Eco-hydrology of wetlands aided by remote sensing
A case study with the REVIVE's GOALS initiative

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ABSTRACT: The eco-hydrological REVIVE's GOALS approach, based on remote sensing time series, and with spectral responses obtained from wetland floodplains, is presented. The test site comprises a 4800 km^2 area of Lower Paraná River inland water bodies in South America. With 10-day composites, a 'present situation' with eco-hydrological features, encompassing statistical probability, time after perturbation, diversity and remote sensing normalised difference vegetation index were chosen so that scenarios could be inferred for the protection and maintenance of inland water bodies. With four time-series samples along the twentieth century, the 'long term' scenarios rely on alternative insights of ecosystem's resilience, using protected contiguous patches. Multi-disciplinary opportunities and eco-compatible strategies for protected aquatic environments are outlined.

1 INTRODUCTION

The depth of total runoff from South America big river systems (Amazon, Paraná and Orinoco, with a total near of 190,000 m^{3}s^{-1} a year) is greater than the combined total runoff from Africa, Asia, and North America (GRDC Repport, Grabs et al, 1996 ; Clarke et al, 2000). Although South America's big rivers are classical examples of floodplain wetland biodiversity, their ecological approaches under environmentally-sound development appeared recently (i.e. Petts, 1990 ; Neiff ; Neiff, 1996). Unlike many areas of the world, in South America, water available for domestic, industrial and agricultural supplies and hydroelectric power production, should not be a major constraint to development. Conversely, the challenge is to ensure that water resource development is sustainable, and environmentally sound. In order to link the gap between ecological demands and scientific skills, the REVIVE's GOALS approach (Mendiondo et al, 2000) is presented. This is an English translation of the Spanish acronym METAS REVIVIR, or "Modelación Espacial y Temporal de Ambientes Sudamericanos a partir de la Respuesta Espectral de la Vegetación Interna, de Valles de Inundación y de Riberas", as "spatial and temporal modeling of South America environments derived from the spectral biomass response of inland water bodies, floodplains and riparian areas". The objective of this paper is to introduce the eco-compatible insights based on REVIVE's GOALS integrated strategy, and through an illustrative example of managing South America's aquatic environments, discussing its scopes for multidisciplinary studies and information exchange.

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2 METHODOLOGY

The REVIVE's GOALS approach follows theoretical background of Holling (1973), White and Pickett (1985), Denslow (1985), Neiff (1996) and Mendiondo (1998). In short, this approach is summarized in three steps: (i) data collection, (ii) wetland analysis and (iii) eco-hydrologic hypothesis-testing, respectively. First, a geographically-based database fosters a matrix, with spatial and temporal dimensions, with serves as a monitoring descriptor of South America's wetland biomass. Second, GIS techniques and remote sensing theory are used so that the wetland spectrum response could be interpreted and supervised with variables usually available, i.e. by vegetation index composites. In order to discriminate the eco-hydrological regimes, i.e. between high water or pothamophase period, and dry phase or limnophase period, this second step offers a proper depicting of ecosystem features on the patches analysed. Third, a present state analysis to aid a decision making process, with feasible long term scenarios based on patch dynamics, is derived. This analysis includes resilience, diversity, recurrence and floodplain biomass related parameters.

2.1 *Remote sensing database*

Under the guidance of the International Geosphere Biosphere Programme, NASA and USGS processed standards for the Advanced Very High Resolution Radiometer – AVHRR data. Those have been developed for the production of global 10-day maximum normalised difference vegetation index (NDVI) composites. The major uses of the composites are related to the study of surface vegetation cover. The NASA Moderate Resolution Imaging Spectrometer land science team concluded that a global land 1-km AVHRR data set is crucial to develop algorithms for several land products for the Earth Observing System (EOS) (Running et al., 1993). The data set is composed of 5-channel, 10-bit, raw AVHRR data, at 1.1-km resolution (at nadir) for every daily afternoon pass over all land and coastal zones using data from NOAA's polar-orbiting TIROS. Initially the data were to be collected continuously for 18 consecutive months beginning April 1, 1992, and continuing through September 30, 1993, subsequently the period has been extended to September 30, 1996. The science requirements for the global land 1-km AVHRR data set are documented by IGBP, CEOS, NASA, CEC and other international research organizations. Among the requirements is the need for higher level products that are derived from the raw 1-km AVHRR data, such as vegetation indices and periodic temporal composites.

