Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: www.tandfonline.com/journals/thsj20

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To cite this article: H.F. Aristizábal & P. Martínez-Santos (2019) An iterative technique to delineate protection buffers for wetlands in regions subject to intensive groundwater pumping, Hydrological Sciences Journal, 64:8, 885-899, DOI: 10.1080/02626667.2019.1610564

To link to this article: https://doi.org/10.1080/02626667.2019.1610564

Published online: 14 May 2019.

HYDROLOGICAL SCIENCES JOURNAL
2019, VOL. 64, NO. 8, 885–899
https://doi.org/10.1080/02626667.2019.1610564

An iterative technique to delineate protection buffers for wetlands in regions subject to intensive groundwater pumping

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ABSTRACT
Wetlands are vulnerable to groundwater extraction, which has proven detrimental to aquatic ecosystems around the planet. As wetlands rank among the world's most endangered ecosystems, versatile strategies are required to protect them. This paper provides a modelling-based method to delineate protection buffers in wetlands subject to groundwater extraction. The technique is sufficiently flexible to cater to a wide variety of conditions, and simple enough to underpin management decisions on a daily basis. A numerical model is used to obtain a map of the critical rate of groundwater abstraction, based on the distance between wetlands and suitable discharge thresholds. The outcomes determine the allowed pumping rate at any point under steady and transient-state conditions. A new iteration is developed every time a new pumping allowance is made. This procedure is demonstrated by means of hypothetical scenarios, as well as by a case study application in the Valle del Cauca region, Colombia.

ARTICLE HISTORY
Received 16 April 2018
Accepted 13 March 2019

EDITOR
S. Archfield

ASSOCIATE EDITOR
E. Rozos

KEYWORDS
wetland buffer; overdraft; groundwater-dependent ecosystems; intensive pumping; Modflow

1. Introduction

Wetlands rank among the world's most threatened ecosystems. Current estimates suggest that approximately two-thirds of the world's wetlands have disappeared since 1900 (RWC 2015), this trend being more acute in the case of inland wetlands than in coastal ones. Some authors point out that the loss may have been as high as 87% since 1700, and that the rate of wetland loss has accelerated considerably during the 20th and early 21st centuries (Davidson 2014).

The disappearance of wetlands can be attributed to a combination of anthropogenic impacts, including changes in land use, water diversions, infrastructure development, contamination and climate change. Groundwater-dependent wetlands are no exception. The reliability of aquifer resources during droughts, together with the increasing availability of affordable drilling and pumping techniques, have caused intensive groundwater use to experience a spectacular growth in the last few decades (Llamas and Martinez-Santos 2005). This is particularly true of many arid and semiarid regions, where the coexistence of intensive pumping for irrigation with groundwater-dependent aquatic ecosystems has proven detrimental to the welfare of numerous springs and wetlands (IWRRI 1996, Martínez-Santos *et al.* 2008, Castaño-Castaño *et al.* 2018).

The notion of groundwater-dependent ecosystems encompasses all those ecological communities that are maintained by direct or indirect access to groundwater, and that rely on the flow or chemical characteristics of groundwater for some or all of their water requirements (Rohde *et al.* 2017). This presents a two-fold implication. First, it recognizes that the aquifer is an important contributor to the maintenance of the wetland's hydrological regime; and second, it means that a change in the quality or quantity of groundwater will necessarily have a major effect on its state (Froend *et al.* 2016). Groundwater-dependent ecosystems not only include aquifer discharge areas above the surface (rivers, springs, wetlands), but also underground environments such as caves, or ecological communities underpinned by shallow groundwater.

The delicate balance between socio-economic development and the conservation of groundwater-dependent ecosystems calls for adequate protection strategies (Rohde *et al.* 2017). The academic literature showcases a series of methods for delineating buffer zones in groundwater bodies. Most of these aim at protecting groundwater quality near drinking supply wells and have been incorporated to legislation in many countries (IGME 2003, Strobl and Robillard 2005).

Wellhead protection methods may be extrapolated to wetland conservation in areas where the wetlands are exposed to inflows of contaminated groundwater. Different approaches are however needed whenever groundwater-dependent wetlands are threatened by intensive pumping. In these cases, the hydraulic gradient is reversed, thus preventing contamination to a large extent. The velocity field and its associated uncertainties may also turn out to be relatively unimportant. Thus, water quantity becomes a more pressing concern than water quality, and determining how much water can be pumped at a given distance from the wetland without causing a negative effect becomes the core issue.

