Real-time information on ENSO state reduces the severity of shortfalls in water supply – the case of Metro Manila, Philippines

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1. Introduction

In this work we investigate:

- the impact of hydro-climatic variability on the performance of Metro Manila's water supply system;
- the operational value of El Niño Southern Oscillation (ENSO) for water reservoirs operation.

In particular, we focus on the Angat-Umiray water resources system, a multi-purpose reservoir network serving 98% of Metro Manila's water demand (about 13 million people). The system is also used for irrigation, hydropower generation, and flood control [1].

The current situation:
To study the anomalies in system performance, we first simulate the storage dynamics using the existing operating rules and historical inflow conditions. Results show that deficits of water supply are strongly correlated to El Niño Southern Oscillation (ENSO) indices.

Our goal:
We then attempt to improve the system operations by designing new operating policies with an Evolutionary Multi-Objective Direct Policy Search framework (EMODPS) [2]. EMODPS is an alternative to (Stochastic) Dynamic Programming that can mitigate the *curse of dimensionality* and the *curse of modelling*—namely the fact that an explicit model of each component of the water system is required to design an operating policy. This is a major limitation if one wants to condition the policy on exogenous information, such as the ENSO state.

We establish three different deterministic EMODPS experiments (over the period 1968 – 2014), where we successively expand the information content on which the release decisions are made. In the first experiment (RBF4*), the operating policy is a function of the reservoir storage only; the argument of the operating policy is then expanded to include information on seasonality (RBF5) and ENSO state (RBF6).

In synthesis, we address the following research questions:

1. Which additional information helps decision-makers and when is such information useful?
2. Is it possible to reduce the conflict between water users if we use ENSO-informed policies?
3. Is it possible to reduce the vulnerability of Metro Manila water supply (without affecting other users)?
4. Can information on ENSO state mislead operators?

* experiments acronym

2. Study area and data

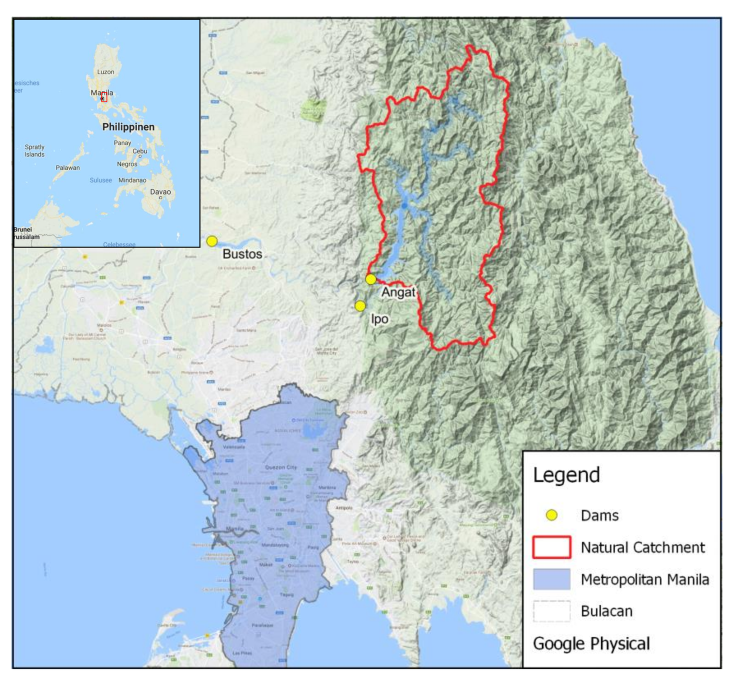

Fig. 1: Topographic overview
The Angat-Umiray water system is located in Bulacan Province, Central Luzon, Philippines. It consists of three dams: Angat, Ipo, and Bustos.

