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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

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Plants versus 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 how groundwater mediates evapotranspiration/streamflow partitioning is still fragmented and catchment studies under changing vegetation conditions can provide a useful frame for integration. We explored this partition in a flat sedimentary dry catchment in central Argentina in which the replacement of native vegetation with rainfed crops was accompanied by the abrupt formation of groundwater-fed streams by subsurface erosion (i.e., sapping) episodes. Historical records indicated widespread water table rises ($\sim$0.3 m y^{-1} on average). Groundwater level and stream baseflow fluctuated seasonally with minima in the warm rainy season, indicating that evaporative discharge rather than rainfall shapes saturated flows. Diurnal groundwater level fluctuations showed that plant uptake was widespread where water tables are shallow (<3 m) but restricted to deep-rooted Prosopis forests where they are deep (7–10 m). MODIS and LANDSAT NDVI revealed a long-term greening for native vegetation, new wetlands included, but not for croplands, suggesting more limited evapotranspiration-groundwater level regulation under agriculture. Close to the deepest (20 m) and most active incisions, groundwater level and greenness declined and stream baseflow showed no seasonal fluctuations, hinting decoupling from evapotranspiration. Intense ecological and geomorphological transformations in this catchment exposed the interplay of five mechanisms governing evapotranspiration/streamflow partition including (a) unsaturated uptake and both (b) riparian and (c) distributed uptake from the saturated zone by plants, as well as (d) deepening incisions and (e) sediment deposits over riparian zones by streams. Acknowledging the complex interplay of these mechanisms with groundwater is crucial to predict and manage future hydrological changes in the dry plains of South America.

KEYWORDS

ecohydrology, phreatophytes, sapping, semiarid watersheds, water yield

1 | 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 is still one of the main attractors of the convergence of Ecology and Hydrology. How catchments partition precipitation inputs between evaporative and liquid losses, 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 remains 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? What is the role of groundwater mediating this partition? In this paper we explore these questions in a dry sedimentary basin taking advantage of its changing vegetation, which involved the expansion of crops over native forests, and its developing stream network, created by subsurface erosion (i.e., sapping) over just four decades (Contreras et al., 2013).

A simplified view of the atmosphere-soil–plant/stream continuum assuming that all the water consumed by vegetation comes from the unsaturated zone (Mechanism 1, Figure 1) has been successfully used to explain streamflow in many catchments up to these days (Rathjens et al., 2015). In dry sedimentary regions where evapotranspiration is water limited, the exhaustive exploration of the wettable soil volume by native vegetation often leads to the total suppression of groundwater recharge through this mechanism, limiting streamflow to storm run-off episodes with no observable base flow (Santoni et al., 2010; Scanlon et al., 2006). Yet, unsaturated uptake runs short to explain many biological and hydrological phenomena such as the presence of exceptionally active vegetation patches in deserts or the daily fluctuation of groundwater levels or stream base flow. Plant roots access saturated water directly, as in the obvious case of riparian or wetland vegetation (Lowry et al., 2011), or indirectly through the capillary fringe, as seen (not as easily) with phreatophytic ecosystems (Jobbágy et al., 2011; Naumburg et al., 2005). Therefore, saturated uptake involves a "second chance" that plants have to take away water from streams, with the lateral connectivity of saturated fluxes allowing vegetation in one place to use water that was not used in another. Catchment models are incorporate these mechanisms (Bailey et al., 2020; Doble & Crosbie, 2017; Immerzeel & Droogers, 2008), but our capacity to parameterize them is incipient. While saturated uptake by wetland and riparian communities in low positions and water body shores is typically constrained to the small fraction of the landscape that they occupy (i.e., focalized saturated uptake, Mechanism 2, Figure 1; Bond et al., 2002), a more widespread contact between roots and the capillary fringe can take place, particularly on flat sedimentary terrains (i.e., distributed saturated uptake, Mechanism 3, Figure 1). This 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 (Fan et al., 2017; Jobbágy & Jackson, 2004; Nosetto et al., 2009).

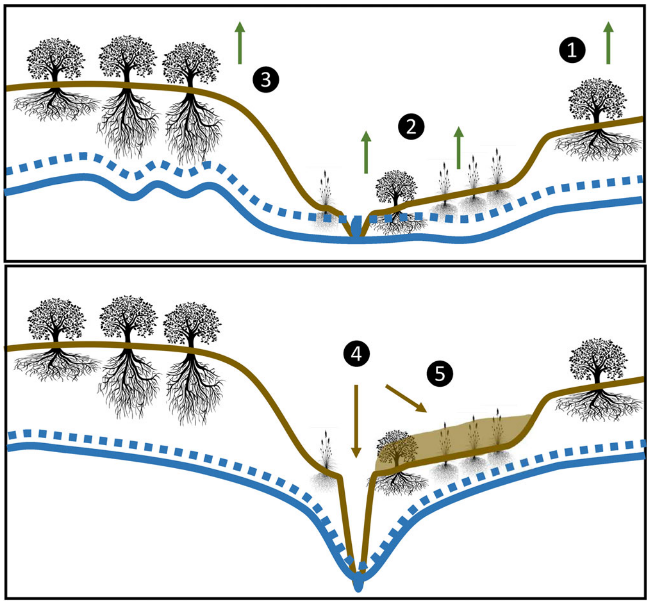

FIGURE 1 Schematic representation of five mechanisms involved in the partition of the water inputs received by catchments towards transpiration and streamflow. The top panel shows three ways in which plant uptake and transpiration takes away water from streams. The first one (Mechanism 1) involves the 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

Far from passively receiving the hydrological left-over of the three main water consumption mechanisms 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 groundwater contributions to base flow, transiently enhancing hydraulic gradients and, more permanently, impairing mechanisms 2 and 3 as water tables plunge away from roots to reach a new equilibrium (i.e., streambed deepening, Mechanism 4, Figure 1; Bravard et al., 1997; Schilling et al., 2004; Wurster et al., 2003; Yang et al., 2015). Another way in which streams can actively restrict plant water consumption is by burying ecosystems with new fluvial sediment deposits, something that is likely to affect active riparian and wetland zones with high water consumption (i.e., sediment deposit, Mechanism 5, Figure 1; Kui & Stella, 2016). In most landscapes, vegetation changes occur at shorter temporal scales than geomorphological changes in streams, making mechanisms 1, 2 and 3 more important drivers of plant-stream water partition shifts than mechanisms 4 and 5. Yet, catchments in which the erosive power of streams get abruptly unleashed by climate or land use changes offer an ideal observatory to explore the interaction of all these mechanisms at matching temporal scales. This is the case of the study catchment presented here, where the gradual replacement of native vegetation by croplands has been accompanied by the spontaneous development of network of permanent streams that is still growing.

