Plants vs. Streams: Their groundwater-mediated competition at "El Morro", a developing catchment in the dry plains of Argentina

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Abstract

Our understanding of the mechanisms routing precipitation inputs to evapotranspiration and streamflow in catchments is still very fragmented, particularly in the case of saturated flows. Here we explore five mechanisms by which plants and streams compete with each other for water, based on multiple scales of observations in a flat semiarid sedimentary catchment of central Argentina subject to abrupt hydrological transformations. Since the 80s, the “El Morro” catchment (1334 km2, -33.64°, -65.36°) experienced a fast expansion of crops over native forests and grasslands, rapid water table level rises (~0.3 m y^{-1}), spontaneous expansion of wetlands and permanent streams by groundwater sapping. Based on episodic and continuous groundwater level, stream flow, and remote sensing data we show that plants not only take away water from streams by drying the unsaturated zone (mechanism 1), but by tapping the saturated zone in the expanding waterlogged environments (mechanism 2) and in the upland environments that remain uncultivated and display increasing tree cover (mechanism 3). Conversely, streams take away water from plants through pulsed bed-deepening and water table depression (mechanism 4), and riparian and wetland zones burying with fresh sediments (mechanism 5). While earlier work established widespread support for mechanisms 1 preventing stream formation, diurnal and seasonal fluctuations of water table levels and base streamflow records in this study proved the importance of mechanisms 2 and 3 under the current high-water table conditions. These data together with remotely-sensed greenness showed a growing but localized relevance of mechanism 4 and 5 as the stream network developed. The distinction of recharge- vs. topography-controlled groundwater systems is useful to organize the interplay of these concurrent mechanisms. Findings point to the unsaturated-saturated contact zone as a crucial and dynamic hub for water partition and for ecological, geomorphological, and hydrological knowledge integration.

Keywords: ecohydrology, phreatophytes, sapping, semiarid watersheds, water yield,

Introduction

Although the critical role of water inputs supporting the growth of plants and the flow of streams is indisputable, the way in which these two major fates of precipitation may compete with each other on a given territory is not always obvious and represents, in fact, a very active front of scientific inquiry. Moreover, this quest is perhaps one of the main attractors of the convergence of Ecology and Hydrology over the last decades. How any given piece of land, and more operatively, each catchment, partitions the water that it receives from precipitation between evaporative losses (among which plant transpiration is usually dominant) and liquid losses (among which stream flow is generally the main protagonist), is something that has been quantified for more than a century using multiple approaches and that has sparked key integrative theoretical developments such as the Budyko curve (Budyko, 1974; Gentine et al., 2012). It is notable, however, that our knowledge about the mechanisms dictating this partition is still very fragmented (McDonnell et al., 2007). In which ways plants can "capture" water that could eventually reach streams or, conversely, what are the mechanisms that allow streams to "capture" water that may be potentially usable by plants? Particularly relevant but disconnected are our representations of the role of saturated flows dictating a "push and pull" dialog between plants and groundwater (Fan, Miguez-Macho, Jobbágy, Jackson, & Otero-Casal, 2017) and eventually, streams. In this contribution we explore conceptually how the competition for water between plants and streams may operate in a dry basin, proposing a list of key mechanisms that involve groundwater-mediated interactions. Plant-stream competition should be particularly evident in dry regions (PET > PPT), where potentially all water inputs can get evaporated (no energy limitation) and the outcomes of the "push and pull" process should leave a strong imprint both on plants, which would increase their growth as their capture of limiting water resources becomes more exhaustive, and on streams, which can potentially have a total suppression of their flow. In this contribution, we illustrate the proposed mechanisms and evaluate their relevance both for land ecosystems and hydrology with data from a semi-arid sedimentary basin subject to strong vegetation changes and, mostly as their consequence, to an extraordinary rapid process of novel stream formation through sapping and surface erosion.

A simplified view of the atmosphere-soil-plant/stream continuum can assume that all the water consumed by vegetation comes from the unsaturated zone and that any by-pass or displacement flow escaping root access becomes free to rich the saturated zone and is no longer accessible to plants. This is still the prevalent representation of many models that can successfully describe the partition of evapotranspiration and streamflow in many catchments (Rahtjens, Oppelt, Bosch, Arnold, & Volk, 2015) based on what we can define as the single most relevant mechanism that plants have to take away water from streams (i.e. unsaturated uptake, mechanism 1, figure 1). In dry regions where evapotranspiration is water limited, flat and loose sedimentary substrates occupied by deep-rooted vegetation often display an exhaustive exploration of the wettable soil volume, leading to the total suppression of groundwater recharge through “mechanism 1”. In these settings any streamflow is limited to storm run-off episodes and there is no observable base flow (Scanlon et al. 2006; Santoni, Contreras, & Jobbágy, 2010). While simple and powerful enough to explain the behavior of many dry catchments, unsaturated uptake runs short to explain many biological and hydrological phenomena such as the presence of exceptionally green vegetation patches in deserts or the fluctuating daily or seasonal reduction of stream base flow during periods of high water demand and no rainfall inputs. Plant roots access saturated water directly, as in the obvious case of riparian or wetland environments were specific vegetation types adapted to the anoxic conditions of the substrate thrive (Lowry, Loheide, Moore, & Lundquist, 2011), or indirectly by tapping the capillary fringe fed by the saturated zone, as seen (not as easily) with phreatophytic ecosystems (Naumburg, Mata-González, Hunter, & Martin, 2005; Jobbágy, Nosetto, Villagra, & Jackson, 2011). Therefore, saturated uptake needs to be included as a “second chance” that plants have to take away water from streams with the unique contribution of lateral connectivity allowing vegetation in one place to use water that plants did not use in another. The most acknowledged component of saturated uptake is the consumption of ground or stream water by wetland and riparian communities in the small fraction of landscapes occupied by topographic low positions and water body shores (i.e. focalized saturated uptake, mechanism 2, figure 1)(Bond et al., 2002). Yet, saturated uptake can be significant in the matrix of the landscape as well, when a more widespread contact between roots and the capillary fringe takes place (i.e. distributed saturated uptake, mechanism 3, figure 1), something that appears to be reciprocally and dynamically modulated by the vertical location of roots and water tables and highly sensitive to vegetation, climate and water managements shifts (Jobbágy & Jackson, 2004; Nosetto, Jobbágy, Jackson, & Sznaider, 2009, Fan et al., 2017). While being increasingly considered in catchment models (Immerzeel & Droogers, 2008, Doble & Crosbie, 2017), saturated water uptake by plants introduces a novel possibility for streams to take away water from plants.