The NDVI is the difference of near-infrared (NIR, channel 2, with spectral range of 0.725 - 1.10 μm) and visible (VIS, channel 1, with spectral range of 0.58 - 0.68 μm) reflectance values normalised over the sum of channels 1 and 2. The NDVI equation produces values in the range of -1.0 to 1.0, where increasing positive values indicate increasing green vegetation and negative values indicate, roughly, non vegetated surface features. These features are strongly correlated with global leaf area index (LAI) and photosynthetically absorbed radiation (PAR). The theoretical limits to the estimation of LAI and PAR, on the basis of VIS and NIR remote sensing data are discussed in Gobron et al (1997) and Mynemi et al (1997). The scaling method is chosen to emphasise different types of vegetation or biomass condition.

One alternative formula is NDVI scaling from -1.0 to 1.0 as 0 to 200, where each value represents 1.0 percent of the total possible range. This type of NDVI data used is available by the USGS and NASA Distributed Active Archive Center. The NDVI is examined pixel by pixel for each observation during the compositing period to determine the maximum value. The retention of the highest NDVI value reduces the number of cloud-contaminated pixels and selects the pixels nearest to nadir. The compositing period that is recommended for the prototype products is approximately 10 days created by month. Thus, January has three composites of 10, 10, and 11 days; February has 10, 10, and 9 or 8 depending on whether it is a leap year, and so on. This procedure has the advantage of creating calendar month composites, which is a common reporting period for agronomic and biophysical characteristics.

2.2 *Wetland analysis: patch dynamics from a present condition*

When working with biomass estimations through NDVI time series, patch dynamics concept is central. Patch dynamics (White and Pickett, 1985) implies, first, a relatively discrete spatial pattern, but does not establish any constraint on patch size, internal homogeneity, or discreteness. Second, a relationship of one patch to another in space and to the surrounding, unaffected or less affected matrix is accepted. Finally, patch change is outlined. The traditional interpretation of perturbation is that there is a reset on the successional clock of the ecosystem without influencing the ultimate, predictable trajectory of that change or the potential biomass supportable on that site.

Perturbation includes environmental fluctuations and destructive events, whether or not these are perceived as "normal" for a particular system. In this way, perturbation could be considered as any relatively discrete event in time and space, i.e. a over-spilled water volume from the main river channel that disrupts floodplain wetland ecosystem and its biomass, in order to produce changes on physical environment. Nevertheless, some semantic as well multidisciplinary problems arise when patch dynamics and ecological models are required. For instance, the term "frequency", as usually adopted by engineers, is the mean number of events per time period, often used for probability of perturbation when expressed as a decimal fraction of events per year. Still, the "visit period" is the mean time needed to perturb an area, i.e. the duration of a ecological decay as the temporary deacceleration of biomass production or the enhancement of the biomass consumption

2.3 *Long term hypothesis testing: eco-hydrological insights for changing scenarios*

Likewise, "resilience" is the degree to which an ecosystem´s long-standing composition and structure can be disturbed and yet return to that domain in which those processes and interactions functions as before (Holling, 1973; Denslow, 1985). A system perturberd beyond its limits of resilience will return to a new domain in the vicinity of a different structure characterised by altered composition and different perturbation pattern. Also, resilience provides alternative uses of river database, as the estimation of historical responses based present and past conditions.