Over the last four decades, in a dry sedimentary area of central Argentina initially devoid of surface water outlets, groundwater has raised steadily, expanding the area where it contacts the surface and triggering an extremely abrupt subsurface erosion process (i.e., sapping) that carved and connected permanent stream segment that now configure what it has been named the "El Morro" catchment (Contreras et al., 2013). Groundwater sapping is a hillslope recession process that manifests in the surface but results from the collapse of a less resistant subsurface once it reaches unstable saturated flow velocities. Stronger groundwater hydraulic gradients towards the incisions caused by sapping in the landscape can self-reinforce this process, which has been proposed as the driver of canyon development in places like the Colorado Plateau and Mars (Grau Galofre & Jellinek, 2017). While increasing rainfall trends, seismic activity and land use changes have been pointed as possible converging causes for this hydrological transformation in the "El Morro" catchment (Contreras et al., 2013), observations in this and other sites have pointed to the onset of groundwater recharge following the conversion of native vegetation to rainfed agriculture as the most determinant factor (Amdan et al., 2013; Contreras et al., 2013; Giménez et al., 2016; Marchesini et al., 2017). Here, we take advantage of the unique setting of El Morro to address the following questions: Under continuously water-limiting climatic conditions can plants regulate or even suppress stream baseflow through saturated water uptake? If so, how is this regulation responding to different vegetation types and groundwater level conditions? As streams beds extend and deepen into the saturated zone, do they restrict vegetation groundwater uptake in favour of stream flow? We explored these questions combining long-term field and remote sensing data together with ongoing hydrological and ecological observations initiated after the last and most intense sapping event in 2015 of the El Morro catchment.

2 | MATERIALS AND METHODS

2.1 | Study area

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 lose water as they traverse it (Marchesini et al., 2020; Poca et al., 2020). A surprising exception emerged in recent decades, when an extremely abrupt groundwater sapping process started carving and connecting permanent stream segments that now configures the "El Morro" catchment (Contreras et al., 2013). Located in the transition from the isolated rock outcrop of the "El Morro" caldera (Sruoga et al., 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. In the exposed walls of incisions, ~5 m-deep aolian Holocene material laying over pre-Holocene fluvial beds suggests that the emerging streams are a new feature over the last interglacial period (Tripaldi & Forman, 2016). Yet, where exposed, the crystalline basement or its overlaying calcretes show signs of fluvial erosion suggesting that a pre-Holocene paleo catchment buried with aeolian material is being reactivated in recent years.

The study catchment has a temperate semiarid climate with 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. Soils are *Entic Haplustolls* in the higher catchment and *Typic Ustipsamments* and *Typic Ustorthents* in the intermediate and lower catchment (Galván & Collado, 2010).

Sitting at the ecotone between the Pampas grasslands and the Espinal woodlands (Oyarzabal et al., 2018; Figure 2a), the native vegetation of the area has been progressively replaced by crops since the beginning of the twentieth century and today more than half its area is under rainfed agriculture with native Caldén (*Prosopis caldenia*) forests covering less than 5% 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 et al., 2018) dominated by *Cortaderia selloana* tussocks and *Typha* sp. in non-salty environments and *Tamarix ramosissima* under saltier conditions (Díaz et al., 2018; Natale et al., 2010).

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

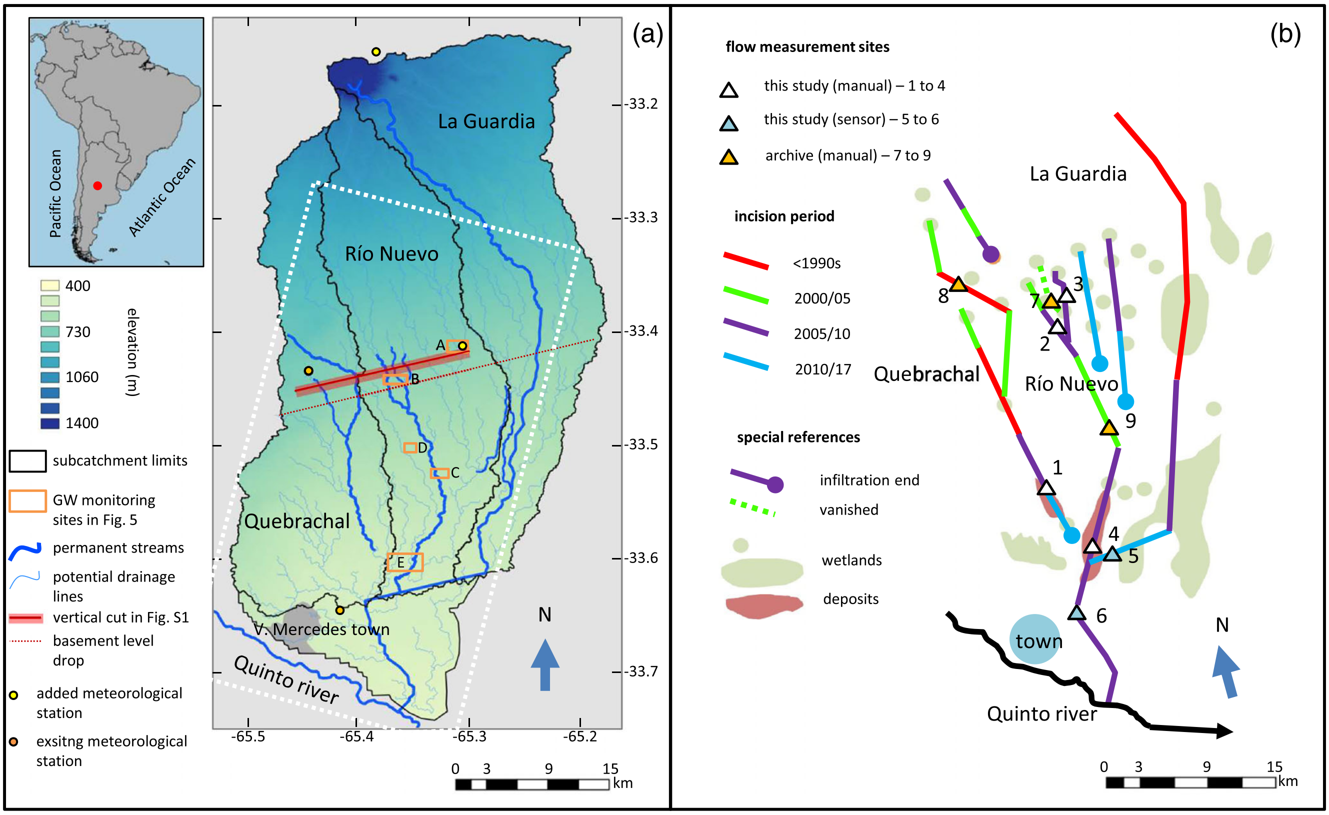

FIGURE 2 The developing catchment of El Morro in Argentina. (a) Map of the catchment illustrating the location of the major sub catchments as defined by their topographic limits, active permanent streams, and potential drainage lines. Groundwater monitoring sites, which in some cases include several 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}

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 (Buono et al., 2018; Contreras et al., 2013). 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 aeolian dunes on the surface and the greatest depth to the crystalline basement (>50 m), associated to a local tectonic depression (Barbeito et al., 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).