Far from passively receiving the hydrological left-over of the three main water consumption mechanisms pathways highlighted above, streams, as active geomorphological agents, can take away water from plants when they remove and deposit sediments. By deepening their beds, streams can increase their groundwater capture into base flow, transiently enhancing hydraulic gradients but more permanently by impairing mechanisms 2 and 3 as water tables plunge to reach a new equilibrium and zones where plant roots can reach it shrink or disappear (i.e. streambed deepening, mechanism 4, figure 1) (Bravard et al., 1998; Wurster, Cooper, & Sanford, 2003; Schilling, Zhang, & Drobney, 2004). Another way in which streams can actively restrict plant water consumption is by burying land ecosystems with new sediment deposits, which are more likely to affect active riparian and wetland zones with higher water consumption than any other landscape component (i.e. sediment deposit, mechanism 5, figure 1) (Kui & Stella, 2016). The relative timing of ecological succession and geomorphological changes is critical defining the resulting balance of mechanisms 1,2 and 3 vs. 4 and 5. Ecological changes such as the establishment of riparian plants with deeper roots where stream incisions have gone deeper or the recovery of buried trees where streams have deposited fresh sediments (Rivaes et al., 2013; Kui & Stella, 2016), may outpace the slower work of streams, yet landscapes in which their erosive power get rapidly unleashed as result of climate or land use changes can match their forces offering an ideal observatory to explore their interaction.

The birth of a catchment

In its subtropical and temperate belt, South America hosts a vast aeolian plain covered by Quaternary loessic deposits and sandy mantles spanning semiarid to subhumid climatic conditions along a 900 km west-east extent (Zárate & Tripaldi, 2012). The few rivers crossing the driest western half of this region have their sources in adjacent mountain systems and loose water as they traverse it (Marchesini, Nosetto, Houspanossian, & Jobbágy, 2020; Poca, Nosetto, Ballesteros, Castellanos, & Jobbágy, 2020). A surprising exception emerged in recent decades, however, when an extremely abrupt groundwater sapping process started carving and connecting permanent stream segments that now configure what has been named the “El Morro" catchment (Contreras, Santoni, & Jobbágy, 2013). Located in the transition from the isolated rock outcrop of the “El Morro” caldera (Sruoga, Ibañes, Japas, & Urbina, 2017) and the adjacent aeolian plain, this topographically well-defined basin had its first active surface water outlet opened less than four decades ago and continues to gain and connect tributaries after discrete but increasingly intense sapping episodes caused by steadily rising groundwater levels. The deepest incision, where the Río Nuevo stream flows permanently, is now 30 km long with the largest cross-sections reaching 20 m of depth and 80 m of width. In its exposed walls, ~5 m-deep aolian Holocene material laying over pre-Holocene fluvial beds suggests that the emerging streams are not only a new feature of this landscape in historical times, but throughout the last interglacial period (Tripaldi & Forman, 2012). Where exposed, the crystalline basement or its overlaying late Tertiary calcretes show signs of fluvial erosion suggesting that a paleo catchment buried with aeolian material is being reactivated in recent years.

Originally covered by grasslands and open woodlands (Oyarzabal et al., 2018), the El Morro watershed has been progressively cultivated since the beginning of the twentieth century and today more than half its area is under dryland agriculture with native caldén (*Prosopis caldenia*) forests covering less than 10% of the area (Contreras et al., 2013). Accompanying these changes, an increasing number of low areas within croplands and to less extent native vegetation become waterlogged by raising water tables, initiating a spontaneous succession towards wetland communities (Contreras et al., 2013; Díaz, Jobbágy, & Marchesini, 2018). While increasing rainfall trends, seismic activity and land use changes have been pointed as possible converging causes for the novel and rapid hydrological transformation of the El Morro catchment (Contreras et al., 2013), observations in this region and other semiarid areas of the plain point to the onset of groundwater recharge following the conversion of native vegetation to dryland agriculture as the most determinant factor (Amdan, Aragón, Jobbágy, Volante, & Paruelo, 2013; Contreras et al., 2013; Giménez, Mercau, Nosetto, Paez, & Jobbágy, 2016; Marchesini, Giménez, Nosetto, & Jobbágy, 2017). The rapid shifts in groundwater level, the unusually fast development of a stream network, and the semiarid climate making both plants and streams highly sensitive to water supply, offer a unique setting to explore the interplay of the five mechanisms described above. Stimulated by this opportunity and the urgency to understand the causes and possible adaptation or mitigation actions to cope with its negative effects on people and nature, we initiated a long-term observation program in the El Morro catchment. In this paper we present hydrological and ecological observations derived from this program together with previous observations and different sources of remote sensing information to characterize groundwater level, stream flow, and vegetation dynamics in three subcatchments of the El Morro basin at two temporal scales (long-term: 20-50 years, short term: following the last sapping event of 2015). We link these observations with the five mechanisms described above to offer a preliminary quantification of their relative weight shaping the current and projected partition of water inputs between plants and streams in this semiarid context.

Materials and Methods

Study catchments

The study area, at the western dry edge of the sedimentary plains of central Argentina, sits in the ecotone of Espinal forests and Pampas grasslands (Figure 2a). Its temperate semiarid climate shows a mean annual temperature of 15.7 C with the coldest (July) and warmest (January) months, having a mean minimum temperature of 1.0 C° and a mean maximum temperature of 28.6 C°, respectively. Mean annual precipitation (1903–2019, Villa Mercedes; -33.65, -65.42; 525 m) was 601 mm y^{-1}. Rainfall is concentrated in the warm season (70% between November and March) originating mainly in convective storms with high spatial variability. A-type tank evaporation is 1640 mm y^{-1} (2006-2009), reaching maximum values of 11 mm d^{-1} during summer.

We run periodic observations in three adjacent sub-catchments of the El Morro Basin that cover together 1334 km^{-2} and range from 1100 to 500 m of elevation along 50 km in a NNW-SSE direction (Figure 2a). These sub catchments show an east-west gradient of developing age with La Guardia having completed its connection to the main pre-existing collector (Quinto river) in 1986, followed by Río Nuevo, connected in 2009 but still developing tributaries, and Quebrachal, which is currently an isolated segment that infiltrates without reaching the collector (Figure 2b). Río Nuevo has the deepest and widest incision (20 x 80 m in 2020) and has generated the largest sediment deposit in its lower section (8 km^{-2} deposited in 2015), while La Guardia displays the shallowest incision and the largest wetland area (Table 1). The most recent incision episodes took place in September 2001, January-February 2008, December 2009 and February 2015, following periods of several months of high rainfall and affecting mainly the Río Nuevo and Quebrachal sub catchments (Contreras et al., 2013; Buono, Menéndez, Cáceres, Jobbágy, & Nosetto, 2018). The landscape of these sub catchments includes a higher section (1100-700 m of elevation, 2% slope) with isolated rock outcrops and dissected surfaces in its high end and the initiation of most incisions in wetlands on its low end, an intermediate section (700-550 m of elevation, 0.7% slope) with a transverse dune surface and the greatest depth to the crystalline basement (>50 m), associated to a local tectonic depression (Barbeito, 2008), and the largest incisions; and the lowest section (550-500 m of elevation 0.5% slope) with a flat sandy mantle that has hosted most of the recent fluvial deposits (Ríos 2020). Soils are

Entic Haplustolls in the higher catchment and *Typic Ustipsamments* and *Typic Ustorthents* in the intermediate and lower catchment (Galván & Collado, 2009).

