach (Sivakumar, 2011), and to climate change which, from a hydrological point of view, makes the assumption of stationarity in long-term weather conditions not valid anymore (Milly et al., 2008; Krysanova et al., 2010), and requires to seek for new approaches, strategies and tools. The Mediterranean basin is perfectly matching both these trends: on the one hand, a continuous increase of human pressure is observed (e.g. Cudennec et al., 2007); and on the other hand, it is considered a 'hot spot' for climate change (Giorgi, 2006; IPCC, 2007).

Climate change impacts on water resources have been researched widely for the

Mediterranean (a review is provided by Garcia-Ruiz et al., 2011); some of these researches focused also on uncertainties related to downscaling to the resolution of the hydrological impact model (Quintana Seguí et al., 2010; Senatore et al., 2011). On the contrary, climate change effects on the regulation of complex watersheds have been studied to a much lesser extent (Fowler et al. 2007). Nevertheless, a proactive approach (Yevjevich et al., 1983; Rossi, 2003), needed for avoiding drought phenomena and assuring a correct water resources management, cannot neglect a careful analysis also on potential effects of varying mean climate conditions.

In literature some examples of use of integrated water resource planning models can be found, aimed at evaluating the effects of climate change on current river and/or reservoirs systems. For example, Payne et al. (2004), Christensen et al. (2004) and Van Rheeën et al. (2004) studied the effects of climate change on river systems adopting from one to three projections, without deeply analyzing possible adaptation of the reservoir operating rules. Similar studies were performed by Markoff and Cullen (2008) on hydroelectric generation, by Veijalainen et al. (2010) on lake regulation, and by Christensen and Lettenmaier (2007) on an extensively developed and regulated river basin, but with a greater number of climate projections. Some other studies instead are more focused on the adaptation/optimization of the operating rules, by using specific algorithms and tools (e.g. Carpenter and Georgakakos, 2001; Yao and Georgakakos, 2001; Vicuna et al., 2010; Minville et al., 2009, 2010; Barthel et al., 2010).

In spite of the increasing expertise in the optimization techniques to be used for the adaptation of the operating rules, in many practical situations water resource is allocated between different stakeholders with no clear rules, especially when complex water supply systems are managed. Calabria is a Southern Italian region potentially very sensitive to climate change, where significant reductions in surface runoff are predicted (Senatore et al., 2011), nevertheless water use concessions for the main multi-reservoir hydropower system of the region, the Neto-Tacina Rivers System (NTRS), are still ruled by an agreement signed several tens of years ago.

In this paper, current configuration of the NTRS will be analyzed, assessing the reliability of the whole system, which includes not only hydropower plants but also some irrigation districts, considering both present and future water availability scenarios (section 3.1). Afterwards, a new configuration with an alternative water resources allocation will be analyzed in the same way, highlighting how a correct water resources management could sensibly reduce the impact of climate change (section 3.2). The objective of the work will be reached by means of several climate, hydrological and integrated water resource management models, which are introduced in the next section. In the same section, also the study area is briefly described.

2 DATA AND METHODS

2.1 Description of the system

The NTRS mainly concerns the watersheds of the Neto and Tacina rivers (respectively about 1073 km² and 427 km²). In the NTRS several elements are involved: the irrigation systems “Basso Neto”, “Basso Tacina” and “Capo Colonna” (about 235 km² of irrigable fields, more than 70 km² actually irrigated); 9 reservoirs (Ariamacina, Migliarite, Orichella, Poverella, S. Anna, Votturino and the three biggest ones Arvo, Ampollino and

Cecita); 3 intakes (Fischio, Juntura and Soleo which is only used for irrigation purposes) and; a system of three consecutive hydropower plants (Orichella, Timpagrande and Calusia). The whole system is shown in figure 1, while figure 2 shows a schematization adopted in the water resources management model. Concerning water requirements, the information derived from the official water concession agreement were followed for the hydropower plants, while for the irrigation systems water demands were estimated depending on the period of the year and soil use (Tables I and II). Water users and related water demands are summarized in Table III.