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Methodological precedents for wetland protection in areas subject to intensive groundwater pumping are limited. This can be attributed to the fact that environmental conservation is a newer concern than the quality of drinking supplies, as well as to the complexity and diversity of the wetland concept (Tomlinson 2011, Gannon 2014). Thus, there is no widely accepted standard for the delineation of wetland protection buffers. Instead, there is a variety of methodological proposals with a strong ad hoc component, most of which basically aim at establishing case-specific thresholds for adequate wetland functionality.

For instance, Bekesi and Hodges (2006) developed an analytical approach that takes into account extraction rates and the distance between the well and the wetland in order to establish the influence radius of the former (i.e. the distance at which drawdown can be considered negligible). Other authors focus on rules of thumb to facilitate management decisions. Thus, Williams *et al.* (1995) developed a "ten-percent rule" based on the study of a set of wetlands in East Anglia, United Kingdom. The rationale behind this approach was to limit the change in head to a certain percentage of the range between mean summer water levels and minimum measured levels in the underlying aquifer. These authors found that, in general, adverse effects could be associated with drawdowns that exceeded 10% of the difference in mean and maximum summer piezometric heads in the aquifer. Along the same lines, Kimberley and Coxon (2013) proposed a system based on expressing the allowable pumping rates as a percentage of aquifer recharge, while Aldous and Bach (2014) developed quantitative relationships between the position of the water table, wetland indicator plant species and the process of peat development to propose groundwater withdrawal thresholds in areas of Oregon.

Over time, numerical approaches have become increasingly relied upon by hydrogeologists and water managers. This is largely due to the versatility of numerical models, which allow for the rapid simulation of a wide range of hydrological scenarios. Thus, Jaros (2015) developed a modelling-based approach to quantify surface-groundwater interactions in Finnish wetlands, justifying the validity of the model as a tool for environmental protection. Similarly, Brown and Hamman (2000) tabulated wetland protection buffers based on distance and hydraulic conductivity, using the Modflow code. Aristizábal *et al.* (2015), in turn, developed a method to delineate protection buffers in Colombian rivers, taking into consideration the effect of horizontal anisotropy.

Few studies deal with the problem of delineating wetland protection areas to prevent the effects of pumping. Even fewer attempt to develop generic methods that can be extrapolated to a wide variety of hydrogeological settings. Within this context, this paper presents an iterative technique to establish wetland protection buffers in areas subject to groundwater pumping. The goal is to provide a method which is (a) flexible enough to deal with different hydrogeological conditions and varying pumping patterns; (b) sufficiently sophisticated to provide accurate results; and (c) simple and agile enough to underpin management decisions on a regular basis.

2. Methods

2.1. Conceptual background

Groundwater systems naturally behave in a state of dynamic equilibrium. This means that, over a sufficiently long period, recharge from various sources will be balanced by discharge through the aquifer's natural outlets, including groundwater-dependent ecosystems such as springs and wetlands. Under these "steady-state" conditions, discharge and groundwater level can be expected to remain roughly constant, although small fluctuations will take place as a result of the alternation of wet and dry periods (Fig. 1). The system will remain close to full storage.

Groundwater pumping disturbs the natural equilibrium. At first, pumping removes water from the immediate vicinity of the well, thus lowering the water table and generating

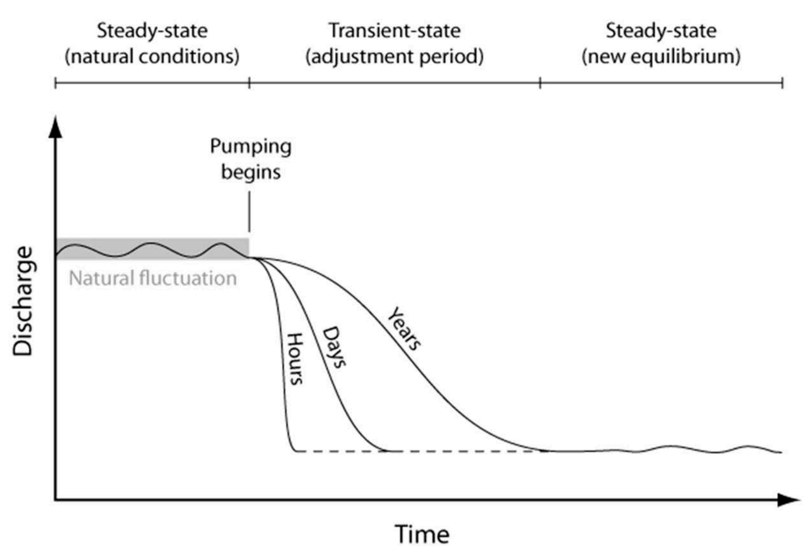

Figure 1. Groundwater discharge through a wetland. In unperturbed conditions, there is a semi-steady state whereby wetland discharge oscillates based on the natural fluctuation of the water table. If pumping begins in the vicinity of the wetland, discharge can be expected to decrease gradually over time. This process may take hours, days or years until a new equilibrium is reached. Under the new regime, wells capture groundwater discharge partially or totally.

a concentric flow towards the point of extraction. The area of influence, i.e. the cone of depression, continues to grow as water is drawn to the well from further away. A new equilibrium is reached when the capture area is large enough for the system to counter the pumping rate. At this point, the system will reach a new steady-state and the cone will no longer grow.