Dryland agriculture is the dominant activity followed by cattle raising on pastures and native vegetation. Dominant crops are soybeans and maize, growing in a spring-summer season that starts slightly after the onset of rains between October and December and ends in April, similarly to what is seen throughout the western plains of Argentina (Gimenez et al., 2020). No till prevails and soils remain free of weeds during the fallow periods. These agricultural systems have progressively replaced native vegetation and perennial pastures of the exotic grass *Eragrostis curvula*, which where the basis of the livestock production systems that prevailed until the end of the twentieth century (Viglizzo, Roberto, Lértora, Lopez Gay, & Bernardos, 1997), and are still present as minor component of the landscape. Native vegetation includes perennial tussock grasslands and forests dominated by the leguminous trees *Prosopis caldenia* (caldén) and *Geoffrea decorticans* (chañar) (Oyarzabal et al., 2018, Cabido et al., 2018). Wetlands have expanded in the area as a result of raising water table levels (Contreras et al., 2013). Two types of spontaneous communities are found, one related to freshwater environments in the higher-intermediate belt of catchments, dominated by *Cortaderia selloana* tussocks and *Typha sp.,* and the other associated to saltier environments in the lower belt of catchments, dominated by *Tamarix ramosissima* (Natale, Zalba, Oggero, & Reinoso, 2010; Diaz et al., 2018).

<u>Hydrological observations</u>

In this article we use two sources of field data, one derived from the compilation of previous studies of our own and other teams working in the region, and the other originated in a specific long term monitoring program in the El Morro catchment motivated by the last and most intense pulse of stream incisions in the area, that took place in February of 2015. We complemented these data sources with several remote sensing tools used to characterize structural and functional changes in ecosystems.

To characterize regional decadal changes in groundwater level we took advantage of an existing synthesis of well surveys (BRS, 2002) and additional records by local farmers. We identified 23 sites in the catchment with observations between 1966-1980 (most measured in 1975), and 4 additional sites measured in 1995. Some of these sites had more than one record through time. For these 27 sites we obtained a water table depth estimate for recent times (1999 to 2020, mean 2007) based on (i) direct measurements or records by farmers (11 sites) and (ii) signals of surface waterlogging or ponding by rising water tables obtained through visual inspection of high resolution imagery from Google Earth as described below in the section about ecological observation (16 sites). In the case of wetlands that were incised we consider water table depths before and after the incision considering the stream bed position below the surrounding surface as the new position. We also took advantage of existing isolated base flow records obtained in the developing streams by our team between 2008 and 2011 (Contreras et al., 2013) and after the last incision episode in 2015 and by others in 2008 (Barbeito, 2008). Combining the earliest groundwater level measurements available with our more recent estimates, together with the wetland and incision emergence mapping described above and available vertical electrical soundings (Barbeito, 2008), indicating depth to the crystalline bedrock; we generated a 2D, 17 km-long vertical, WSW-ENE-oriented cut representing ecohydrological changes at the high-intermediate belt of the Quebrachal and Río Nuevo sub catchments over the last 45 years (Figure 2a), for this purpose we used all available observation within a range of 600 m at the sides of the transect line.

In April of 2017, 26 months after the last and most intense incision episode, we initiated a cycle of periodic water table depth and stream flow. Aimed to follow the behavior of the groundwater and stream system to new sapping episodes, the period covered up to the present has been drier than the long term average (496 vs. 608 mm y^{-1} at Villa Mercedes), offering a good opportunity to explore the mechanisms highlighted above as ecosystems become more sensitive to groundwater contributions and streams spend most time under their base flow regime.

We installed a full meteorological station (Davis Instruments) at Site A to complement an existing network with three operating stations within or close to the catchment (Villa Mercedes, Coronel Alzogaray, La Esquina; Figure 2a). All these stations provided hourly precipitation, temperature, wind direction and velocity and relative humidity data. We obtained an integrated averaged daily precipitation series after accounting for gaps (<5% of the data). We established a network of 16 monitoring groundwater wells (Figure 2a), that included pairs of wetlands with their adjacent croplands in the higher (sites A and B) and intermediate belts (site D), the largest sediment deposit and its adjacent cropland (site E) in the lower belt, a transect running 1.2 km away from the deepest Río Nuevo incision along paired forest-cropland stands with three sites in each vegetation type (site C) and two additional wells sampling a cropland adjacent to the Quebrachal incision and a suburban area in the lowest segment of the Río Nuevo. All these wells were hand augered at least 1.5 m below the water table and cased with cribbed PVC pipes. The bottom of the wells ranged from 2 to 16 m of depth. These wells were monitored three times a year manually and sampled for chemical and stable isotopic composition (data not shown here) after purging. Water table levels were also recorded hourly with pressure transducers connected to data loggers (Campbell Scientific Instruments).

Streamflow was measured monthly during the first year and three times per year thereafter at 6 locations (Figure 2b). These included the Quebrachal stream close to its terminal zone (Site 1), two tributaries of the Río Nuevo (Sites 2 and 3) in the higher catchment and the same stream at the end of the lower catchment (Site 4). At this same point we gaged the La Guardia stream just before its convergence with the Río Nuevo (Site 5) and then the two merged streams after the flow through a 5 km-long rectified tract (Site 6). We could complement base flow series with data obtained before (Sites 1 to 4 and 6) and shortly after the incision episode of 2015 (Sites 1,3 and 5). We also included in the analysis older data for other sites, such as an active tributary of the Río Nuevo that dried after 2015 (Site 7), the higher and oldest segment of Quebrachal (Site 8) and the oldest segment of the Río Nuevo before it was deepened in 2015 (Site 9). In all cases flow was gaged using an electromagnetic velocity sensor (Marsh-Mc Birney Flo-Mate 2000) at 10 to 25 positions across the section of the stream. At sites 5 and 6 we performed several attempts to obtain continuous flow gaging that were hampered by the unstable nature of the streambed and high sediment and plant debris transport. Stage records obtained with pressure transducers in the stream bed first, and with radar distance meters under bridges or culverts next, proved to be unreliable, yet they were useful to qualitatively identify peak flow events and qualitatively sort them into minor and major ones. These provided the context for manual peak flow measurements performed during two of these events and used to obtain a maximum boundary estimate of the contribution of peak flow to stream discharge during the study period.