The head pond of the water resources system is Angat Reservoir, which has an active storage of about 743 hm³ and is designed as a seasonal storage. The water system serves two main users, namely Metro Manila and the irrigation districts located in Bulacan Province. The municipal water demand is almost constant throughout the year and is on average 45.5 m³/s (Fig. 2). The irrigation demand varies throughout the seasons, reaching its peak in the period between December and February (at the beginning of the dry season), and is on average 23.8 m³/s (Fig. 2).

Angat Resevoir collects water from the Angat River and drains a natural catchment of about 545 km². After the realization of the Umiray-Angat Trans-basin Project (in 2000), additional water is diverted from the Umiray watershed to Angat Reservoir. This results in a mean annual inflow of about 71.4 m³/s. The catchment is affected by two different types of rainfall patterns. The summer rainy season is associated with the Asian south-west monsoon, while the winter rainy season is affected by the north-east monsoon. The latter contributes to most of the total annual inflow. Moreover, Typhoons occur during the winter rainy season and are an important source of water. The different rainfall patterns result in two rainfall peaks (Fig. 2).

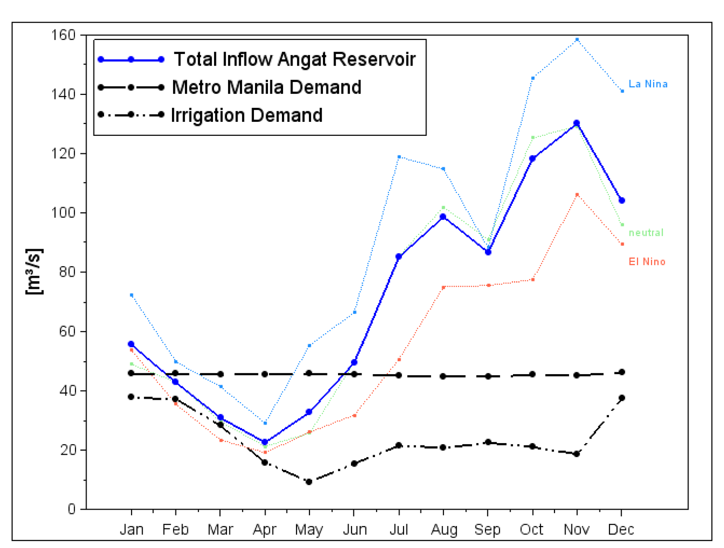

Fig. 2: Monthly* inflow and demand patterns
Monthly inflow patterns calculated for the different phases of the El Niño Southern Oscillation (over the period 1968 – 2014), and monthly demand patterns (over the period 2001 – 2014).

* based on COAPS classification

3. Reservoir operation

The management of a water reservoir can be formulated as a sequential decision-making problem, which can be solved with optimal control techniques. The key element is the design of a feedback control policy, namely a sequence of control (or operating) rules that suggest how much water to discharge as a function of the system state [3]. Typically, decisions are made at discrete time steps and are based on the reservoir storage $\mathbf{S_t}$ and other information $\mathbf{I_t}$ (e.g., hydrological information, etc.). The transition of the storage from $\mathbf{S_t}$ to $\mathbf{S_{t+1}}$ depends on the release decision $\mathbf{u_t}$, evaporation $\mathbf{e_{t+1}}$, and inflow $\mathbf{q_{t+1}}$—plus a few legal and physical constraints. The problem of design an optimal control policy can be solved with various techniques, such as (Stochastic) Dynamic Programming or Direct Policy Search.

Evolutionary Multi-Objective Direct Policy Search (EMODPS): The key idea of DPS is to adopt a (nonlinear) function to describe the relationship between system state (e.g., storage) and release decision, and to then optimize the parameters of this function with the aid of a global optimization algorithm. In our study, we use Borg MOEA to calibrate the parameters of a Radial Basis Function Network [2]. Note that the function has two outputs, corresponding to the release decision for Manila and the Irrigation district.