Extractions change the natural water balance by offsetting aquifer recharge, either partially or totally. Thus, less water will be available to leave the system through its natural outlets. In areas subject to intensive pumping, drawdown cones may reach gaining surface water bodies, turning them into net losers. This generates an induced recharge to the aquifer at the expense of groundwater-dependent ecosystems, which may dry up as a result.

2.2. Objective and pre-requisites

While any extraction is ultimately detrimental to the welfare of wetlands, it must also be recognized that a zero-pumping policy will often be unfeasible (Sophocleous 2000). Thus, the ultimate goal of any attempt to balance pumping with wetland discharge is to determine how much water can be pumped from an aquifer without causing adverse effect on its groundwater-dependent ecosystems. In the case of this research, this translates into a series of critical pumping rate (CPR) maps, which must be updated iteratively every time a new extraction allowance is granted.

There are two pre-requisites to mapping pumping buffer zones. The first one consists in picking a suitable hydrological indicator. This will typically be the minimum required groundwater discharge through the wetland, the maximum allowable drop in piezometric heads in its immediate vicinity, or both. The former has been selected for demonstration purposes due to the ease with which it can be modelled. A number of techniques exist to quantify the interaction between aquifers and surface water bodies, including direct measurements, tracer methods, mass-balance approaches, Darcian techniques and heat transport (Table 1). In practice, establishing a suitable threshold of wetland discharge may be far from straightforward. This is largely due to the fact that wetlands are complex ecosystems and that groundwater discharge is only one of many factors affecting the ecological equilibrium (Eamus *et al.* 2006, EC 2012, Johansen *et al.* 2017). The work of interdisciplinary teams will most likely be needed, and decisions may ultimately rely on expert judgement (Whiteman *et al.* 2010). Hence, providing guidance as to how to compute these thresholds is considered beyond the scope of this paper.

The second pre-requisite is the existence of a calibrated groundwater flow model. This is to be used to predict the impact of extractions on wetland discharge. Model calibration should not only reproduce the observed heads, as these may often be obtained through different combinations of boundary conditions and hydrodynamic parameters (Evers and Lerner 1998, Levy and Ludy 2000). It should also be ensured that it is able to reproduce the changes in other important variables, most importantly discharge rates. Whenever possible, the modelled area should be large enough to prevent boundary effects.

Once these two pre-requisites are met, the technique consists on the application of the numerical model to develop a map of critical pumping rates across the aquifer (Fig. 2).

Table 1. Techniques for the quantification of surface-groundwater exchange flows. Modified from Kalbus *et al.* (2006).

Group	Instruments	Scale	Some references
Direct measurements	Seepage-meters	cm to m	Lee (1977), Lee and Cherry (1978), Landon *et al.* (2001)
Heat transport	Temperature profiling Heat balance	cm to m	Conant (2004), Anderson (2005), Duque *et al.* (2010)
Darcian methods	Piezometric analysis Flow nets Pumping tests	cm to km	Freeze and Cherry (1979), Conant (2004), Martínez-Santos *et al.* (2013).
Mass-balance approaches	Differential gauging Hydrograph separation Environmental tracers	m to km	Chow (1964), Harvey and Wagner (2000), Carey and Quinton (2005)
Numerical techniques	Numerical models	cm to km	Aristizábal *et al.* (2015), Martínez-Santos *et al.* (2010)

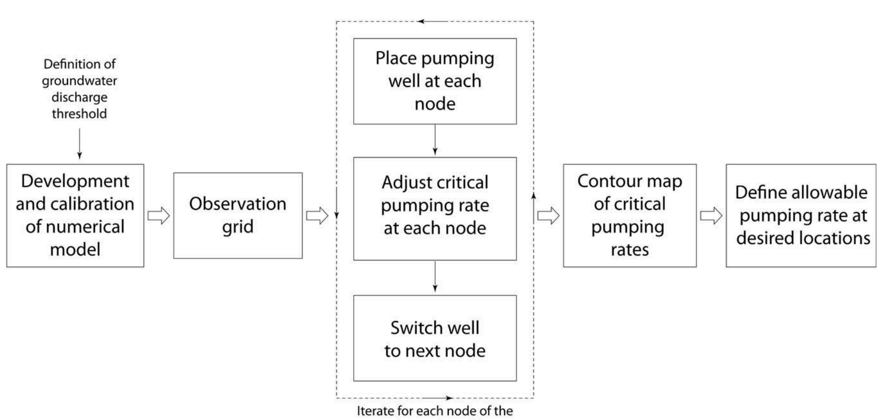

Figure 2. Methodological overview.