Catchment integration

In order to estimate base water yields for different areas we considered that base flows were generated either by the full watershed as defined by its surface topography (i.e. topographically defined catchment) or, alternatively, by a more restricted zone that was defined considering the uniform spacing among the relatively parallel stream lines observed in the region and recognized as the typical fishbone structures of sapping erosion regimes (Grau Galofre & Jellinek, 2017). We observed distinctive regular spacings of 2.6 and 12.5 km in the higher-intermediate and intermediate-lower belts of the catchment (respectively upstream and downstream of the rock basement level drop line, Figure 2a), and used those widths combined with the length of streams crossing each zone to calculate their contributing area (i.e. geometrically defined catchment)

Ecological observations

We used complementary sources of remote sensing to characterize structural and functional vegetation changes in the catchment. In first place, we combined our field surveys of the region with detailed satellite imagery from Google Earth (2000-2020) and aerial photographs (1962, see Bogino & Jobbágy, 2011) to describe the advent of new wetlands, lagoons, sediment deposits, and incisions/streams in the landscape. All these features were easily identified with high spatial detail imagery but given its associated poor temporal resolution (up to 10 years in some cases), we narrowed down their timing with a complementary analysis of Landsat imagery. In the case of wetlands, and in order to obtain a single date for their advent to be used in the regional water table depth analysis described above, we used the mean between the latest date without an earliest date with evident surface signals, as the time of the observation. In the case of stream incisions, we adjusted this date to the most likely year of occurrence based on the precipitation series and local observations by farmers. Based on our experience observing wetland vegetation and groundwater levels in the field we were able to distinguish sites with <0 (surface water) and 0-1 m of water table depth in the images, using these ranges as an estimate for the long-term regional analysis described above.

To obtain relative estimates of water uptake trends for the different types of vegetation or vegetation change trajectories we used greenness indexes. Although real evapotranspiration estimates are available from platforms like MODIS, they tend to have very negatively biased estimates which end being extremely dependent on surface greenness (Normalized and Enhanced Vegetation Indexes, i.e. NDVI and EVI). In previous studies across neighboring regions we found that the direct use of these indexes provides better estimate of relative transpiration rates for cultivated and native vegetation (Contreras, Jobbágy, Villagra, Nosetto, & Puigdefabregas, 2011; Nosetto, Paez, Ballesteros, & Jobbágy, 2015). Using 16-day and 250 m resolution NDVI MODIS data and a supervised classification of the current (year 2018) vegetation into forests, grasslands and pastures, croplands and wetlands together with field/ground truth control points, we estimated greenness trends from 2000 to 2020 for all the pixels corresponding to each one of this cover types. We used two criteria to illustrate greenness trends. In the first one we obtained an average decadal trend comparing the first and the second decade mean values for each pixel. In the second one, we obtained linear regressions of mean annual NDVI in response to the number years elapsed since 2000 for each individual pixel, computing the proportion of them that showed significant trends ($p<0.05$) and averaging the slope of that subgroup for each vegetation type. Since the low spatial resolution of MODIS imagery (250 x 250 m) did not allow for a precise description of wetlands and sediment deposits and comparisons with their adjacent cropland or forest stands, we performed a complementary analysis using LANDSAT 8 images with a monthly and a higher spatial resolution (30 x 30 m) for the years before and after the last erosion episode (2013-2020). We analyzed three stable vegetation types (forests, croplands and wetlands) and three vegetation transitions during that period (croplands to wetlands, croplands to deposits, incised wetlands). In all cases we had at least 6 stands except in the case of incised wetlands where a single site was considered. Statistical greenness differences among the first five cases within each year of analysis were evaluated using ANOVA.

Results

Groundwater dynamics

Over the last four decades the El Morro catchment experienced a dramatic rise of groundwater levels leading to an expansion of the areas occupied by wetlands, lagoons and seepage zones. Water table levels raised on average 3.06 meters per decade across 27 wells where groundwater depth was measured in the past (most commonly in 1975) and measured or estimated again over the last decade (Figure 3). Noticeably, while the majority of those points showed level raises throughout one or two measuring intervals, those located within or very close (< 500m) to stream incisions (6 sites) showed absolute water table depth declines that were largest in the intermediate belt of the catchment. In the lower belt, a site that received the thickest deposit of fluvial sediments showed a relative decline of its water table level as the surface raised (Figure 3). The observed groundwater level raises were highest in the higher belt of the catchment where the most extreme case approached a 37 m level ascent and levels climbed on average 4.83 meters per decade (initial mean depth of 15.33 m)(Figure 3). That area was followed by the intermediate and lowest (terminal plain) belts where, ignoring the incision cases, decadal raises averaged 3.50 and 3.77 meters per decade, respectively (initial mean depths of 11.55 and 7.85 m, respectively) (Figure 3). The smallest changes were observed in the lower belt of the catchment, where the average ascent was 0.97 meters per decade, reflecting the fact that water tables were already shallow at the beginning of the study period there (initial mean depth of 3.6 m)(Figure 3).

Water table depth observations in the network of monitoring wells reflected the dry conditions of the 3-year study period with an overall deepening trend (Figure 4). However, important contrasts were found between vegetation types and landscape positions. At site A, the wetland, which appeared in 2000 and has the crystalline basement close to the surface (see Figures 3 and S2), showed the most stable levels, always less than 15 cm below the surface, likely as a result of sustained seepage at that site (Figure 4a). The neighboring cropland instead, showed seasonal oscillations (summer declines, winter raises) over imposed to the general declining trend, suggesting that water consumption during the period of high vegetation activity and evapotranspirative demand, which is also the rainy season, outpaced recharge fluxes during the study years (Figure 4a, d, e). Wells at site B showed a more extreme, steady and parallel decline during the first year (Figure 4b) (they had to be deepened to continue measurements afterwards), revealing the likely effects of the recently carved or deepened incisions flanking the site (Upper Rio Nuevo and Uke tributaries), drying a wetland that emerged in the late 90s and interrupting its stream (site 7 in Figures 2b and 5). A particular aspect of this level decline is its constant rate in the wet and dry season of the first year, which suggests drainage from below rather than consumption from above as the likely cause of this behavior. Located by the deepest incision of the catchment (enlarged from 9 to 20 m of depth and 28 to 60 m of width in 2015), site C represented the deepest water table situation showing a strong contrast for its three pairs of forest-cropland wells (Figure 4c). There, the forest, similarly to the cropland and wetland sites with shallower water tables, displayed seasonal oscillations suggesting a pulsed consumption of groundwater by the dominant winter-deciduous trees whose active roots were found growing around sensors at 9 m of depth. Croplands, only 600 m away at this site, showed a steady decline with very subtle seasonal rates of change. Differences along the transect at this site suggest that wells at position 1, ~100 m away from the deepened incision are closer to rich there a new equilibrium while those at positions 2 and 3 may still be yielding water towards the stream (Figure 4c). Two additional monitoring wells not shown in the figure reflected similar patterns with Site F hosting a cropland with deep water tables close to the Quebrachal incision. That site followed croplands in site C until no saturated conditions could be detected above the crystalline bedrock at 14 m of depth. Site G, in a suburban area of the low catchment affected by periodic waterlogging followed the same pattern of the wetland at site E.