2.2 | Hydrological observations

Here, we use data derived from the compilation of previous studies of our own and other teams working in the region, and data 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 (February 2015).

To characterize regional decadal changes in groundwater level we took advantage of an existing synthesis of well surveys (BRS, 2000) and additional records by local farmers. We identified 23 sites in the catchment with observations between 1966 and 1980 (most measured in 1975), and four 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 (1999–2020, mean 2007) based on (a) direct measurements or records by farmers (11 sites) and (b) 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 et al., 2008).

TABLE 1 Synthesis of base flow and yield for the El Morro catchment

		Base flow			Stream configuration				Catchment definition criteria			
					Horizontal			Vertical	Topographic		Geometric	
		Mean	CV	Summer drop	Total	Deposits	Wetlands	Max. depth	Area	Yield	Area	Yield
Site ID	Location	$l\ s^{-1}$	%	%	km	km	km	m	km^2	$mm\ y^{-1}$	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	227	7.7
Site 2	Río Nuevo - R33	214.3	13%	-7%	16.3	0	0.7	10	121	55.8	42	159.4
Site 3	Uke West - R33	40.7	32%	−50%	4	0	1.2	3	63	20.4	10	123.4
Site 4	Río Nuevo - R8	478.0	32%	−31%	44.4	5.6	1.9	20	412	36.6	354	42.6
Site 5	La Guardia - R8	182.0	49%	−43%	55.2	0	21.3	3	508	11.3	246	23.3
Site 6	Rio Nuevo - R7	647.9	34%	−48%	104.1	5.6	23.2	20	1070	19.1	700	29.2
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	301	25.8
B, Site 6 - (Sites 4 + 5)	Rio Nuevo lowest	−46.2	338%	70%	4.6	0	0	1	150	−9.7	99	−14.7
Archive												
Site 7-2008 (*n* = 1)	Río Nuevo - dry branch	46.2	-	-	3.4	0	1.7	0.5	90	16.2	9	164.8
Site 8-2008-2009 (*n* = 4)	Quebrachal	136.5	25%	-	6.1	0	2.7	1	190	22.7	16	271.4
Site 9-2010-2011 (*n* = 12)	Río Nuevo	364.0	18%	1%	14.2	0	3.1	9	255	45.0	118	97.2

Note: 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.

In April of 2017, we started a cycle of periodic measurements of water table depth and stream flow. Originally aimed to follow the behaviour of the groundwater and stream system under new sapping episodes, the period covered (2017–2020) has been drier than the 60-year average (496 vs. 608 mm y^{-1}), offering a useful opportunity to explore groundwater contributions to plants and streams. 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. Water table levels in these well were monitored three times a year manually as wells as 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 six 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 artificial channel (Site 6). We could complement base flow series with data obtained before (Sites 1–4 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 10–25 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 sensors 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.

2.3 | 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).

2.4 | Ecological observations

To obtain relative estimates of water uptake trends for the different types of vegetation or vegetation change trajectories we used greenness indexes. In previous studies across neighbouring regions, we found that the direct use of green indexes provides better estimate of relative transpiration rates for cultivated and native vegetation than actual evapotranspiration products (Contreras et al., 2011; Nosetto et al., 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 change 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 analysed 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 six 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.

3 | RESULTS

3.1 | Groundwater dynamics

The imprint of vegetation and stream formation on groundwater levels was evidenced at three temporal scales of analysis. In the long-term (four decades) the catchment has experienced a sustained and widespread water table level raise with exceptional declines close to stream incisions (Figure 3). In the mid-term (3 years) seasonal level fluctuations have evidenced the imprint of groundwater uptake by different vegetation as wells as steady level depressions caused by deepening streams (Figure 4). Short-term level changes (hours to months) highlighted vegetation effects on recharge, which was highest in croplands, and the importance of new wetlands and forests respectively consuming shallow and deep groundwater that could flow to streams in their absence (Figures 5 and 6).

Since the late 1970s there was a widespread rise of groundwater levels at the El Morro catchment, except close to (<500 m) stream incision and within stream sediment deposits (Figure 3). Water table depth raised on average 3.06 metres per decade with largest gains in the higher belt of the catchment (4.83 metres per decade on average starting from a mean depth of 15.33 m), followed by the intermediate and lowest (terminal plain) belts (respectively, 3.50 and 3.77 metres per decade on average starting from mean depths of 11.55 and 7.85 m), and the lower belt (0.97 metres per decade starting from a mean depth of 3.6 m; Figure 3).

Three years of more detailed observation across the network of monitoring wells showed accelerated level declines close to incisions within an overall trend of slightly lowering levels likely associated to a series of dry years (Figure 4). Groundwater uptake by vegetation was evidenced by summer declines and winter rises of water tables in many wells, suggesting that evapotranspiration outpaces rainfall (both peaking in summer) in its control of groundwater levels (Figure 4). These seasonal fluctuations tended to disappear with increasing water