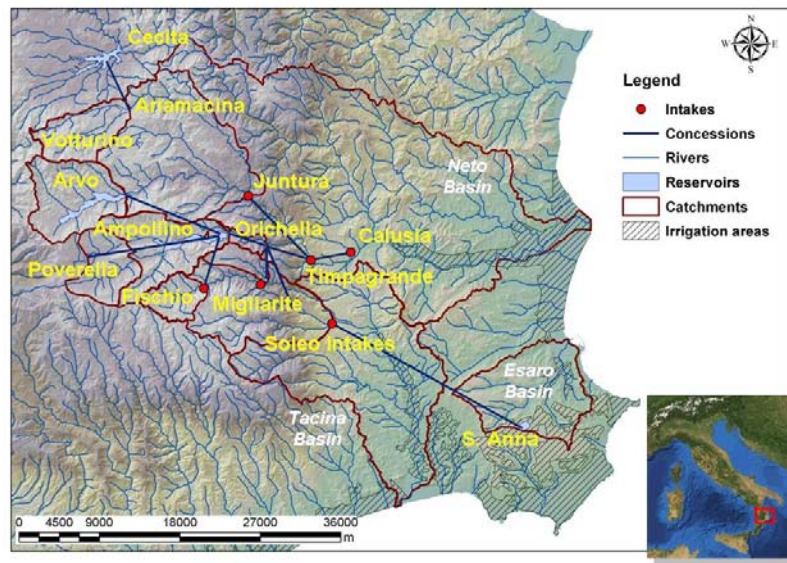


Figure 1. The Neto-Tacina Rivers System.

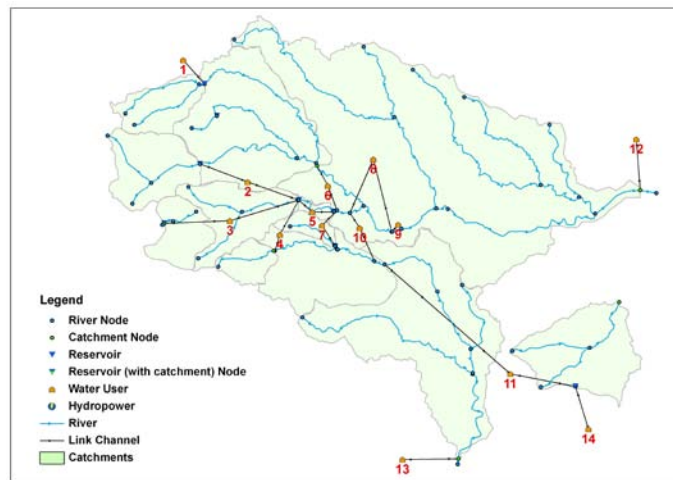


Figure 2. Schematization of the NTRS in the water resources management model MIKE BASIN.

Table I. Derivable water (m^3s^{-1}) from Soleo intake towards S. Anna reservoir.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2.0	2.0	1.8	1.4	2.1	1.9	1.7	1.5	1.9	1.2	1.4	2.0

Table II. Water demand (m^3s^{-1}) from the irrigation areas.

	Apr	May	Jun	Jul	Aug	Sep
Basso Neto	0.09	0.90	2.72	3.99	1.84	0.78
Basso Tacina	0.02	0.10	0.85	1.26	0.67	0.27
Capo Colonna	0.03	0.62	1.28	1.92	1.01	0.56

Table III. Water demand (m^3s^{-1}) for all the water users.