Continuous monitoring of groundwater depth with pressure transducers offered a more precise perspective on the recharge and discharge dynamics of the study sites

(Figures 5 and 6). At Site A we highlight contrasting periods of net water gains (summer-fall 2018) and losses (spring-summer 2019-2020), showing the contrasting behavior of the wetland and the cropland. In the first of these periods, the wetland displayed high daily level fluctuations that amplified progressively following rainfall events (Figure 5, left panels), suggesting an increasing reliance on groundwater as the rainfall pulse was consumed. No fluctuations were observed in the cropland, that at that time was in fallow stage prior to the establishment of a pasture (see NDVI in figure 5, left panel). A single and intense rainfall event in this period (74 mm on April 1 measured at the precise site) switched the wetland to a flooded condition reducing but not eliminating fluctuations, likely as a result of the shifting groundwater yield-depth relationship under flooding. The same event and the following two triggered direct recharge episodes under the fallow with level rises of 2.7 – 3.8 mm per mm of rainfall (or a specific yield of 0.26-0.37)(Figure 6, left panels). In the second period, which followed three consecutive dry growing seasons, the wetland displayed wider diurnal fluctuations with the same pulsed reduction and gradual amplification in response to rainfall events (Figure 5, right panels). These fluctuations averaged 15.2 cm d^{-1} (daily maximum – minimum level) and, based on Loheide, Butler and Gorelick (2005) methodology, generated an average groundwater level depletion of 16.6 cm d^{-1}. Noticeably, in spite of its apparent reliance on groundwater, the wetland greenness increased after rainfall events (see NDVI in figure 5, right panel). The cropland in this period was covered by an active (and typically deep-rooted) alfalfa pasture which was likely responsible for sustained water table fluctuations averaging 1.6 cm d^{-1} with an estimated mean depletion of 4.9 cm d^{-1}. The largest rainfall pulse of this period (125 mm in November 17-20), triggered a slow 36 cm level raise of 10 days in the cropland which had a much lower velocity than the recharge pulses of the previous study period (Figure 5, right vs. left panel), suggesting that the level recovery resulted from the interruption of groundwater consumption.

Deep water table levels at site C, likely favored by its neighboring incision, provided an opportunity to explore vegetation-groundwater interactions under conditions that could have been more common for the catchment in the past (Figure 6). Sensor data provided here a more detailed description of the seasonal departure of water tables at forest stands with regard to their neighboring croplands (Figure 6 vs. Figure 4), showing that forest trees produce similar diurnal fluctuation, seasonal depression and slow level recoveries after rainfall events than those described for the alfalfa pasture above, yet they do so with water tables that are 8-10 m deep (Figure 6). Groundwater uptake, as indicated by daily water table fluctuations, started a few days after the deciduous tree species leafed out in mid-October (see NDVI cycles in Figure 6) and levels initiated their sustained and asymptotic recovery when the trees gradually lost their leaves in late May, approaching equilibrium with the surrounding cropland matrix throughout the dry (by ecologically inactive) season (Figure 6). Diurnal water table level fluctuations during the active period of the forest (October 15 - April 15) averaged 1.7 cm d^{-1} with an estimated mean depletion of 3.1 cm d^{-1}. In the three consecutive years of observations, levels dropped/recovered -89/47, -71/55 and -79/57 cm in the forest site. The same net drop of -80 cm over the three-year measurement period was observed in the cropland but without seasonal fluctuations. No direct recharge episodes were documented at any of these wells (Figure 6), yet slow and partial level recoveries in response to rainfall pulses were observed in the forest, as depicted in detail for a series of events in March 2019 (Figure 6, bottom left panel) and recorded in November 2019 and January 2020 when of 15 cm-recoveries took place along 8 and 17 days following rainfall pulses of 90 and 77 mm, respectively (Figure 6).

<u>Stream flow and yield</u>

Periodic base flow measurements obtained during the monitoring program together with previous data revealed contrasting seasonal and multiannual trends across different streams in El Morro catchment (Figure 7). During the three years of frequent measurements, a clear seasonal pattern with higher flow in the dry (and cold) season and lower flow in the rainy (and warm) season was evident at all sites (-31 to -50% in summer compared to the rest of the year, Table 1) except Site 2. Matching the seasonal patterns of water table depths (Figure 4), these fluctuations illustrate the dominant effect of groundwater uptake rather than precipitation inputs controlling stream base flow. Noticeably, the only site with no seasonal fluctuation corresponded to a segment of the Río Nuevo with deep incisions down to the gaging point (riparian consumption less likely), whereas most intense fluctuation were seen at site 3 and 5 (running dry in February 2020), which had shallow incisions and a large fractions of their trajectory surrounded by wetlands (Table 1). Older base flow data obtained before and shortly after the last erosion episode show how sites 1, 2, and 3 gained flow while site 7, which was flanked by the first two, got completely dried out after being a high-yielding stream before (Figure 7, Table 1). Matching water table observation at site B, this switch in stream dominance suggests competition of neighboring incisions capturing groundwater as they deepen. While showing no seasonal trends, the deeply incised segment of Río Nuevo gaged at site 2 showed a slight but significant decline in its base flow with time between (-23 l s^{-1} per year between November 2016 and August 2020, $r2=0.60$, $p<0.01$).

Base flow water yield estimates were obtained considering a topographic (larger) and geometric (smaller) definition of the feeding catchment area for each site (Table 1). These two criteria suggested specific yields ranging from 4 to 56 and 8 to 159 mm y^{-1}, respectively, with the highest values corresponding to the upper Río Nuevo sub catchment (Site 2) and the lowest to the Quebrachal sub catchment (Site 1). Along the Río Nuevo catchment, water yields appear to be highest in the higher belt (Sites 2 and 3), declining but maintaining a positive contribution in the intermediate belt (site 4 and "site 4 - (sites 2 + 3)" in Table 1). In the final segment where the merged La Guardia and Río Nuevo streams enter the terminal plain, negative yields were consistently observed (site 6 and "site 6 - (sites 4 + 5)" in Table 1). At this closure point, the total specific yield of the catchment was 19/29 mm y^{-1} (topographic/geometric area definition) (Table 1). While not accurately measured, a high-end estimate of peak flow contributions achieved at this site suggested that it would add less than 11% to the total yield of the catchment (Supplementary material).

Ecosystem activity

Vegetation activity as captured by NDVI from MODIS and LANDSAT images showed divergent temporal trends for croplands, native vegetation and wetlands (Table 2 and Figure 8). The long-term analysis of the whole El Morro catchment based on MODIS data revealed a decreasing greenness across the forests > grassland/pasture > cropland (all differences being significant with $p<0.01$, Table 2). An increased vegetation activity with time, and likely water transpiration, was observed comparing the second decade (2011-2020) with the first (2000-2010) with average greenings of 5.5 and 3.5 % for forests and grasslands/pastures, respectively. In the same temporal comparison, croplands and sediment deposits experienced a -1.1 and -6.7 % drops, respectively (Table 2). The catchment as whole, displayed a small decadal greenness increase of 1.3% as the previous contrasting trends compensated out, particularly between the dominant components of grassland/pastures vs. croplands (Table 2).

Focusing on the shorter period that encompassed the last erosion episode and our field observations (Figure 8), we found that forests sustained the highest greenness throughout the whole period while croplands the most temporally variable. Pre-existing wetlands and new wetlands emerging in croplands, displayed a sustained and stable greenness raise (Figure 8). Deposits landed on croplands in 2015 showed a sharp greenness decline followed by a steady recovery that was still not completed but close to wetlands and croplands four years later. The single dried wetland location (site B), had a high greenness that matched that of forests until one year after the new incisions drained the area. After that time its greenness dropped steadily for three consecutive years approaching levels that are close to those in the recovering sediment deposits (Figure 8).