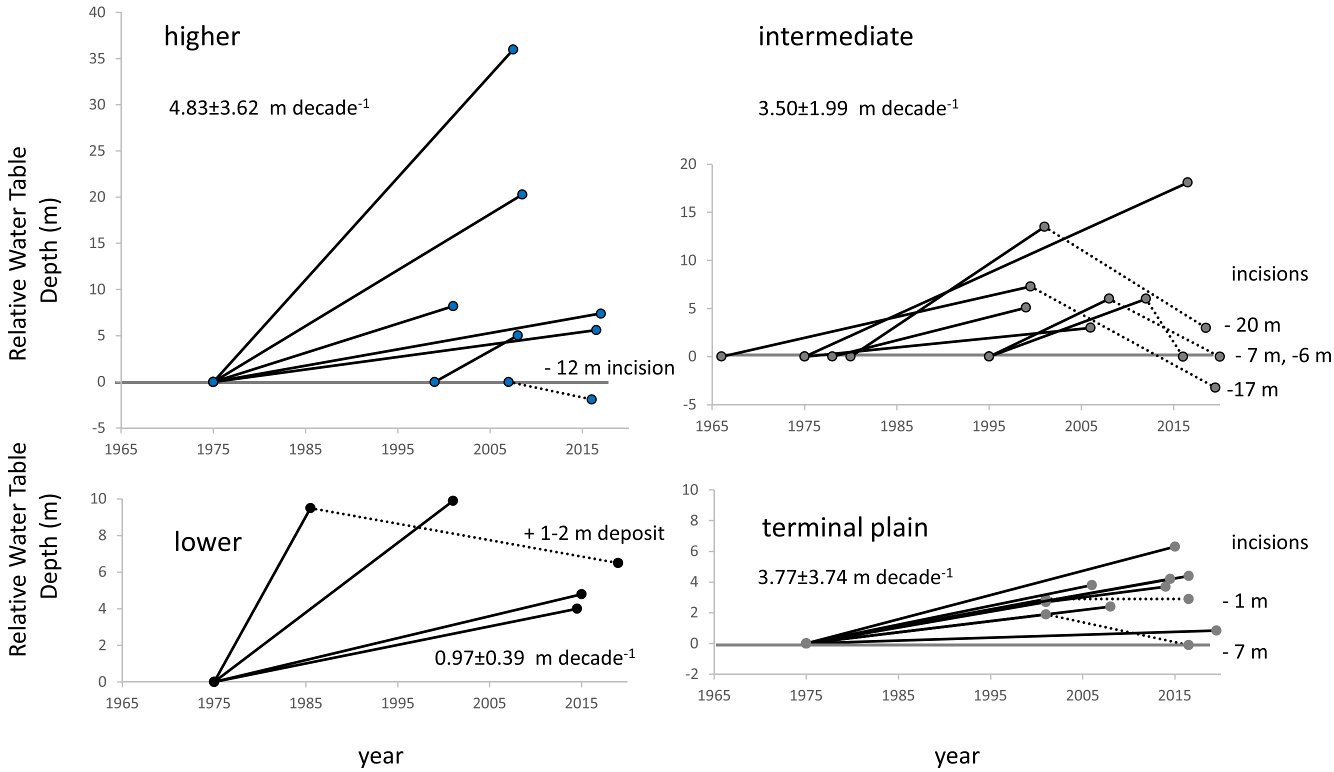

FIGURE 3 Decadal groundwater level trends in the El Morro basin. The 27 sites are grouped according to their corresponding elevation belt within the catchment (higher >700 m, intermediate 700–550 m, lower 550–500 m, terminal plain <500 m). A zero level is assigned at the time of the first measurement 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 lakes

table depths in wetlands (>1.5 m) and croplands (>5 m) but where sustained at some of the deepest wells in forests (~10 m; Figure 4). A seepage wetland (Site A) initiated in 2000 (see Figures S3 and S2) showed the most stable levels whereas its neighbouring cropland showed seasonal oscillations (~1 m-deep in 2019–2020; Figure 4a). The effect of deepening streams on groundwater was revealed at both wetlands and croplands at a site flanked by two incisions (Site B) with a steady decline (Figure 4b) with constant rates in the wet and dry season that suggested that drainage from below rather than consumption from above was causing it. Remarkably, incisions at this site dried both the wetland and its outlet stream, originated in the late 90s (see Site 7 in Figures 2b and 5). Where the water tables were deepest (Site C), a strong contrast between forest and croplands was found (Figure 4c). At the forests wells seasonal oscillations suggested pulsed consumption of groundwater by the dominant winter-deciduous trees whose active roots were found growing around sensors at 9 m of depth. In contrasts, cropland wells (600 m away) showed very subtle seasonal changes. Transect at this site suggest that wells nearer to the stream incision (position 1, ~100 m away) are closer to rich a new equilibrium while those at positions 2 and 3 may still be yielding water towards the stream (Figure 4c), as shown by the overall level trends in the whole study period.

Continuous observations under shallow water table conditions revealed contrasting discharge/recharge dynamics for wetlands and croplands (Site A, Figure 5). Two periods were identified, one associated with net groundwater gains (summer–fall 2018) and the other with net losses (spring–summer 2019–2020). In the first period the wetland displayed high daily level fluctuations, interrupted first and then progressively amplified following rainfall events (Figure 5, left panels), suggesting increasing groundwater uptake as the rainfall pulse was consumed. At this time, no fluctuations were observed in the cropland, which remained in fallow stage prior to the establishment of a pasture (see NDVI in Figure 5, left panel). An intense rainfall event in this period (74 mm on April 1 measured at the precise site) flooded the wetland reducing the fluctuations. The same event and the following two triggered direct recharge episodes under the cropland with level rises of 2.7–3.8 mm per mm of rainfall (associated specific yield of 0.26–0.37; Figure 6, left panels). During the second period net groundwater losses prevailed (spring–summer 2019–2020) and the wetland displayed wider diurnal fluctuations (Figure 5, right panels) that averaged 15.2 cm d^{-1} (daily maximum – minimum level). Noticeably, in spite of its apparent reliance on groundwater, the wetland greenness increased after rainfall events during this period (see NDVI in Figure 5, right panel).With the cropland covered by an active alfalfa

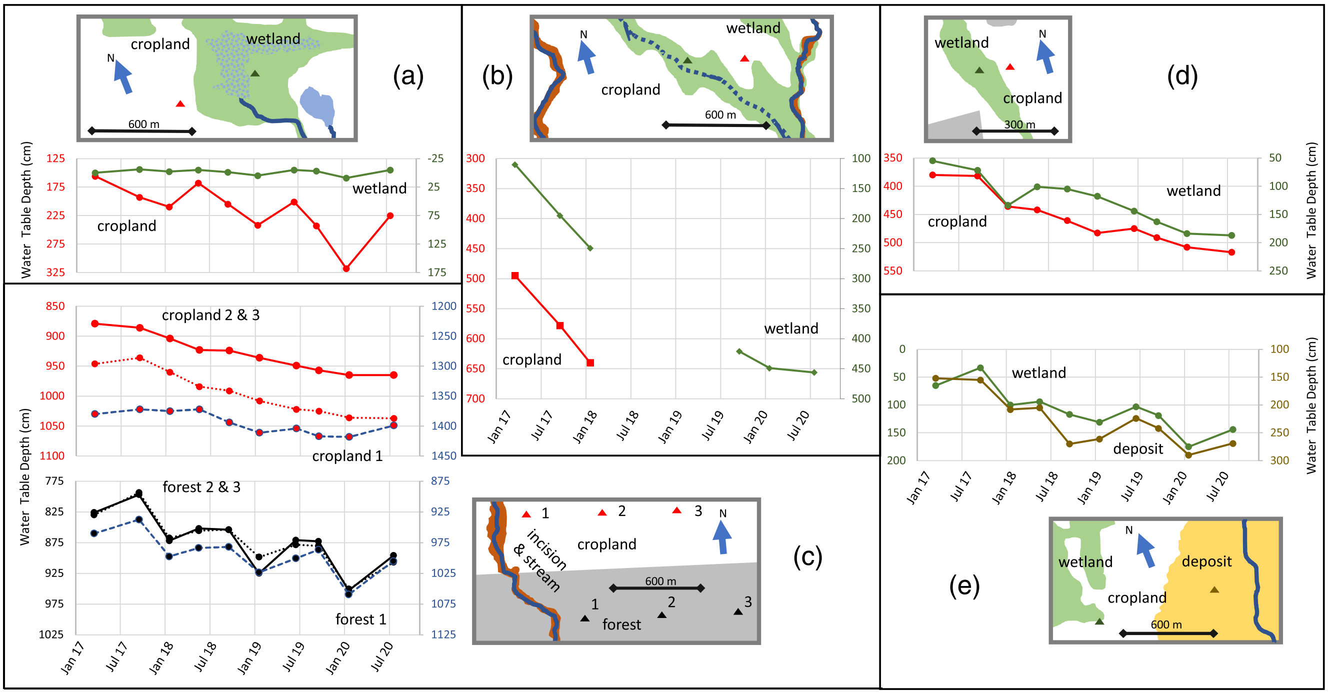

FIGURE 4 Water table depth in 14 monitoring wells at the El Morro catchment. Levels were manually measured in hand augered wells. The locations of each pair or group of sites and their corresponding vegetation and relevant neighbouring features are shown accompanying each plot. Dual numbering in the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