Complementary to these concepts and through studying large South America rivers and their floodplains as binary systems, a multidimensional approach supported on frequency, intensity, tension, recurrence, amplitude and seasonality – FITRAS – is proposed (Neiff, 1996). In this case, "frecuency", as the number of phases of inundation or drought in a temporal series of various decades, could select plant and animal bioforms in wetlands and must be selecting the real permanence of the people in floodplain areas. Second, the "intensity" (or magnitude reached by a drought or inundation) could temporally exclude determined populations that live in the margins of the river. Third, the "tension" or value of the standard deviation from the maximum or minimum means in a curve of pluriannual hydrometric fluctuation allows to establish the variability of the events of droughts and inundation. Fourth, the "recurrence" is the statistical probability that an event of inundation or drought of a determined magnitude occurs within a period. Fifth, the "amplitude" of the phase is the duration of droughts and floods of a determined magnitude. Finally, the "seasonality" is the seasonal frequency with which the drought or inundation occurs. A "pulse" is defined here as the time between the beginning of the flooding and the end of the isolated period.

3 APPLICATION EXAMPLE: THE LOWER PARANA RIVER FLOODPLAIN WETLANDS

The Lower Paraná River drains more than 2 million km^2 of South America and between 27^{o}50´ and 29 ^{o} S (Fig. 1) has a real pulse's regime with normal floods, of water level closes to 3.3 - 3.5 m, and extreme floods with water level greater than 5 m. Since the nineteenth century (Seelstrang, 1878), this site known as Argentinian Chaco has historical evidence of ancient oxbows and paleochannels of the Parana floodplains. This historical files provide helpful identification of the more preserved parts of the floodplain in nowaday and in order to address pulse behavior scenarios.

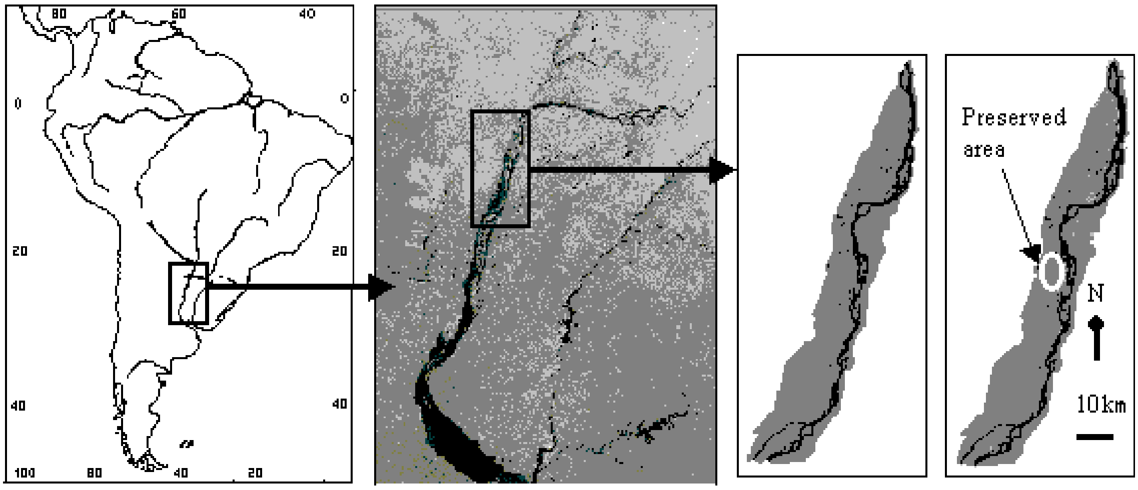

Figure 1. From left to right: first, the localisation of study area in South America, second, the Lower Parana river floodplain wetlands, immediately downstream of the confluence of Upper Parana and Paraguay rivers, from a global 10 day 1 AVHRR km^2 NDVI composite of June 1-10, 1992 ; third and fourth, examples of 10-day 1 km NDVI composite time series of June 20-30 and August, 1-10, 1992, over the entire floodplain and with a selected preserved area. The three NDVI images correspond to mean 10 day discharges of 44,250, 34,500 and 31,487 m^3/s, respectively, of the Parana river (mean discharge of 17,000 m^3/s).