Operating Objectives:

- Squared deficit of water supply for both Manila and Irrigation (to be minimized, "RV² Metro Manila" and "RV² Irrigation")
- Resilience of Manila's water supply (to be maximized, "φ Metro Manila")
- Largest water shortfall for Manila's water supply (to be maximized, "η Metro Manila")

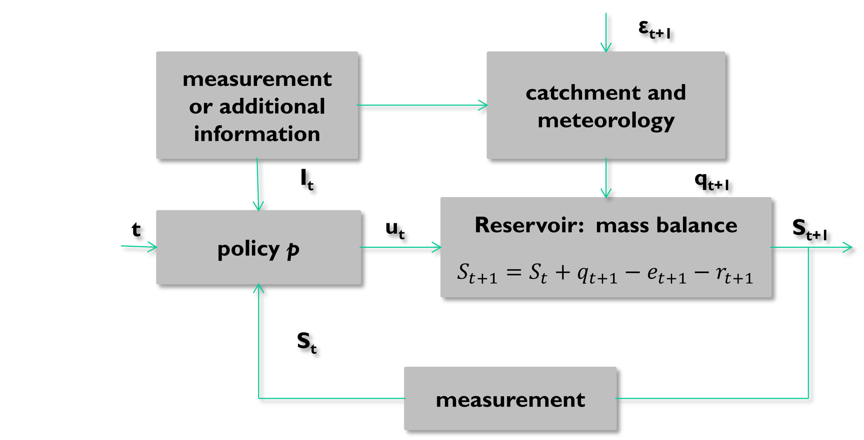

Fig. 3: Feedback-Control Framework
Simplified schematic for the main elements of the reservoir operation problem.

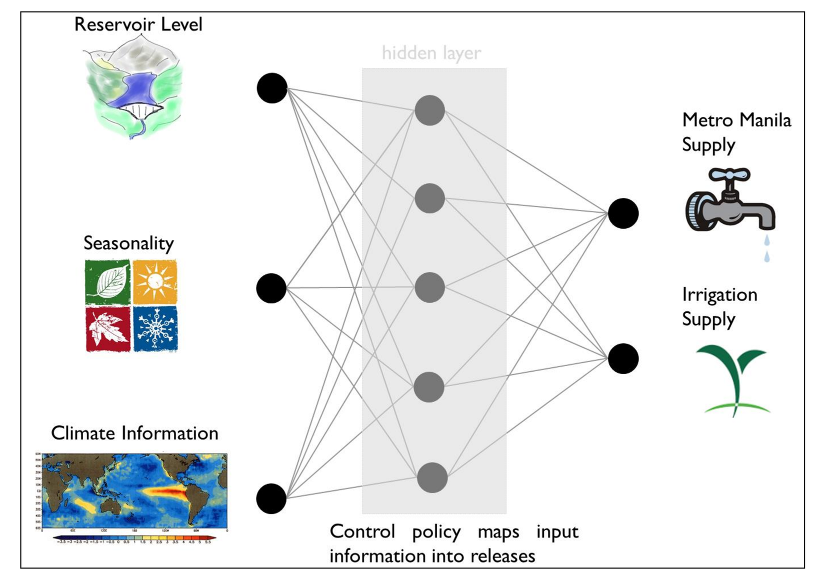

Fig. 4: Simplified schematic of the Radial Basis Function Network (RBFN)
The RBFN is a non-linear function approximator. The hidden layer consists of N+K+1 neurons (where N is the number of inputs and K is the number of outputs). The activation functions are radial basis functions.