pasture at this time, sustained water table fluctuations averaging 1.6 cm d^{-1} were observed. The largest rainfall pulse of the whole study period (125 mm in November 17–20), triggered a slow 36 cm level raise of 10 days in the cropland, a slow level recovery that may resulted from the interruption of groundwater consumption that was dwarfed by the recharge pulses of the fallow period (Figure 5, right vs. left panel). These observations evidenced a window of groundwater recharge in croplands during fallow periods and higher and more continuous groundwater discharge in the wetlands.

Under deep water table conditions, continuous monitoring wells provided more detailed evidence on the contrasting capacity of trees and crops to consume deep groundwater (Site C, Figure 6). Forest trees produced similar diurnal fluctuations, seasonal depression and slow level recoveries after rainfall events than those described for the cropland above, yet they did 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 (and 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}. Deep water table levels at this site provided the opportunity to explore vegetation-groundwater interactions under the conditions that prevailed decades ago (Figure S1), showing that during the active season forests can keep groundwater levels "at bay" even at 10 metres of depth. The fact that the forest site represents an isolated relict within a vaster cropland matrix explains its seasonal level recovery but suggests that a widespread forest cover, like the one hosted by the catchment before the onset of agriculture, could have sustained deep groundwater consumption and levels even under occasional recharge events.

3.2 | Stream flow and yield

Periodic baseflow measurements revealed a consistent seasonal patterns mirroring those described for groundwater levels with the exceptions of the newest and most deeply incised stream (Figure 7). Baseflow was highest in the dry (and cold) season and lower flow in the rainy (and warm) season at all sites (−31 to −50% in summer compared to the rest of the year, Table 1) except Site 2, where riparian consumption is less likely given the depth of the incision. In contrast, the most intense seasonal fluctuation were seen at Sites 3 and 5 (running dry in February 2020), which had shallow incisions and a large fractions of their trajectory surrounded by wetlands (Table 1).

Interannual baseflow were also indicative of incision effects. Measurements obtained before and shortly after the last erosion episode showed how streams at Sites 1, 2, and 3 gained flow while the stream at Site 7, which was flanked by those at the first two sites, got completely dried out after being a high-yielding stream (Figure 7, Table 1). Combined with water table observation at site B, this switch in stream dominance suggests competition of neighbouring incisions

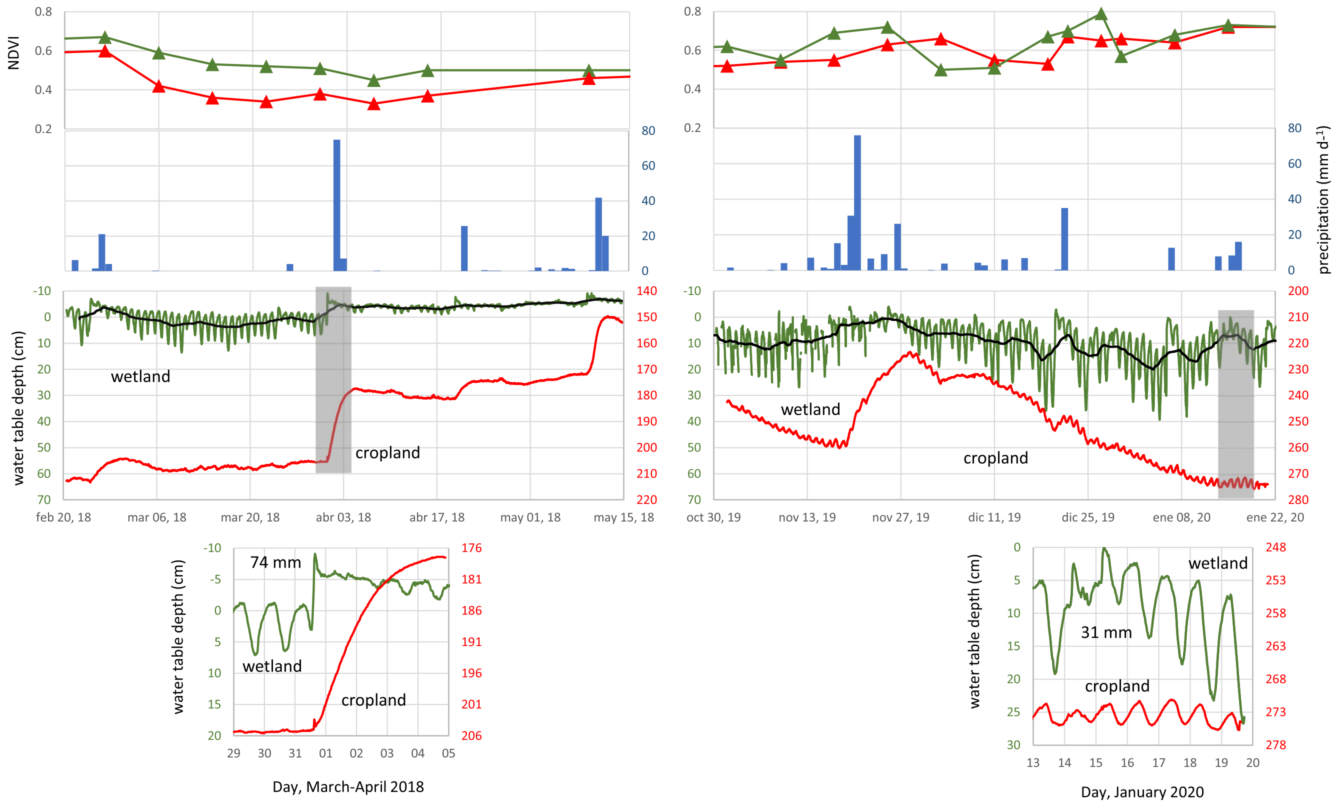

FIGURE 5 Vegetation greenness, precipitation and water table depth dynamics for two periods of 84 days with contrasting hydrological conditions (recharge vs. discharge) at site. (a) Greenness is represented by an 8-day MODIS product, precipitation was recorded at the site and water table levels were measured with pressure transducers. The absolute elevation of the ground is ~2.4 m higher in the cropland than in the wetland. Note the colour-coded numbering in the *Y* axis matching the line colour of each stand (green = wetland, black = 5-day moving average in wetland, red = cropland). Grey zones represent the subperiod zoomed at the bottom

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 (-23 L s^{-1} per year between November 2016 and August 2020, $r^2 = 0.60$, $p < 0.01$). This may reflect the gradual reduction of hydraulic gradients at the sides of the stream hinted by groundwater level measurements (Figure 4).