Generally, from May to October each year, the Lower Parana River has normal floods. Hence, each floodplain patch has different pulse according to their location in the geomorphological gradient. For instance, the preserved area of 80 km^2 (Fig. 1, right) is representative of riparian gallery ecosystems of floodplain. This is pristine area is connected with the main channel more often, in comparison to the rest of the floodplain. During the XXth century, 8 floods of great magnitude occurred in the Lower Paraná (Neiff et al, in press; Depettris et al, in press), affecting the land use, with human settlements over floodplain. Most of these events are known as “damaging situations” of infrastructure of cities, bridges, roads, and even led to human deaths, but with misunderstanding the real eco-hydrological function and structure of floodplains. Moreover, the stage inventories of Parana river reveals four time series samples: 1901-30, 1931-60, 1961-90 and 1991-99. The later has a different record extension, but with ENSO, El Niño Southern Oscillation, effects that produces three of the biggest XXth floods. After the 1997-98 event, the Argentine Government decided to invest approximately 420 million dollars to seek solutions to floods, legal aspects of environmental hydraulics on risk mapping as well as land use control in Lower Parana river.

3.1 *The sampled eco-hydrological database*

During the 1992-95 period, a time series of global 10 day 1 km NDVI composites were selected from NASA database (all with corresponding radiometric calibration, atmospheric correction, geometric registration as well as 10-day compositing). From those, two long pulse samples, of 18 and 14 intervals respectively (Fig. 2), and three short pulse samples of 4, 4 and 3 intervals of 10 day composites, were appropriately selected. Among these pulse samples, the river behaviour ranged between 2.6 and 7.19 cm, or, by rating curve conversion, between 9292 m^3/s and 44,237 m^3/s, respectively. The long term discharge in this section of the river is approximately 17,000 m^3/s. Due to 1992-93 ENSO effects, the annual precipitation along the first pulse sample year was 46 % greater than the mean annual precipitation of 1350 mm. Likewise, the statistical probability of the river discharges ranged from 3.9 - 99.4 % of the 1991-2000 decade. With regarding the period of 1901-30, 1931-60 and 1961-90, the probability range was 0.7 - 71.3, 0.1 - 69, and 3.1 - 83.6 %, respectively.

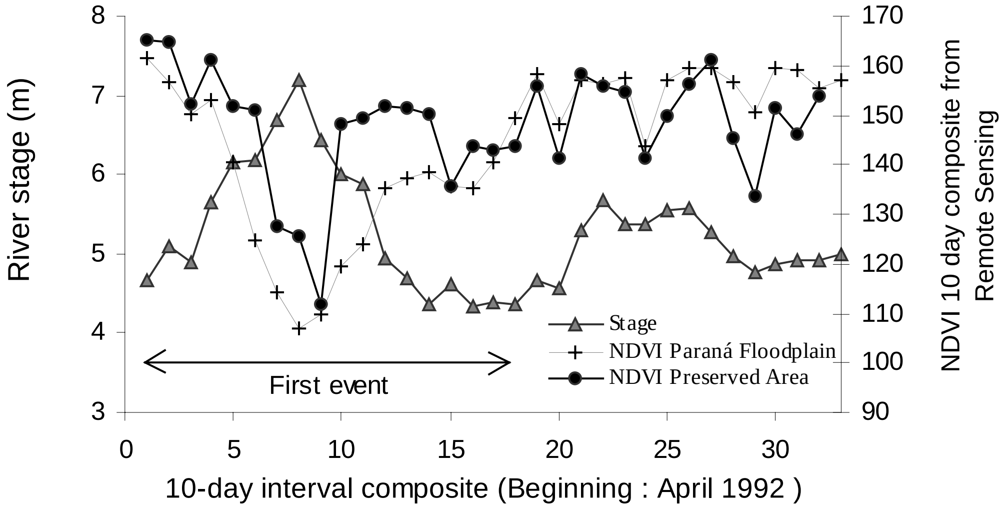

Figure 2. Time river stages with the respective spectral response, through NDVI, of the floodplain and a preserved area inside, Lower Parana River. The ‘first’ event is selected accordingly to river regime pulse.