ID	Water user	Water demand	Period of the year
1	Ariamacina → Cecita	0.92	Jan – Dec
2	Arvo → Ampollino	2.30	Jan – Dec
3	Poverella → Ampollino	1.40	Jan – Dec
4	Fischio → Ampollino	0.90	Jan – Dec
5	Ampollino → Orichella	7.00	Jan – Dec
6	Juntura → Orichella	3.98	Jan – Dec
7	Migliarite → Orichella	0.81	Jan – Dec
8	Orichella → Timpagrande	10.92	Jan – Dec
9	Timpagrande → Calusia	8.80	Jan – Dec
10	Orichella → Tacina (irrigation)	1.06	May – Sep
11	Soleo → S. Anna (irrigation)	Table I	Jan – Dec
12	Basso Neto irrigation area	Table II	Apr – Sep
13	Basso Tacina irrigation area	Table II	Apr – Sep
14	Capo Colonna irrigation area	Table II	Apr – Sep

2.2 Water availability and system simulation

The hydrological simulations for the single sub-catchments were carried out by means of a distributed water balance model (Mendicino et al., 2008), that simulates soil moisture and groundwater storage changes, snow accumulation and melt, evapotranspiration and runoff on a 5 km regular grid and monthly time step (Fig. 3), using data sets that include climatic drivers (temperature and precipitation), vegetation and soil properties. The model was extensively tested over the whole Calabria region, providing reliable results.

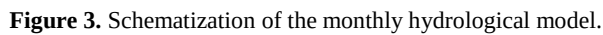
The mathematical river basin management software used for taking into account water transfers among reservoirs and intakes was MIKE BASIN (DHI, 2006), a software specialized in the management of hydrographic data and their interconnections with anthropic factors.

2.3 Regional climate and hydrological change projections

The results of the climate change simulations are based on newly available climate change data at spatial resolutions below 20 km provided by the Regional Climate Models (RCMs) HIRHAM and RegCM.

HIRHAM is a hydrostatic model of the Danish Meteorological Institute (DMI). Its dynamical part originates from the High Resolution Limited Area Model (HIRLAM)

Results of the climate change simulations for the Neto basin led to an average annual decrease in precipitation (-7.2% and -19.3% respectively with HIRHAM and RegCM), increase in temperature ($+4.0\text{ }^{\circ}\text{C}$ and $+3.9\text{ }^{\circ}\text{C}$), and an even more marked decrease in total runoff (-13.7% and -30.1%). These changes are not uniform along the year, as it is shown in figure 4.



The time slices considered by the RCMs are a 30-years control period (1961-1990) and another 30-years period at the end of the XXI century. Since a 30-years period could be not enough for observing a significant number of drought events, the assessment of the performances of all the configurations was based on the analysis of 1000 years temperature and precipitation series, generated with a stochastic periodic ARMA (PARMA) model through the SAMS software (Sveinsson et al., 2007). Specifically, five

temperature and five precipitation 1000-years generated series, preserving the main statistics of the original series, were derived from five monthly temperature and five monthly precipitation series, related to: the observed data in the control period 1961-1990; the control runs of the RCMs HIRHAM and RegCM for the same time slice and; the runs of the RCMs for the time slices 2071-2100 (HIRHAM) and 2070-2099 (RegCM). The generated series were used as input data of the water balance model, while the results of the hydrological analysis were used for simulating, through the software MIKE BASIN, the behaviour of the system. In MIKE BASIN simulations some priorities in water uses were assumed, privileging the satisfaction of: 1) minimum flow requirements (calculated with the method adopted in the Regional Water Conservation Plan) and, 2) irrigation requirements, as it is ordered by law, even though in practice it is not easy to assess the actual fulfilment of this priority list. Furthermore, evaporation from lakes was taken into account using some empiric relations depending on mean monthly temperature.

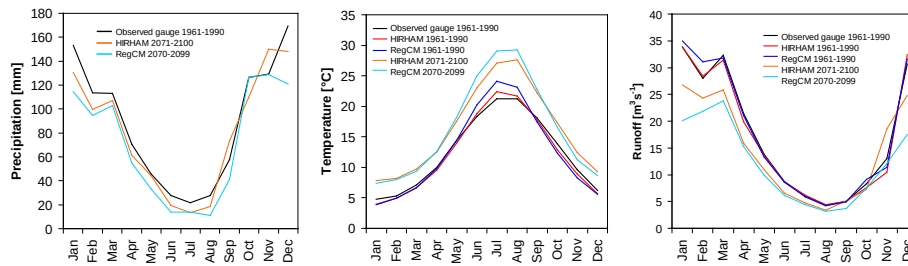


Figure 4. Mean monthly changes in precipitation (left), temperature (centre) and runoff (right) in the Neto river basin.