Stream baseflow takes away approximately a 3% of rainfall inputs in the El Morro catchment with yields being higher in the most incised sub catchments. Baseflow 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 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 (Supporting Information).

3.3 | Ecosystem activity

Over the last two decades of high hydrological changes, different greening patterns were observed for natural and cultivated vegetation, with most positive changes found for forest relicts followed by grasslands, pastures and agricultural crops showing slightly negative trends (Table 2). These contrasts suggest a regulating capacity (negative feedback) of evapotranspiration over rising water tables for native but not agricultural covers. Increased MODIS NDVI 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 versus croplands (Table 2).

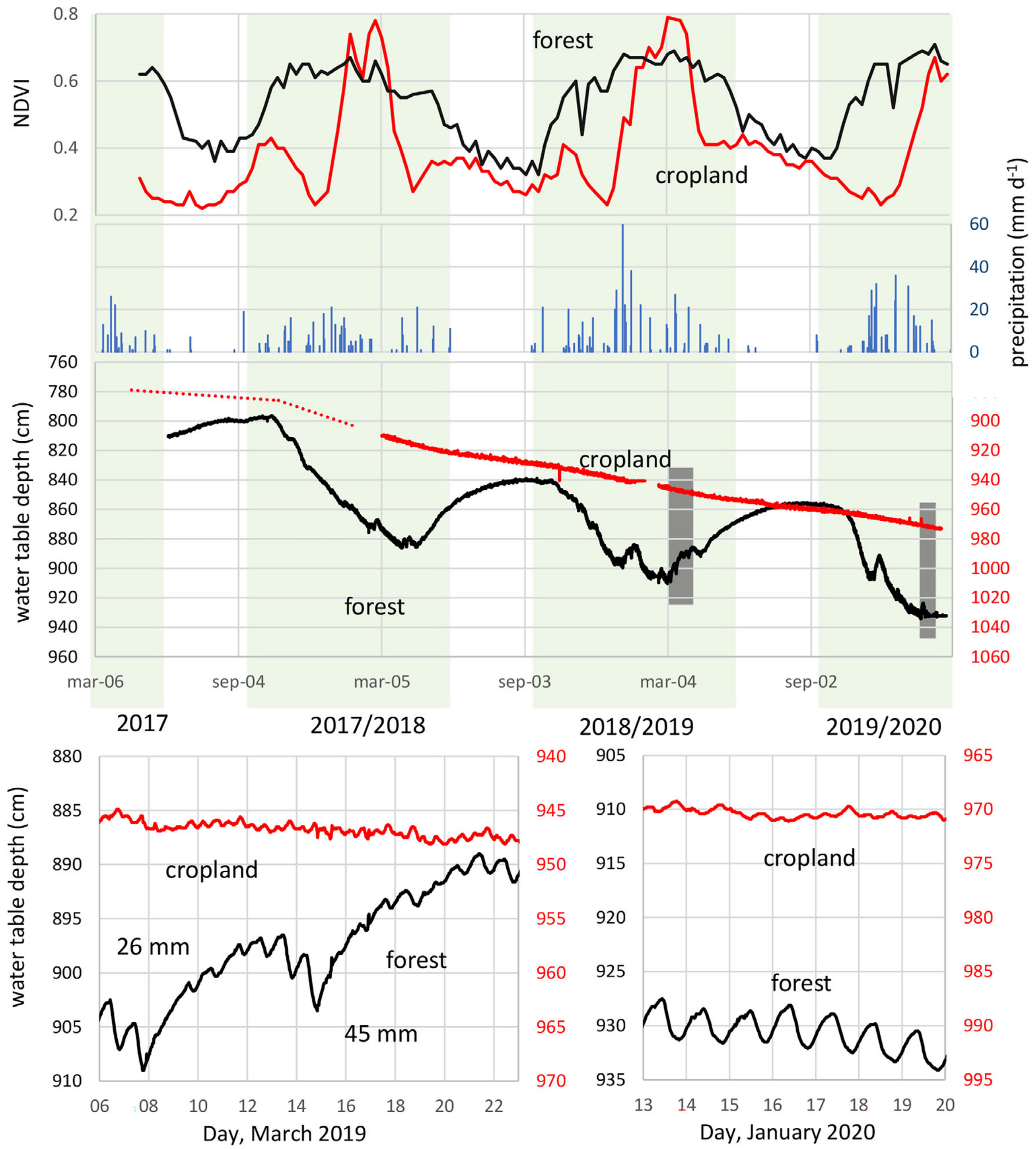

FIGURE 6 Vegetation greenness, precipitation and water table depth dynamics for the whole study period in neighbouring wells at site C (cropland and forest at position 2). Greenness is represented by an 8-day MODIS product, precipitation was recorded at "coronel Alzogaray" meteorological station, 15 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 colour-coded numbering in the Y axis matching the line colour of each stand (black = forest, red = cropland). The absolute elevation of the ground is ~1 m higher in the cropland than in the forest. Light grey bands depict each growing season while darker grey bands represent the subperiod zoomed at the bottom

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 4 years later. The drying wetland (Site B) had a high greenness that matched that of forests until 1 year after the new incisions drained the area. After that episode, its greenness dropped steadily for three consecutive years approaching levels that are close to those in the recovering sediment deposits (Figure 8).