Discussion

Ecohydrological changes at multiple scales

The El Morro catchment underwent intense and interconnected hydrological, ecological and geomorphological transformations over the last 45 years. In the longer term (1975-present) a widespread increase in groundwater storage was accompanied by the expansion of wetlands and the extension of a network of permanent streams opened by episodic sapping events (Figure 2b, 3 and S1). Raising groundwater levels and increased flooding have been reported for the same period in different locations across the sedimentary plains of Argentina during periods of higher than normal precipitation likely in connection with long term shifts from native forests, grasslands and planted pastures to continuous annual crop cultivation (Nosetto et al., 2015; Kuppel, Houspanossian, Nosetto, & Jobbágy, 2015; Gimenez et al., 2016, Giménez et al. 2020; Alsina, Nosetto, & Jobbágy, 2020). Similar transitions have been documented in dry farmlands of North America, Australia and Africa (George, McFarlane, & Nulsen, 1997; Scanlon, Reedy, Stonestrom, Pruderic, & Dennehy, 2005; Leblanc et al., 2008). The peculiar context of the El Morro basin, with higher slopes and closer depths to the rock basement than most of the central plains of Argentina (Jobbágy et al., 2008), is that this hydrological change has triggered an unusually rapid and pronounced sapping process that seems to have no precedents at the site for the whole Holocene (as suggested by sediment dating by Tripaldi and Forman et al 2016). Under a similar context of deforested farmlands, sapping and piping processes have been recently documented in a piedmont loessic plains 600 km north of our site (Pereyra, Fernández, Marcial, & Puchulu, 2020), and massive sapping episodes may have accompanied the long-dated expansion of cultivation in the loessic plains of China (Zhu, 2012).

In the mid-term (2000-present) the process of stream formation expanded exponentially with episodes of increasing magnitude in 2001, 2008, 2009 and 2015 (Figure 2b and S1, Supplementary material). Meanwhile, two opposite and coexisting trends of vegetation activity were observed. On one hand, currently cultivated areas decreased their greenness, likely in response to the replacement of pastures by continuous agriculture (Contreras et al., 2013), but more so to the adoption of no-till cultivation and the narrowing and delaying of the active growing season, which are part of a general drought avoidance strategy (Gimenez et al., 2020)(see Figure 6, top panel). On the other hand, remaining uncultivated areas including forests and grasslands increased their greenness, likely in response to rising water table levels favoring the expansion of wetlands and the growth of forests (see Gonzalez Roglich, Swenson, Villarreal, Jobbágy, & Jackson, 2015 for similar forest trends in other areas of the caldén belt). In the short-term (last erosion episode to the present) our study shows that despite the relative low precipitation of the last three years (Figure 8), wetlands kept expanding and greening and streams flowing (Figure 7). Groundwater uptake by plants appeared to be widespread in forests but limited to shallow water table depths (< 2 m) in croplands (Figures 4, 5 and 6 and Supplementary material). Mean water yields for the three years of periodic observations approached 20 mm y^{-1} (3.3% of long-term average rainfall inputs) with higher yields in the most deeply incised sub catchment sections of Río Nuevo (30-50 mm y^{-1}). This output was considerably stable for a dry region, with a seasonality governed by water demand rather than rainfall, since lowest flows occurred in summer when rainfall was highest but water uptake too. The observed water yields at the outlet of the catchment are still lower than those predicted by the most widely used global empirical model (Zhang, Dawes, Walker, 2001), which under pure grassland or forest cover predicts yields of 83 and 33 mm y^{-1}, respectively, based on the mean climatic conditions of our site.

Mechanisms of plants vs. streams competition

The unusual temporal match between the vegetation change (typically faster) and stream expansion processes (typically slower) at the El Morro catchment combined with its aridity offer a unique opportunity to assess the five mechanisms by which plants and streams may compete for water. Unsaturated water uptake (**mechanism 1,** Figure 1), has been likely the dominant source of transpired water under the deep groundwater table conditions before the 70s (Figure S1). Diverse sources of evidence point to the absolute prevalence of mechanism 1 and its capacity to fully inhibit stream flow in dry sedimentary plains in Argentina and elsewhere, including geoelectrical profiles and deep sediment cores showing dry vadose zones with an uninterrupted buildup of atmospheric chloride accumulation under native vegetation (Santoni et al., 2010; Jayawickreme, Santoni, Kim,Jobbágy, & Jackson, 2011; Amdan et al., 2011 in our study region; Scanlon et al., 2006 for a global synthesis).

At the El Morro catchment, like in many semiarid sedimentary regions subject to intense cultivation, mechanism 1 has been relaxed thanks to the reduced capacity of annual crops to exhaustively use of vadose moisture (Peck & Williamson, 1987;

George et al., 1997; Santoni et al., 2010; Giménez et al., 2016). As a result, water table levels have raised, likely following pulses of high rainfall (Giménez et al., 2016), creating the opportunity for a more widespread contact between plant roots and groundwater. While in first place, such hydrological shifts may favor localized groundwater use in lowland areas or incipient streams by waterlogging-tolerant species (mechanism 2), contact zones can be widespread enough to favor a more distributed use of groundwater in the whole catchment (mechanism 3). At our study catchment, the progressive appearance of wetland communities displaying an intense groundwater consumption was manifested in water table depth and greenness patterns (Figures S1, 5 and 8), providing qualitative evidence for **mechanism 2** (Figure 1). Complementary, base streamflow provided more quantitative evidence, with stream segments having shallow incisions and greater proportions of their shores flanked by wetlands showing stronger summer flow drops than the deeply incised upper Río Nuevo segment that was seasonally invariant (Table 1). Assuming that summer baseflow drops reflect the effect of mechanism 2, it would have accounted for 48 and 20% water yield reduction in summer and the whole year, respectively, at the closure of the catchment (Table 1). Mechanism 2 may not only capture groundwater feeding streams but streamflow directly as well, yet, disentangling these two sources has proven difficult (Dawson & Ehrlinger 1991; Bowling, Schulze, & Hall, 2017).