3.1 Current configuration: present and future water availability scenarios

Figure 5 shows for each water user the probability of monthly deficits lying in one of the four classes of deficit 0%-25%, 25%-50%, 50%-75% and 75%-100%, expressed as a percentage of the whole demand. For each graph, the first column (Obs) is related to the simulations obtained using the precipitation and temperature 1000-years series derived from the observed data; the second (H-cs) and the third (R-cs) columns are related respectively to HIRHAM and RegCM simulations with the current climate scenario; finally, the forth (H-A2) and the fifth (R-A2) columns show the results of the runs of the same RCMs with the A2 scenario. The monthly deficits probability is referred to the months when water is actually required, hence in the graphs only 5 and 6 months per year are taken into account, respectively for users 10 and 12-14 (see Table III).

H-cs and R-cs runs can be considered as control runs with respect to Obs results. Their outputs are generally very close to Obs, with few exceptions (e.g. class 75%-100% in the Arvo → Ampollino HIRHAM simulations). Specifically, the scatterplots of the whole probability (i.e. 0%-100%) of observed and simulated monthly deficits for all the users provide a slope of the regression curve equal to 1.01 for H-cs and 1.00 for R-cs, with the R^2 coefficients equal to 0.99 and 1.00 respectively.

H-A2 and R-A2 predict a significant increase in the monthly deficits probability, mainly owing to the increase in the highest class of deficit (75%-100%), as it is highlighted in figure 6. This means that drought events are predicted to be more impacting

and frequent in the analyzed area. The mean increase among all users in the 75%-100% class of deficit will be +6.19% with HIRHAM and +15.45% with RegCM, while the class 0%-25% shows a little decrease (−0.33% and −1.59% respectively).