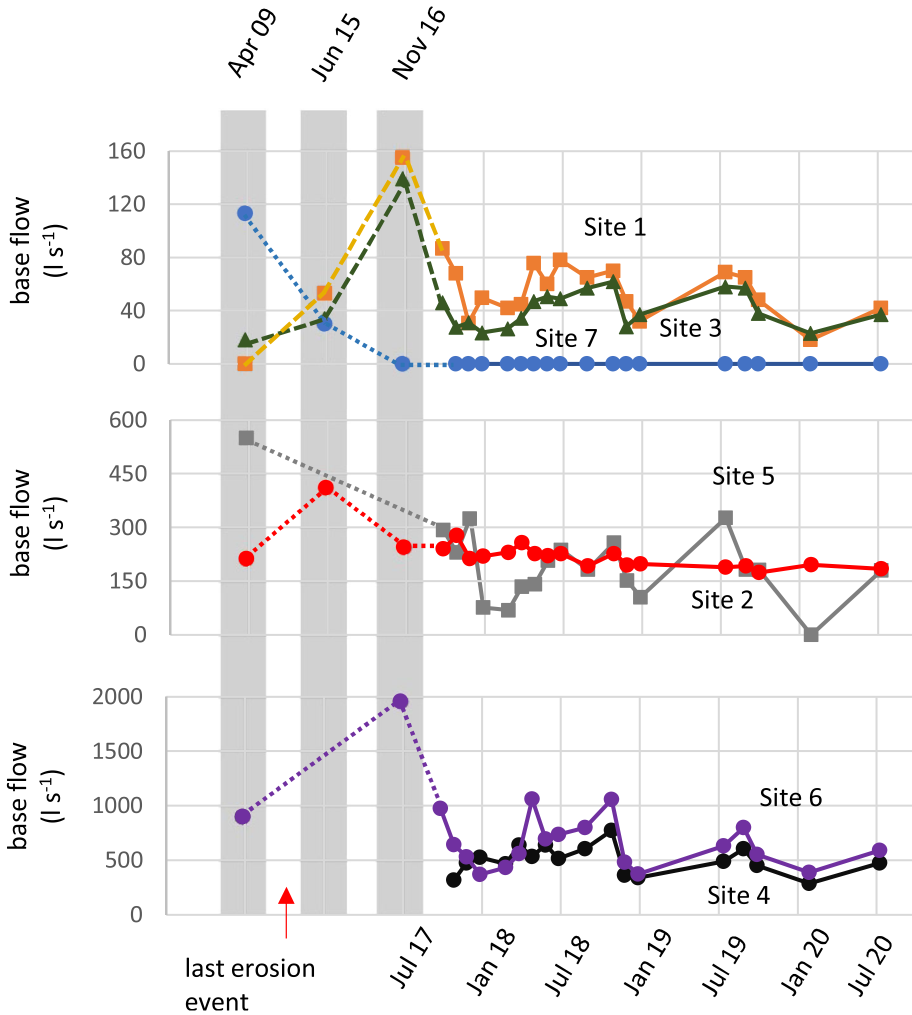

FIGURE 7 Base flow at different locations within the El Morro catchment. Grey areas depict isolated measurements before the continuing monitoring program started. Site location and baseflow synthesis are presented in Figure 2 and Table 1

TABLE 2 Greenness trends derived from MODIS data for the El Morro catchment

Vegetation type	NDVI Mean	NDVI Interannual SD	Area %	Decadal NDVI shift % Change 2010s vs. 2000s	Positive linear trend: Significant pixels %	Positive linear trend: Slope Units 10^{y-1}	Negative linear trend: Significant pixels % Pixels	Negative linear trend: Slope Units 10^{y-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

Note: 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 ($p < 0.05$).

4 | DISCUSSION

While part of the intense hydrological changes displayed by the El Morro catchment, such as rising groundwater levels and wetland emergence are repeating trends observed elsewhere in the plains of Argentina and other deforested dry regions of the world, the rapid geomorphological transformation brought by groundwater sapping is relatively unique and introduces quests about its causes, conditioning factors, and future trends. Shifts from native forests, grasslands and planted pastures to continuous rainfed annual crop cultivation resulted into more positive water balances triggering water table rises in Argentina (Alsina et al., 2020; Giménez et al., 2016, 2020; Kuppel et al., 2015; Nosetto et al., 2015), matching similar ecohydrological transitions documented in dry farmlands of North America, Australia

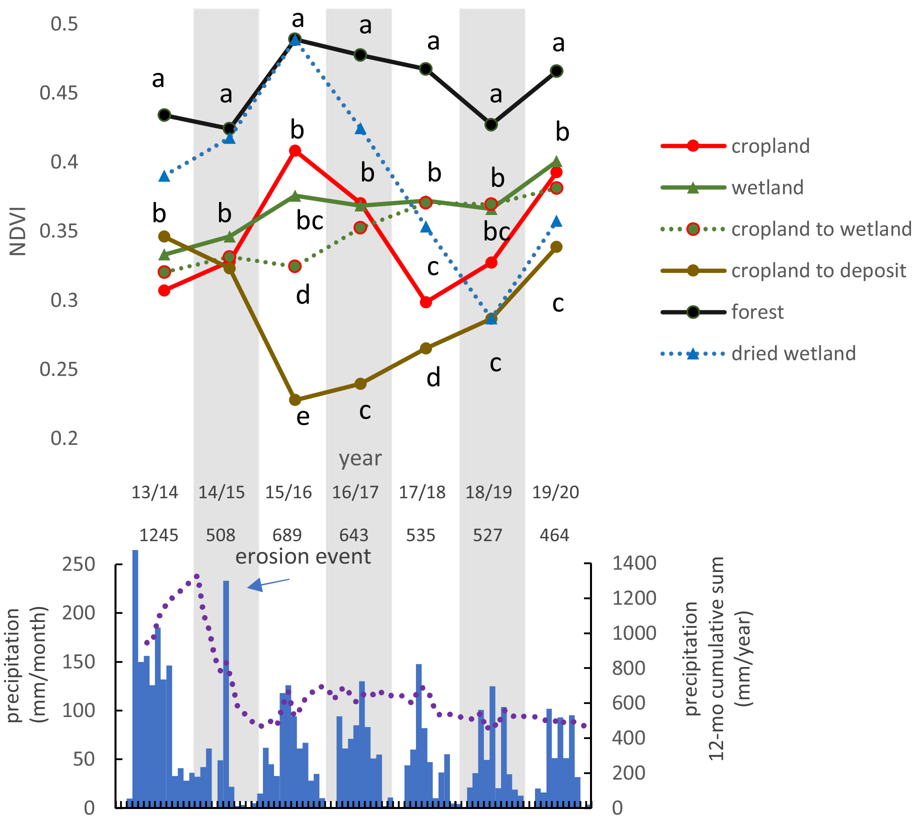

FIGURE 8 Greenness trends at sites with contrasting vegetation types/trajectories in El Morro catchment. NDVI from Landsat imagery for areas occupied since the beginning of the period by forests ($n = 11$), croplands ($n = 16$), and wetlands ($n = 20$) where compared with areas experiencing the transition 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

and Africa (George et al., 1997; Leblanc et al., 2008; Scanlon et al., 2005). Catchment studies have shown how transitions between forested and herbaceous vegetation have a strong impact on stream flow, particularly in dry regions (Farley et al., 2005; Jobbágy et al., 2013). While tree expansion over previously tree-less dry watershed has been shown to eliminate permanent streamflow completely in several cases (Farley et al., 2005; Le Maitre et al., 1999), streamflow initiation following the opposite transition (i.e., forests to tree-less conditions), as it happened in the El Morro catchment, has not been reported to our knowledge.