4. Effect of ENSO on inflow and water supply

Precipitation in the Philippines shows strong inter-annual variability, which can be partially explained by ENSO [4]. This also applies to inflows at the study site, where we found a correlation equal to -0.27 between inflow anomaly and the Oceanic Niño Index (ONI) (with a 4-month lag). The negative correlation means that during warm ENSO phases (El Niño) inflows are reduced, whereas during cold ENSO phases (La Niña) inflows are increased. In order to understand the system behaviour, we classified the simulation period into El Niño, neutral, and La Niña phases (Fig. 5). We found that positive and negative inflow anomalies match the classified timeseries quite well. During El Niño phases, the anomalies are significantly negative, while during La Niña phases the inflow anomalies are significantly positive. During neutral phases we see positive and negative anomalies, that are on average 5.0 m³/s (see Table 1).

Table 1: Mean deficit of water supply and inflow anomalies
p-values: statistical significance is assessed by bootstrapping the deficits over 1,000 repetitions of each category (El Niño, neutral and La Niña)

	1968-2014	El Niño		neutral		La Niña	
	m³/s	m³/s	p-value	m³/s	p-value	m³/s	p-value
Metro Manila	-1.3	-3.5	0.000	-0.2	0.035	-1.0	0.095
Irrigation	-3.8	-6.6	0.000	-3.5	0.000	-2.9	0.005
Inflow	0.0	-11.4	0.000	5.0	0.222	13.2	0.000

The current operating policies determine the release as a function of the reservoir water level [5], and do not implement any hedging rule. Simulation results show that the deficit of water supply encountered by the two users (Metro Manila and Irrigation) is negatively affected by positive ENSO phases. Even in wet phases, the demand cannot be always fulfilled.

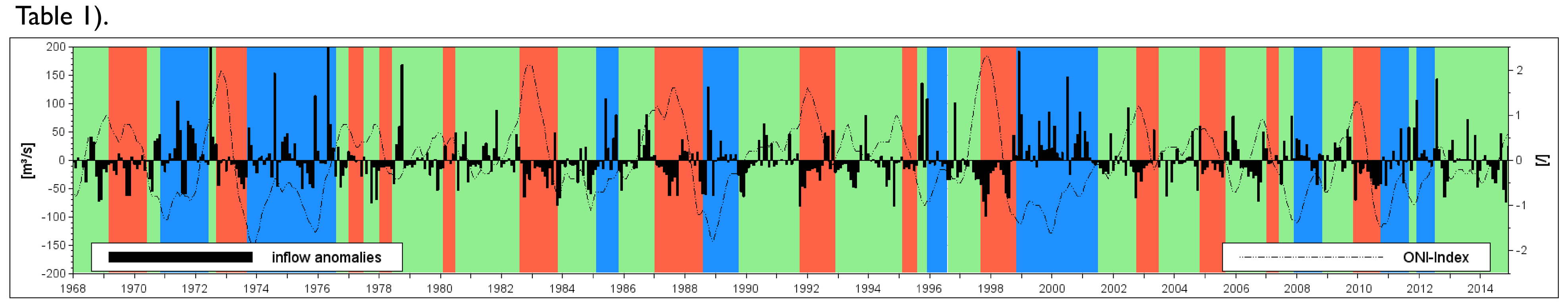

Fig. 5: ENSO-phases and inflow anomalies
Oceanic Niño Index (ONI), defined as the 3 month running mean of ERSST.v4 SST anomalies in the Niño 3.4 region. *Classification:* We identified months whose preceding 4 months have exceeded (El Niño) or fallen below (La Niña) threshold of +/- 0.5. If a month was identified, the next 4 months are assigned to the corresponding ENSO phase. If there are consecutive months identified within a certain period, the identified period is extended accordingly.