Accordingly to all remote sensing images sampled, the NDVI was 144.3 ± 15.7 for the all 4800 km^2 over floodplain, and 147.2 ± 16.1 for the selected preserved area. The total pixel NDVI range was between 94 and 177. Taking out transient water-logged or eventually water flooded pixels from the remote sensing images, the mean Shannon NDVI diversity H, of all 10 day composite time series images comprised 3.02 ± 0.52. Discharge time series, Q, outlines a bankfull discharge ca. 19,500 m^3/s. When NDVI is checked with Q, a characteristic “loop” depicts the non linearity of floodplain environment. This is due to successional effects of biomass spectral response along the patches analysed. Moreover, and especially after passing an extraordinary perturbation, patchiness diversity H is inversely related to the NDVI mean response. Despite this behaviour, a new equilibrium condition of patch dynamics is expected, with not only a minor diversity, of 25 % smaller than pre-flood conditions, but also arriving to the pre-flood NDVI mean spectral response.

Furthermore, the NDVI difference between preserved area and entire floodplain is expected to have differentiated behaviour, whether the rising limb or recession phase is studied. In one hand, and driven by biomass rate decomposition, a positive 13.6 ± 8.8 NDVI difference is observed along 340 days, when rising limb floods occurs. In other hand, this difference may decay to negative NDVI 3.3 ± 2.5 during 50 days, when recession phase comes. This inverted ecosystem response explains the relative localisation of the preserved area being tested : rising-limb hydrograph’s changes collaborate of accumulating new water volumes into the floodplain and into the preserved area. However, when recession arrives, a river stage rate of -0.03 m a day is enough for re-directioning the water circulation across floodplain towards, and rather perpendicular to, the main channel. This often enhances extra-debris inputs, from floodplain into the channel riparian areas. So, the necromass (dead biomass) thereby generated on floodplain migrates to the riparian preserved areas and is sometimes newly trapped. Hence, this “routing-trapping mechanism” provokes riparian NDVI lesser than entire floodplain, even so during short periods, i.e. 20 - 50 days (Fig.2). Finally, when long potamophase periods are finished, ca. 200 – 360 days, the mean NDVI responses’ differences could remain between – 2 and –3 %.

Obviously, this example introduces one case of multiple another situations when preserved areas dominates successional patchiness, even so the routing-trapping mechanism is more evident under remote sensing analysis than with point surveys.

3.2 *NDVI related to biomass production and decomposition*

Meanwhile, the above results must address in situ experimental biomass rates, coping with, and linking to, the scale disparities, i.e. global 10 day 1 km database frequently contrasting microscale and short-term observations. In general, and for the region studied, the time required for a 95 % loss of *Tessaria integrifolia*, *Salix humboldtiana*, *Polygonum accuminatum*, *Panicum grumosum* and *Eichornia crassipes* are 88, 158, 176, 353 and 50 days, respectively, under aerobic conditions (Neiff, 1996). The decomposition rate of *E. crassipes* leaves is three times quickler in well-oxygenated waters in lakes connected to the mainstream of the river during the larger part the year than in anaerobic conditions in lakes only sporadically coupled to the river. For 95 % decomposition of *P. repens*, *Thalia multiflora* and *Typha latifolia* leaves, the estimated times were 325, 545 and 1,000 days, respectively, under anaerobic conditions. When the water-level falls abruptly and the soil remains dry, the decomposition time of the necromass of the same plant doubles. Hence, the spectral response fuzzyness of different stands which create 1 km sub-pixel biomass variability is hereafter presented in terms of NDVI mean and variance patterns regarding to floodplain stages.