Distributed use of groundwater by vegetation (**mechanism 3**, Figure 1) was confirmed in the El Morro catchment. With water table depths >7 m caldén forests used groundwater (Figure 6), as documented earlier for forest relicts north of our site (Gimenez et al., 2016). More generally, across the semiarid and subhumid loessic plains of Argentina, Hungary and China tree stands within herbaceous matrices have often shown intense groundwater use (Jobbágy & Jackson, 2004; Nosetto, et al., 2013; Yasuda et al., 2013; Toth et al., 2014). Mechanism 3 could have massive effects on streamflow if a large fraction of the El Morro catchment gets reforested. A simple comparison of the trajectories of water table depths at site C (Figure 4) suggest that the mean drop of 93 cm during three years in the forest (69 cm in the croplands) would have get magnified to 196 cm if winter level recoveries would not have taken place (something expectable in full forest coverage scenario). The more precise estimate of groundwater depletion rates derived from diurnal water table depth fluctuations suggests potential depression of 4-5 meters per year (5 active at 3.1 cm d^{-1}, Figure 6). These rough estimates suggest that the water table raises that expanded wetlands and created new streams could revert in less than a decade with full reforestation. Paired catchment experiments have shown how streams in dry regions can fully vanish following massive afforestation, yet the relative weight of mechanism 1, 2 and 3 explaining these ecohydrological transitions was not disentangled (Farley, Jobbágy, & Jackson 2005; Jobbágy et al., 2013). Mechanism 3 opens the possibility for opposing feedbacks, as hinted by tree ring observations for the same *Prosopis* species at another site (Bogino & Jobbágy, 2011), where raising water tables boosted tree growth first (negative feedback), but caused their massive waterlogging die-off afterwards (positive feedback). Croplands consumed groundwater too at our catchment, but their shallow rooting depth limited the extent of this effect (Figure 5, Supplementary material)(Nosetto et al., 2009). Rather than assuming rigid and additive effects of vegetation types in the catchment, the fact that mechanism 3 can compensate the relaxation of mechanism 1 creates more opportunities for plants to take away water from streams. The notable match between rooting depths and water table depths globally (Fan et al., 2017), suggests that the dynamic coexistence of these two mechanisms may be widespread.

While the previous discussion focused on the mechanisms favoring plants over streams, other our study illustrated reciprocal case as well (Figure 1). By deepening their incisions (**mechanism 4**, Figure 1), streams not only created the hydraulic gradients needed to capture groundwater (comparison of positions 1 to 3 in site C in Figure 4), but hampered mechanism 2 (wetland at site B in Figure 4, drying wetland in Figure 8) and, likely, mechanism 3 (cropland at the same site, Figure 4), favoring their own baseflow (positive feedback). While in the flat areas of the sedimentary plains of Argentina raising groundwater recharge and levels lead to flooding (Kuppel et al., 2015, Gimenez et al., 2020), the more tilted and shallow sedimentary system of the El Morro has likely favored the observed abrupt sapping process that tend to decoupled water table levels from the surface, as they were in the 70s (Figure S1). An approaching saturation of stream density is hinted by their regular spacing and the observed episode of rapid “stream piracy” (Calvache & Viseras, 1997) where they may be too close (effect of the upper Río Nuevo and Uke tributaries on the stream that they flanked, Figure 2b and 7). Theoretical approaches explaining the switch of groundwater surfaces from topography- to recharge-dominated show that increases in recharge can couple water tables to the surface (linear effect) while stream length and depth growth can decouple them (quadratic and linear effect, respectively) (Haitjema & Mitchell-Bruker, 2005; Gleeson, Marklund, Smith, & Manning, 2011). A simple exercise with one of these models suggests that the stream network is reestablishing a recharge-controlled equilibrium in the La Guardia and Río Nuevo sub catchments, but is still far in the Quebrachal sub catchment (Table 2, supplementary material).

The final mechanism favoring streams involves the burial of riparian and wetland areas with fluvial sediments (**mechanism 5**, Figure 1). In the El Morro catchment this mechanism accounted for a relatively small fraction of the area (Table 2) but had a very strong effect on vegetation activity that lasted at least 4 years (Figure 8). While likely negligible in terms of its contribution to baseflow yields, this mechanism can create ideal conditions for repeated sapping erosion events as it tends to sustain saturated conditions along the present and future stream bed for longer periods, increasing the chances of successive high precipitation years accumulating their effects. Dry sedimentary regions experiencing deep recharge and water flushing for the first time in geological scales may have salinization as an additional mechanism that favors the partition of water to streams. Increasing salinity in soils and groundwater has the capacity to reduce or even eliminate completely plant transpiration fluxes, as found already in the El Morro catchment (Jobbágy et al 2020) and in deforested areas of the plains of Argentina and Australia (Marchesini, Fernández, & Jobbágy, 2013; Marchesini et al. 2017). While the "winner" flux under salinization is direct evaporation, the restriction of transpiration would hamper mechanisms 2 and 3 favoring water table level raises and, as a result, sapping or surface processes due to the reduced unsaturated thickness of the catchment. To some extent natural ecosystems adjust to increasing salinity when salt-tolerant species like *Tamarix sp*. start dominating wetlands (Rios, 2020) or where native forest relicts consume groundwater with >20 dS/m of electric conductivity (Gimenez et al., 2016, at site C in this study). Currently cultivated species in our study system (soybean, maize, alfalfa) however do not show this adjustment capacity (Ashraf & Wu, 2011, Jobbágy et al., 2020).

Plants vs. streams: Many aces under their sleeves

Far from following a simple predictable partition of rainfall inputs into evapotranspiration and streamflow, the El Morro catchment has shown over the last decades a rapidly switching balance between them. After an early stage in which mechanism 1 has kept the system free of streamflow (and streams), away from the expected water yield suggested by global empirical models (Zhang et al., 2001), the expansion of cultivation, aided by a relatively rainy period, has brought the system to a new stage of higher groundwater storage. Saturated water consumption (Mechanisms 2 and 3) in this new stage had increased evapotranspiration locally but was unable to prevent stream formation (Mechanism 4) and the onset of a stable water yield that approaches empirical global predictions. Sapping erosion is still taking away water from plants in the catchment, yet its long-term outcome is hard to predict. Climate fluctuations, but more importantly, land use changes and spontaneous vegetations shifts can twist it.

Acknowledging the non-additive and non-linear effects of vegetation and streams on groundwater is crucial to develop more successful hydrological models for dry sedimentary catchments. The peculiarities of the El Morro catchment may cast light on overlooked (and not so peculiar) hydrological mechanisms.

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Table 1. Synthesis of base flow and yield for the El Morro catchment. The location of sites is presented in Figure 2b. For each stream base flow mean, coefficient of variation of all observations and the proportional flow decline during the warmest season (December to April) compared to the rest of the year (May to November) is indicated as “summer drop”. Segmented estimates are based on the subtraction of nested sections of the catchment. All base flow estimates are based on 17 sampling dates obtained between November 2017 and August 2020 except for archive data whose year and number of repeated measurements is presented in the table. For each sub catchment or segment the total length, corresponding to the linear extension of all continuous permanent streams feeding it is shown. Length of deposits and wetlands represents the extension of those streams intersecting those features without prominent incision (> 1 m). The maximum incision depth corresponds to present conditions. Catchment area and their associated base yield were defined according to a purely topographic rule following surface contributing areas to the sampling point and a geometric rule considering constant supply width of 2.6 and 12.5 km in the upper-mid and mid-lower catchment, respectively.