5. Results

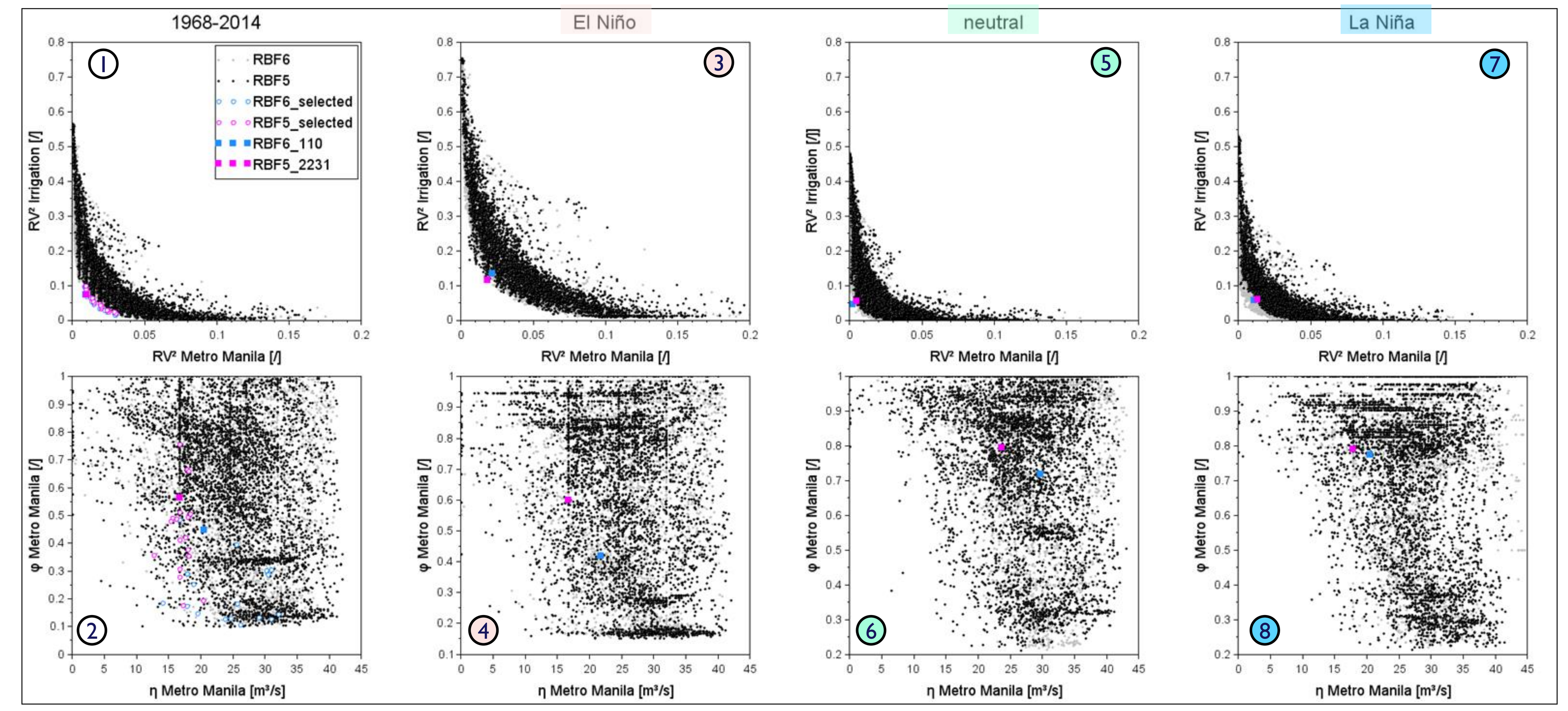

Fig. 6: Pareto optimal solutions
(1,2): Illustration of the 4 dimensional Pareto fronts obtained with deterministic optimization over the historic period 1968 – 2014. Results show a strong conflict between Metro Manila and Irrigation that can be weakly reduced by the ENSO-informed policies (panel 1 and Table 2). Interestingly, some selected ENSO-informed policies (blue dots) can reduce the severity of shortfalls at the cost of resilience (panel 2).
(3-8): These panels show the average performance measures split into distinct periods (see Fig. 5) and show that additional information influences the reservoir performance.
(3,4): The Pareto front cannot be extended by ENSO informed policies during dry periods. It can be seen that RV² measures are slightly worse, which suggests the presence of misguided decisions (see Fig. 8).
(5-8): The performance of the reservoir is clearly improved during wet periods when using ENSO-informed policies, because the policy gains information that there is enough water in the system. Policies, that do not have this kind of information always tend to hedge in order to avoid heavy shortfalls. This leads to higher reservoir levels and too conservative policies during wet periods.