When seeking a theoretical climax and the preservation of natural systems, it is called the attention to the uncertainty principle of sampled data being related to a universe of unknown but likely events. Accordingly to, and *sensu strictu* to plausible hypothesis, the data sampled show three "eco-hydrological thresholds" of the floodplain system grouped into the A's, B's, and C's observations (Fig. 3). First, the "non overspilled" observation, or A range, presents small NDVI's deviations spatially assessed, where no river water volume entries the floodplain.

Second, there is a "partially-overspilled" condition, or B range, from the bankfull stage to a characteristic height, i.e. of the understory canopy and/or the mean depth of secondary, meandered, inner-floodplain channels and oxbows. Field visits, supported with aerial flights in the test area, revealed with characteristic height from 1.5 to 2.5 m. This height range is traduced to spatial dispersion on NDVI of more than twice of the NDVI spatial dispersion of A-range observations.

Third, water depths beyond this "partially-overspilled" threshold height inherently provide much water entry into the system that provokes higher NDVI negative rates, and with higher spatial dispersion. Consequently, a "full-overspilled" spatial pattern, or C range, is enhanced, regardless large trees special conditions, i.e. *Salix sp*. For instance, the transition from B-range to C-range condition outlines a 18 % reduction of floodplain study area due to logged pixels, with 30 % biomass decay. In short, mean NDVI values express intensity of the perturbation, whereas the NDVI variance accounts the tension accordingly to biomass response captured for the satellite.

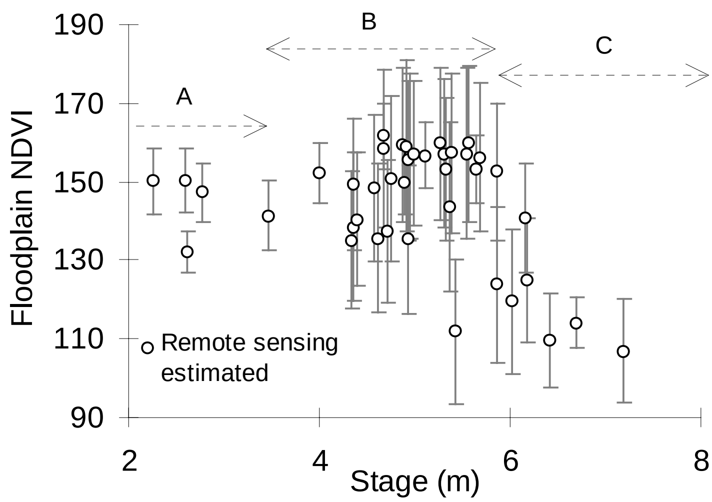

Figure 3. Eco-hydrological thresholds (A, B, C) of floodplain biomass estimations (dots) with one standard deviation (vertical lines).

3.3 *Resilience's estimations under long term scenarios and sustainable use*

NDVI data are related to biomass estimation, which occurs in isolated and dynamic parts of the floodplain and with alternative forms of vegetation growth, leaf density difference and root systems. Part of these features are capable of being related, when bigger stands are spatially spread, to LAI rate and, so, to the NDVI spectral response. Meanwhile, the decomposition rate of the organic matter allows the use of production ÷ respiration ratio of these large floodplains when investigating the efficiency of decomposition during the flood-phase (potamophase) and dry-phase (limnophase). It also allows comparison of the kinetic disintegration of the organic matter for species growing from semi-lotic waters to the external border of the floodplain. The biomass decomposition rate mainly depends on two principal factors: quality of organic substance (C:N ratio), and the availability of the oxygen in the water (Neiff, 1996). The duration for the process and record period when it takes place are just as important as necessary in a resilience point of view (Fig. 4).