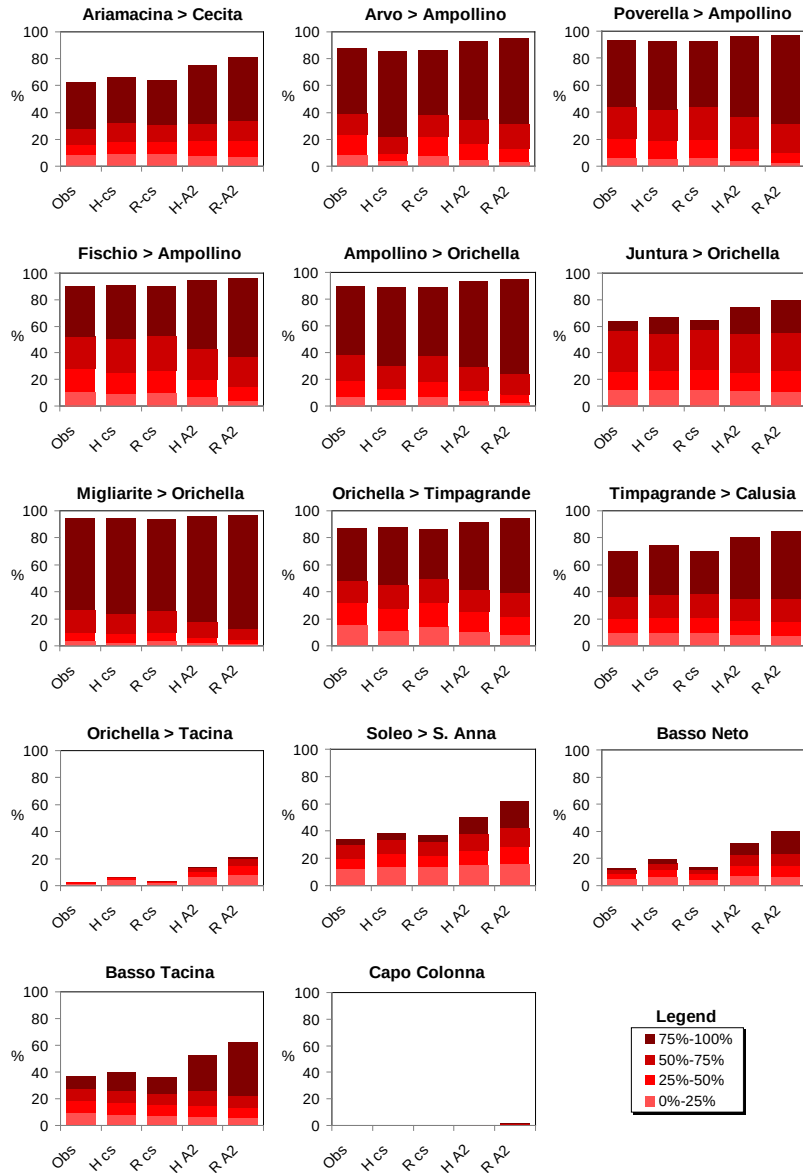


Figure 5. Current water resources allocation; probability of monthly deficits lying in one of the four classes of deficit expressed as a percentage of the whole demand.

Apart the changes in the monthly deficits probability predicted by the climate change

projections, the main feature characterizing the current configuration of the system is the persistently high percentage of deficit probability for users 1-9 even in the current water availability scenario. These users are involved in the hydropower generation system, hence the deficit is caused by the too high water concessions awarded to the companies managing this system. In fact, since the simulations with MIKE BASIN are organized in a way to satisfy first minimum flow and irrigation requirements, deficits for users 1-9 highlight that remaining water for hydropower purposes is less than allowed, or, alternatively, that all the remaining water will be almost certainly used in the hydropower system. Some deficits are detected also for the irrigation systems, mainly in future scenarios and in the Basso Neto and Basso Tacina systems. These deficits are only partially linked to the hydropower system, since the intakes of the irrigation systems are rather downstream and depend on other sub-catchments, besides the ones interested by the multi-reservoir system. Nevertheless, the almost null deficit in the Capo Colonna irrigation system, which is fed by the S. Anna reservoir, suggests that water diversion from Soleo to S. Anna (water user no. 11), moving water outside the Tacina watershed, could be reduced to a constant value, equal only to the water demand of user no. 10.

In the next section an alternative water allocation configuration is proposed, taking into account the comments concerning both the hydropower and the irrigation system.

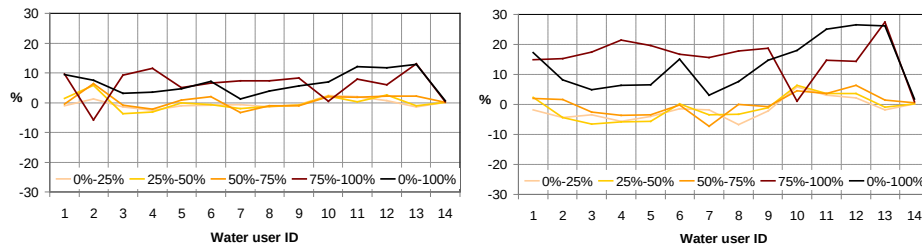


Figure 6. Differences in the probability of monthly deficit due to climate change, calculated by HIRHAM (H-A2 – H-cs, left) and RegCM (R-A2 – R-cs, right). For water users ID, see Table III.

3.2 New configuration: present and future water availability scenarios

In the new configuration, water demand for hydropower purposes was calculated taking into account current water availability of the hydrological system. For each sub-catchment, starting from the modelled monthly discharges the average monthly and annual available volumes were estimated. From these volumes some fractions were subtracted owing to minimum flow requirements and evaporation from reservoirs. Furthermore, a higher hydropower request was hypothesized in summertime, hence 60% of the total available volumes for the water users 1-9 was supposed to be derived in this period, and the remaining 40% in wintertime. Finally, concerning the irrigation system, water demand for user no. 11 was reduced to a constant value, $1.06 \text{ m}^3 \text{ s}^{-1}$. Table IV shows the new water demands for all the users.