					stream configuration				catchment defini	
			base flow		horizontal			vertical	topographic	
Site ID	Location	mean	CV	summer drop	total	deposits	wetlands	max. depth	area	yield
		l s^{-1}	%	%	km	km	km	m	km^2	mm y^{-1}
This study										
Site 1	Quebrachal - R33	55.1	34%	-42%	38.1	6.5	13.4	8	414	4.2
Site 2	Río Nuevo - R33	214.3	13%	-7%	16.3	0	0.7	10	121	55.8
Site 3	Uke West - R33	40.7	32%	-50%	4	0	1.2	3	63	20.4
Site 4	Río Nuevo - R8	478.0	32%	-31%	44.4	5.6	1.9	20	412	36.6
Site 5	La Guardia - R8	182.0	49%	-43%	55.2	0	21.3	3	508	11.3
Site 6	Rio Nuevo - R7	647.9	34%	-48%	104.1	5.6	23.2	20	1070	19.1
Segmented estimates										
A, Site 4 - (Sites 2 + 3)	Río Nuevo mid-low	246.3	48%	-44%	24.1	5.6	0	20	228	34.1
B, Site 6 - (Sites 4 + 5)	Rio Nuevo lowest	-46.2	338%	.(70%)	4.6	0	0	1	150	-9.7
Archive										
Site 7 - 2008 (n=1)	Río Nuevo - dry branch	46.2	-	-	3.4	0	1.7	0.5	90	16.2
Site 8 - 2008-2009 (n=4)	Quebrachal	136.5	25%	-	6.1	0	2.7	1	190	22.7
Site 9 - 2010-2011 (n=12)	Río Nuevo	364.0	18%	1%	14.2	0	3.1	9	255	45.0

Table 2. Greenness trends derived from MODIS data for the El Morro catchment. Vegetation was classified in 2018. For each vegetation type mean NDVI across pixels was calculated each year and then mean and standard deviation across years were obtained. NDVI shifts are described based on the proportional change observed between the average values of each pixel in 2000-2010 and 2011-2020 and by identifying and selecting those which displayed significant long linear term trends ($p<0.05$).

					Positive linear trend		Negative linear trend	
Vegetation Type	NDVI		area	decadal NDVI shift	significant pixels	slope	significant pixels	slope
	mean	interannual SD	%	% change 2010s vs. 2000s	%	units 10y-1	% pixels	units 10y-1
Forest	0.489	0.028	6.2	5.47	**29.77**	0.0427	0.25	NS
Grassland & Pasture	0.412	0.020	41.6	3.49	**11.46**	0.0514	1.04	NS
Cropland	0.388	0.019	50.7	-1.12	4.39	NS	**6.34**	-0.0447
Deposits	0.351	0.032	1.5	-6.70	0.25	NS	**8.88**	-0.0947

Figure Legends

Figure 1. Schematic representation of five mechanisms involved in the partition of the water inputs received by catchments towards transpiration and streamflow. The top panel shows three ways in which plant uptake and transpiration takes away water from streams. The first one (mechanism 1) involves the most acknowledged process of uptake from the unsaturated zone. The second one (mechanism 2) incorporates uptake from the saturated zone or the capillary fringe above it in focalized wetland and riparian areas with a closer contact between plant roots and water tables. The third one (mechanism 3) encompasses distributed uptake from the saturated zone or the capillary fringe in the matrix of the catchment. The second panel illustrates processes by which streams can take away water from plants reducing transpiration and enhancing stream flow. They include deepening streambeds (mechanism 4), which enhance hydraulic gradients and limit plant access to water tables in low areas or even in the matrix of the landscape; and burying riparian and wetland vegetation with sediment deposits (mechanism 5) which temporarily reduces transpiration in those highly transpiring zones.

Figure 2. The developing catchment of El Morro in Argentina. A. Map of the catchment illustrating the location of the major sub catchments as defined by their topographic limits, active permanent streams, and potential drainage lines. Groundwater monitoring sites, which in some cases include several wells, and meteorological stations are indicated. The dotted white frame shows the limits associated with the schematic view on the right. B. Scheme of new permanent streams indicating their period of formation (also referencing vanished or dead-ended segments). The area occupied by wetlands and sediment deposits is depicted together with the location of streamflow measurement points corresponding to the present study or to previously available records. The Quinto river is the pre-existing permanent water course receiving the new streams with a mean discharge of 5.5 m3 s^{-1}.

Figure 3. Decadal groundwater level trends in the El Morro basin. The twenty seven sites are grouped according to their corresponding elevation belt within the catchment (higher > 700 m, intermediate 700-550 m, lower 550-500 m, terminal plain < 500 m). A zero level is assigned at the time of the first measurement in order to highlight the absolute level shifts starting from that point. Dotted lines illustrate periods and sites in which incisions were carved less than 500 m away or where sediment was deposited right on the location. Mean level changes per decade were calculated excluding the incision/deposit situations. All sites correspond to water wells used for ranching whose static level was recorded in the past. In 11 of them, modern levels were measured directly in the same well or in a new ad-hoc borehole whereas in the rest levels (always < 1.5 m) were estimated by the presence of wetlands or lagoons.

Figure 4. Water table depth in 14 monitoring wells at the El Morro catchment. Levels were manually measured in hand augered wells. The locations of each pair or group of sites and their corresponding vegetation and relevant neighboring features are shown accompanying each plot. Dual numbering in the Y axes is color-coded like the markers in the plot and used to capture depth offsets between wells using an identical scaling across all plots.

Figure 5. Vegetation greenness, precipitation and water table depth dynamics for two periods of 84 days with contrasting hydrological conditions (recharge vs. discharge) at site A. Greenness is represented by an 8-day MODIS product, precipitation was

recorded at the site and water table levels where measured with pressure transducers. Note the color-coded numbering in the Y axis matching the line color of each stand (green=wetland, black=5-day moving average in wetland, red=cropland). Grey zones represent the subperiod zoomed at the bottom.

Figure 6. Vegetation greenness, precipitation and water table depth dynamics for the whole study period in neighboring wells at site C (cropland and forest at position 2). Greenness is represented by an 8-day MODIS product, precipitation was recorded at “Coronel Alzogaray” meteorological station, 15 km away, water table levels were measured with pressure transducers. At the cropland an early gap on sensor data was filled with manual measurements (red dotted line). Note the color-coded numbering in the Y axis matching the line color of each stand (black=forest, red=cropland). Light grey bands depict each growing season while darker grey bands represent the subperiod zoomed at the bottom.

Figure 7. Base flow at different locations within the El Morro catchment. Grey areas depict isolated measurements before the continuing monitoring program started. Site location and baseflow synthesis are presented in Figure 2b and Table 1.

Figure 8. Greenness trends at sites with contrasting vegetation types/trajectories in El Morro catchment. NDVI from Landsat imagery for areas occupied since the beginning of the period by forests (n=11), croplands (n=16), and wetlands (n=20) where compared with areas experiencing the transition from croplands to wetlands (n=14) and fluvial deposits (n=7). A single case of wetland drying (site B) is also depicted. Alternate white and grey bars highlight successive growing seasons and letters indicate significant differences within years based on ANOVA. The lower panel shows mean monthly precipitation for the whole catchment and its 12-month moving average. The erosion episode took place in February 2015.