The hypothesis to test the sampled data of the period 1991-1999 with respect of the time series' record of 1901-30, 1931-60 and 1961-90 is only supported when: (i) no changes in hydraulic regime conditions, (ii) no significant land use and (iii) any dam was built in the site study. The resilience of system is expected to change under these constraints.

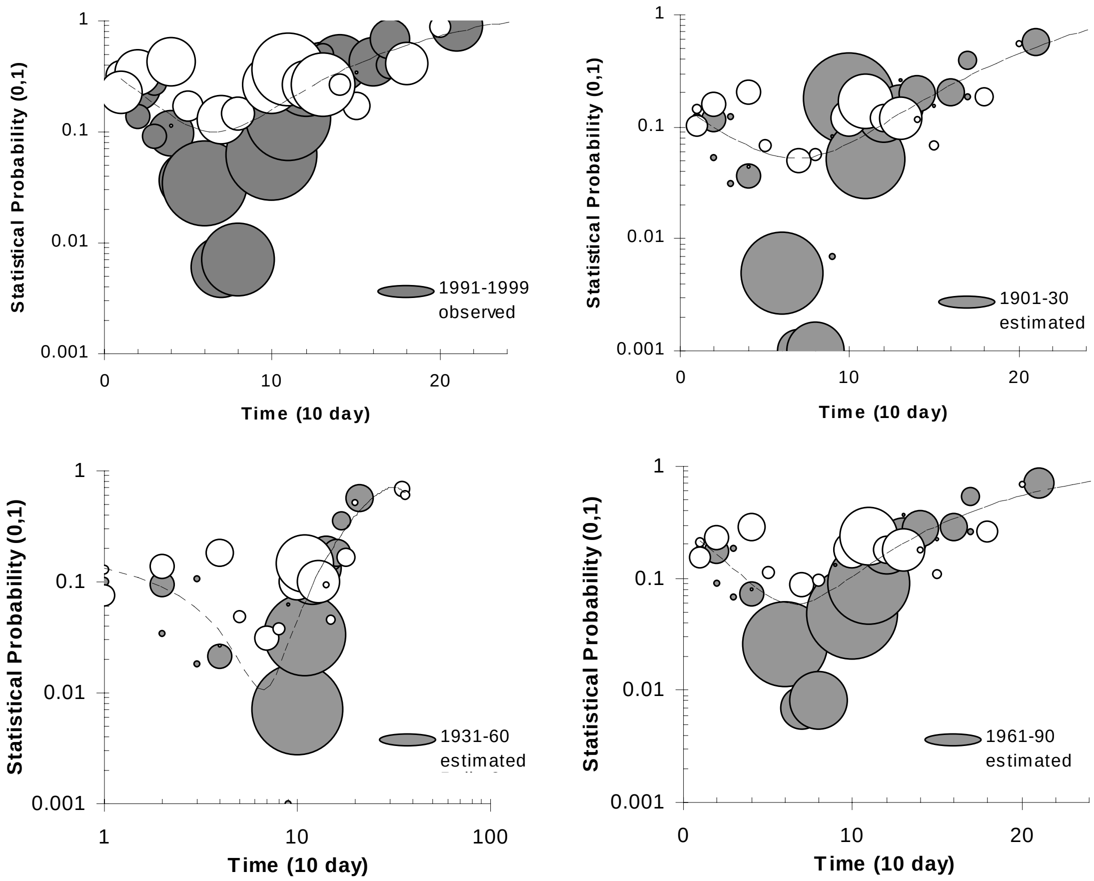

Figure 4. Resilience's diagrams of (from upper left to lower right): 1991-99, 1901-30, 1931-60 and 1961-90 periods, respectively. Time is measured after beginning of a rising-limb flood pulse. Statistical probability is related to river stage permanency of the period. The radii of circles are proportional to the biomass difference, expressed as 10 day 1 km NDVI mean, between a preserved area and the entire floodplain wetland, revealing positive (black) and negative groups (white). Discrimination of groups is made by deterministic curves.