Figure 7 shows the monthly deficits probability lying in each of the four classes of deficit, considering the alternative water resources allocation. From a comparison with graphs in figure 5 an evident deficit percentages reduction is highlighted for all the users, even though in several cases values higher than 50% remain. Specifically, for the hydropower-related users 1-9 the following mean reductions are obtained if the whole

monthly deficits probability is considered: -32.82% for Obs simulation, -23.52% for H-A2 and -18.80% for R-A2. For the users 10-14, instead, the following reductions are obtained: -9.23% for Obs, -10.29% for H-A2 and -10.28% for R-A2.

Table IV. New configuration: water demand (m^3s^{-1}) for all the water users.

ID	Water user	Water demand		Period of the year	
1	Ariamacina → Cecita	0.90	0.60	Apr – Sep	Oct-Mar
2	Arvo → Ampollino	1.18	0.79	Apr – Sep	Oct-Mar
3	Poverella → Ampollino	0.71	0.47	Apr – Sep	Oct-Mar
4	Fischio → Ampollino	0.46	0.30	Apr – Sep	Oct-Mar
5	Ampollino → Orichella	3.22	2.14	Apr – Sep	Oct-Mar
6	Juntura → Orichella	3.46	2.31	Apr – Sep	Oct-Mar
7	Migliarite → Orichella	0.30	0.20	Apr – Sep	Oct-Mar
8	Orichella → Timpagrande	6.98	4.65	Apr – Sep	Oct-Mar
9	Timpagrande → Calusia	6.98	4.65	Apr – Sep	Oct-Mar
10	Orichella → Tacina (irrigation)	1.06		May – Sep	
11	Soleo → S. Anna (irrigation)	1.06		Jan – Dec	
12	Basso Neto irrigation area	Table II		Apr – Sep	
13	Basso Tacina irrigation area	Table II		Apr – Sep	
14	Capo Colonna irrigation area	Table II		Apr – Sep	

An important feature to highlight is the combined effect produced by the new water resources allocation and water availability reduction due to climate change. Figure 8 shows the monthly deficit probabilities differences, between respectively H-A2 and R-A2 from the new configuration, and H-cs and R-cs from current configuration. In the graphs several negative percentage values can be observed, meaning that for many water users, if water concessions more coherent with real current availability are adopted, the estimated deficits in the future water limited scenarios are less than the estimated deficits with the current climate scenario (and current water resources allocation). Therefore, the effects produced by the re-modulation of water resources allocation in most cases are prevailing on the effects of climate change.

4 CONCLUSIONS

The simulations carried out in the present study show how the water concessions for hydropower purposes in the complex multi-reservoir NTRS are incoherent with water resources availability. This could lead to conflicts among different water users and requirements, which will be exasperated by reduction of water resources availability due to climate change. A first attempt for a re-modulation of water allocation in the system is proposed, which contributes to a significant reduction in water deficit frequency and intensity with respect to current configuration, even considering future ‘drier’ climate scenarios.

The proposed re-modulation is based on simple considerations about water volumes. Adopting adaptation/optimization models of the operating rules will improve the results, such as the use of water balance models with a time step more detailed than monthly (for example, some reservoirs in the system are based on a weekly regulation). Furthermore,

evolution in time of water demand should be considered. However, the study clearly shows that a shift to wiser planning and management of water resources could significantly counterbalance climate change effects in Calabria.