Experiment	Hypervolume indicator 1968-2014	El Niño	neutral	La Niña
RBF4	70%	72%	71%	65%
RBF5	75%	73%	75%	66%
RBF6	76%	72%	84%	78%

Table 2: Hypervolume indicator for several periods
The hypervolume indicator (to be maximized) determines the volume of the objective space dominated by the reference set compared to the approximation set. The values reported in the table confirm the results illustrated in Fig 6.

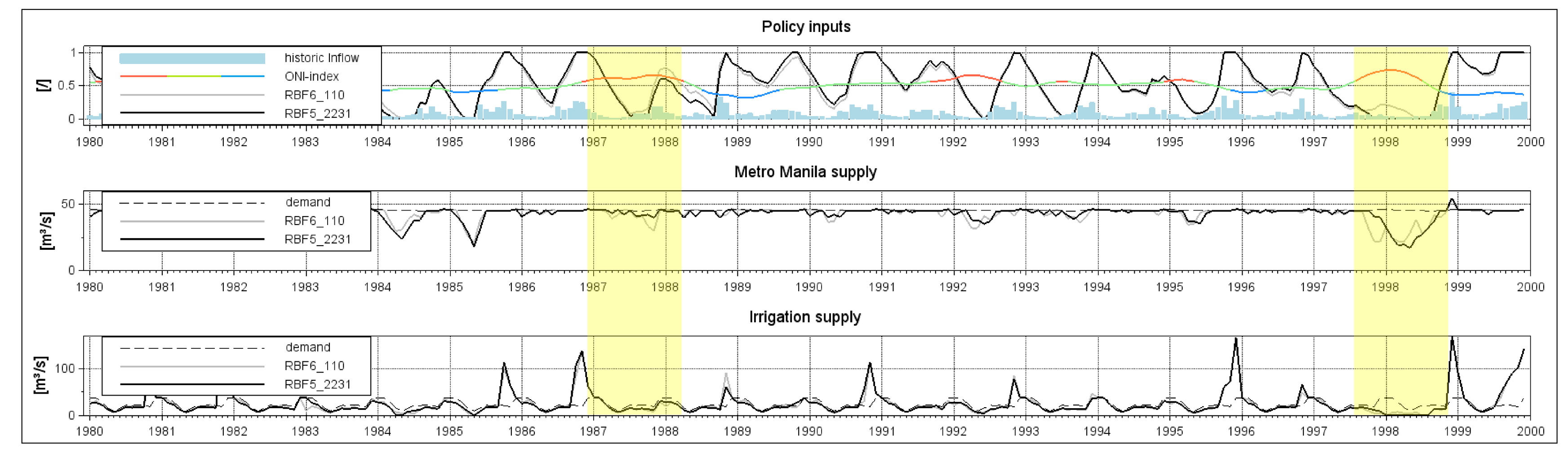

Fig. 7: Selected trajectories in detail (1980 – 2000):
Focus on the year 1987: the ENSO-informed policy is misguided since inflows in the winter rainy season are higher than expected. Focus on the high ENSO-phase in 1997/98: looking ahead, the ENSO-informed policy starts hedging in August '97, which leads to less severe shortfalls.

6. Conclusions and Outlook

- Information on ENSO improves the system performance, especially during wet phases.
- ENSO information has an impact on the release decisions, but cannot reduce the conflict between the users.
- ENSO information allows policies to hedge in advance of drought events.
- Misguided decisions occur during the simulation period if the ENSO signal is not consistent with the inflow process.
- Future work will focus on a Robust Optimization approach to reduces the chances of misguiding operators

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