Usually, the present condition offers more information than past inventories, with exception of permanency curves which are easy-to-get and friendly-used in multidisciplinary teams of engineers, biologists and ecologists. These curves provide the baseline requirements for alternative resilience diagrams (Fig. 4), maintaining estimated values of time after flood´s beginning and of NDVI's difference between of protected areas and the all surrounding floodplain patches. Thus, statistical probabilities changes accordingly to the time records particularly analysed.

The alternative use of resilience diagrams in the REVIVE's GOALS strategy, or similar ones, is enhanced by the fact of above hydraulics, land use and dams restrictions are partly not easy of addressing in large South America rivers. And we have no exception here. First, it is noticed that rating curves of main river channel remain practically the same along the second half of XXth century (Neiff et al, in prep; Depettris et al, prep.), supporting "non overspilled" comparisons, i.e. when statistical probability is below, in average, of 0,5. This first attempt provides, further, novel insights to binary approaches and complementation of FITRAS theory (Neiff, 1996).

Second, there are discrepancies, in a quantitative manner, whether hydraulic changes were experimentated on the Paraná floodplains or not. Until today, regional surveys showed that cattle and sporadic agricultural incursions are the most common land uses into the floodplains, depending on the observed, or predicted, annual river regimes. The measured discharge range of Parana river at Corrientes, with maximum close to 67,000 m^3/s during the 1982-83 ENSO event, depicted that both numerical uncertainties and also stationary condition of the river (Clarke et al, 2000) are not less important than the biomass production and decomposition (Neiff, 1990; Neiff, 1996), and affecting hydraulic conditions, at least locally (Depettris et al, 1990). In this way, compounded rating curves, i.e. multivariate rating curves with the addition of ecological variables as NDVI mean or NDVI variance, with their respective diversities assessments, are recommended.

Third, no dams were built on case study area; however, and especially during the 1960-90 period, several hydropower stations were built on the Upper Paraná system (Tucci and Clarke, 1998). This introduces hydrosedimentological changes, in cumulative cycles, only evident in the next decades. This over-extends the scope of this contribution. Nevertheless, it is theoretically well known that non cumulative perturbation may enhance species diversity (i) lowering the dominance of one or a few species, or (ii) by increasing environmental heterogeneity (Denslow, 1985). That could be viewed as the changes in species diversity, biomass heterogeneity patch classes, etc. during succession since a large-scale perturbation. In this way, communities or biomass patch classes frequently subject to perturbation creating large patches are, theoretically, most diverse early in succession and become less diverse with time in the absence of perturbation. On the contrary, in communities or biomass patch classes rarely subject to large scale perturbation, species diversity is greatest late in successional time. The validity of this later hypothesis was not tested yet with regard NDVI remote sensor and GIS techniques, but it is possible to access under low cost information exchange through multidisciplinary REVIVE's GOALS framework, coping with long term scenarios of sustainable use.

4 CONCLUSIONS

In the past, integral strategies that try to link the gap between short-term social demands, i.e. big floods, with long-term eco-hydrological floodplain scenarios derived from remote sensing, seemed initially cumbersome because (i) many multidisciplinary insights were not successfully implemented, usually due to budgetary constraints and (ii) amounts of data collected in the XXth century suffered by a no-information-tradition between interesting parts, inclusive between decision makers. In contrast, scientific approaches of nowadays attempt to both capture new information technology and revalidate eco-hydrology hypothesis. Namely, the REVIVE's GOALS initiative, with the practical example briefly showed in this contribution, is one alternative approach to cope with these multidisciplinary information exchange constraints, updating feasible new trends in water and in environmental engineering of South America wetlands.

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