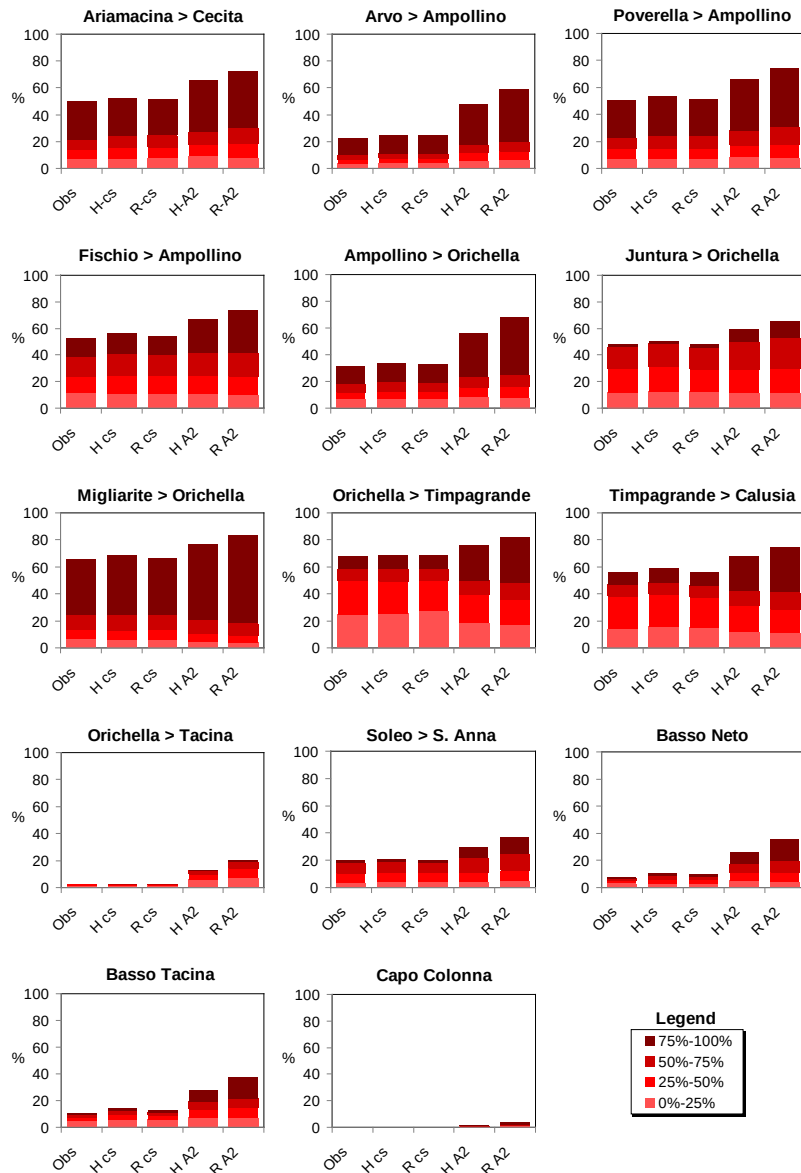


Figure 7. Alternative water resources allocation: probability of monthly deficits lying in one of the four classes of deficit expressed as a percentage of the whole demand.

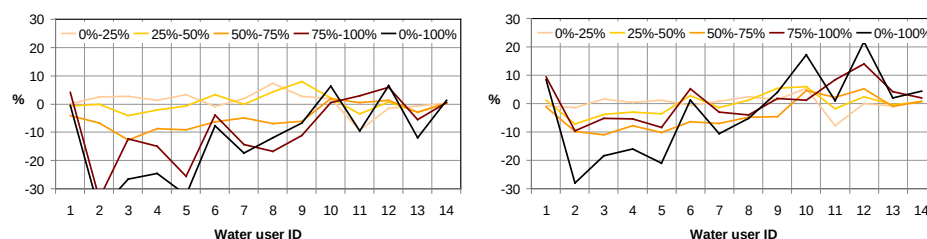


Figure 8. Differences in the probability of monthly deficit. Left: $H-A2_{\text{new configuration}} - H-CS_{\text{current configuration}}$; right: $R-A2_{\text{new configuration}} - R-CS_{\text{current configuration}}$.

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