The unusually rapid and pronounced sapping process at the El Morro catchment, which had no precedents throughout the Holocene (Tripaldi & Forman, 2016), is paralleled currently at smaller scales in neighbouring watersheds around San Luis. In another agricultural hotspot in a previously forested piedmont loessic plain located 600 km north of our site, sapping and piping processes have been documented recently (Pereyra et al., 2020). These novel geomorphological features suggest that the young unconsolidated loessic sediments of central Argentina may be particularly prone to collapses, particularly when overlaying slightly tilted bedrocks at the contact between plains and mountain systems. They also indicate that the rapid modern land use changes in this context have likely pushed water storage beyond the threshold required to trigger sapping erosion and stream formation for the first time since the upper aeolian mantle was deposited. Coarse aeolian substrates host sapping streams in other region of the world (Devauchelle et al., 2012; Guhman & Pederson, 1992; Yang et al., 2015) and may develop them catastrophically as suggested by paleo-environmental data in the Hunshandake dunes of China, where groundwater-fed vegetation (and evapotranspiration) declined rapidly 4000 years ago following the onset of sapping incisions of uncertain triggers (Yang et al., 2015). Groundwater-mediated links between land ecosystems and streams can operate in the opposite direction, favouring the former. This has been clearly evidenced by the effects of massive groundwater withdrawals for irrigation on the baseflow of streams in sandy landscapes of Nebraska (Hobza & Schepers, 2018). At El Morro, we show that the subtle but cumulative effect of dryland agriculture on the water balance is a likely cause of sapping events and that these in turn can influence groundwater uptake by plants. In this regard, revising the five mechanisms outlined above (Figure 1) helps to integrate this complex and interplaying effects.

4.1 | Plants versus 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 helped to address how plants and streams may concurrently 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 1970s in El Morro (Figure S1). Diverse sources of evidence point to the absolute suppression of recharge and, hence, the full inhibition of stream baseflow in dry 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 (Amdan et al., 2013; Jayawickreme et al., 2011; Santoni et al., 2010 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, this mechanism has been relaxed thanks to the reduced capacity of annual crops to exhaustively use vadose zone moisture (George et al., 1997; Giménez et al., 2016; Peck & Williamson, 1987; Santoni et al., 2010). 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 favour localized groundwater use in lowland areas or incipient streams by the waterlogging-tolerant species that occupy them (Mechanism 2, Figure 1), contact zones can be widespread enough to favour a more distributed use of groundwater in the whole catchment (Mechanism 3, Figure 1). In the case of the first of these two mechanisms, its onset is evidenced by the progressive appearance of wetland communities displaying an intense groundwater consumption (Figures S1, S5 and S8) as well as by stream baseflow seasonality accentuating in segments with shallow incisions and more flanking wetlands (e.g., Upper Rio Nuevo at site 1 vs. La Guardia at Site 5 in Table 1). Assuming that summer baseflow drops reflect the effect of this mechanism it would have accounted for 48 and 20% stream flow reduction in summer and the whole year, respectively, at the closure of the catchment (Table 1). This mechanism may not only account for groundwater feeding streams but for direct streamflow consumption, yet, disentangling these two sources has proven difficult (Bowling et al., 2017; Dawson & Ehleringer, 1991).

Distributed uptake of groundwater by vegetation was confirmed at the El Morro catchment too, being highly dependent on vegetation type. Forest relict created a seasonal water table depression zone that was reverted every winter when consumption ceased. Across the semiarid and subhumid loessic plains of Argentina, Hungary and China tree stands within herbaceous matrices have often shown intense groundwater use and local depression (Giménez et al., 2016; Jobbágy & Jackson, 2004; Nosetto et al., 2013; Tóth et al., 2014; Yasuda et al., 2013). We speculate that a full forest coverage in these landscapes would cause perennial depressions as the sources for lateral supply (fed by the recharge of adjacent croplands and wetlands) disappear. Estimates of groundwater depletion rates derived from diurnal water table depth fluctuations suggest potential depression of 4–5 metres per year after the saturated supply manifested in overnight rises is considered (3.1 cm d^{-1} after Loheide et al., 2005, Figure 6). Explicit "biodrainage" reclamation initiatives worldwide show sustained water table depressions (Singh & Lal, 2018). Important in this consideration is the fact that distributed saturated uptake creates opposing feedbacks on groundwater levels, as hinted by tree ring observations for the same *Prosopis* species at another close site (Bogino & Jobbágy, 2011), where rising water tables boosted tree growth first (negative feedback) but caused their massive waterlogging die-off afterwards (positive feedback). At the El Morro catchment forest greening suggest the prevalence of the first feedback so far. Rather than assuming rigid and additive effects of vegetation types in the catchment, the fact that Mechanism 3 could 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.

The developing catchment of El Morro showed how streams can increase their share of saturated water flow in detriment of that used by plants (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, Figure 4), but hampered saturated uptake (mechanisms 2 and 3, see wetland and cropland at Site B, Figure 4; drying wetland, Figure 8) favouring their baseflow (positive feedback). Yet, an approaching saturation in the density of streams is hinted by their regular spacing and the observed episode of rapid "stream piracy" (Calvache & Viseras, 1997), suggesting that they may be too close to coexist (see the 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; Gleeson et al., 2011; Haitjema & Mitchell-Bruker, 2005). A simple exercise with one of these models suggests that the stream network is re-establishing a recharge-controlled equilibrium in the La Guardia and Río Nuevo sub catchments, but is still far from it in the Quebrachal sub catchment (Table 2, Supporting Information).

The final mechanism favouring 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 but had strong and long-lasting effects (Table 2, Figure 8). Likely negligible in terms of its direct contribution to baseflow yields, this mechanism can create ideal conditions for repeated sapping erosion events as sustain saturated conditions along the present and potentially expanding stream path, favouring run-off and erosion (see Williams et al., 2019 for a useful analogy in a tiled landscape).

5 | CONCLUSION

This catchment study showed that under continuously water-limiting climatic conditions (precipitation < potential evapotranspiration) the full suppression of stream flow sustained by native vegetation for decades or even millennia was relaxed after the establishment of croplands. Since then, a self-reinforcing process of stream development by sapping has coexisted with the regulatory effect of increasing water use by native vegetation relicts and novel wetlands in the landscape. Groundwater level changes are the core of these transformations. Whether streamflow or evapotranspiration will increase in coming decades at El Morro remains a complex issue given the mentioned feedbacks. Acknowledging the non-additive and non-linear effects of vegetation and streams on groundwater is crucial to develop successful hydrological models in dry sedimentary catchments, particularly under land use and climate changes that push them into novel stages. Transformations at El Morro show that these interactive effects can change the partition of water between evapotranspiration and streamflow, even to the point of creating streams where they did not exist before. While extreme and rare, events at the El Morro catchment cast light on general mechanisms governing water partitioning that tend to be overlooked when ecological and geomorphological changes occur at slower and mismatching paces.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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