This is best illustrated by means of a series of hypothetical scenarios, which will be discussed later on.

2.3. Modelling approach

Ideally, wells should be drilled and pumping rights allocated so that there is no detrimental effect on groundwater-dependent wetlands. Unfortunately, this is not always possible. The next best strategy is to ensure that pumping rates are managed so that aquifer discharge through the wetland does not fall below a given threshold. Holding all other factors equal, wells located closer to the wetland can be expected to have a more immediate impact than those located further away. This suggests, first, that there is a limited amount of groundwater that can be pumped from the system, Q_s; and, second, that this amount is constrained by the distance between the well and the wetland. An immediate corollary is that the value of the available resource, Q_s, is non-unique, as it will depend on the spatial distribution of wells in each specific setting.

Since the key variables involved are spatially-distributed, this approach assumes that the allowable groundwater extraction rates can be mapped. In practice, the procedure is implemented as follows (Fig. 2):

(i) A grid of observation points is established around the wetland cells of the model. The grid should cover a radius such that all pumping effects on the wetland can be taken into account (typically several kilometres). The grid may adopt the shape of a cross, but may also be radial, rhombic or square. This choice does not matter provided that the spatial distribution of the nodes is dense enough to minimize the uncertainty of the geostatistical interpolation to be carried out later on. The optimal distance between nodes is case-specific and need not be constant.

(ii) A pumping well is placed on the first node of the grid. The pumping rate for the well is adjusted so that a critical value, Q_c, is obtained. The critical extraction rate, Q_c, is defined as the pumping rate that reduces aquifer discharge through the wetland to the minimum acceptable threshold.

(iii) The well is removed from the first node and placed on the next one. The above procedure is carried out again and repeated for all nodes. At the end of the process there should be a Q_c value for each one.

(iv) A critical pumping rate (CPR) contour map is made by geostatistical interpolation (typically some form of kriging) based on the Q_c values. The map represents the maximum amount of groundwater that can be pumped from any one cell in the model while keeping discharge through the wetland at an acceptable level.

The CPR map can then be used to determine sustainable pumping rates. It must be kept in mind that pumping should not be allowed to exceed the value of Q_c at the spot where the well is located, as that would cause wetland discharge to drop below the acceptable threshold.

If a user is allocated a pumping rate equal to Q_c, – that is, if the user is allowed to extract all the water that can be pumped from a given location – there will be no room left for other users. Conversely, the aquifer will remain open to new users if a pumping rate below Q_c is allocated. In that case, a new iteration of the CPR map will need to be developed. The procedure will be exactly the same, except that it will include two wells in each model run (the existing one and the one that switches from a node to the next).

The CPR map may be complemented with distance-extraction curves and capture zone analysis. Distance-extraction curves plot the maximum acceptable pumping rate at different distances from the wetland. Because aquifer properties change spatially in real life, curves can be expected to be different in each direction. On the other hand, most groundwater modelling packages allows for the delineation of capture zones, which may be useful to determine the maximum influence radii of pumping wells.

2.4. Scenario design

The above is best described through a series of concrete examples. Six hypothetical scenarios will be considered, all referring to the case of a highly-sensitive wetland located within an arid region. All six cases are deliberately uncomplicated, yet realistic. Simplicity is an advantage, for it makes it clearer how the procedure can be used to tackle the three most frequent scenarios for a water manager.

Inevitably, some figures will need to be assigned. Thus, the system will be assumed to be a rectangular 20 × 10 km sector of a large unconfined aquifer, and each cell will span a square surface area of 100 m × 100 m (Fig. 3). For simplicity the model comprises one single layer.

The northern and southern limits are no-flow boundaries, while constant-head boundaries make up the eastern and western borders of the system. Regional groundwater flow follows an east-west gradient, from a maximum elevation of 100 to a minimum 80 m a.s.l. The system is assumed homogeneous and isotropic, with an average hydraulic conductivity of 15 m/d and an effective porosity of 5%. A wetland (drain condition) is located in the centre of the aquifer. The wetland presents a square shape and takes up nine cells (9 hectares). Discharge elevation is established at 87 m a.s.l. and hydraulic conductance at 1000 m^2/d.

The first three scenarios assume steady-state conditions, i.e. wells are allowed to pump at a constant rate until the hydrogeological system reaches a new equilibrium (Fig. 1). This approach is conservative in the sense that it maximizes the potential influence of the well on the wetland. Thus, the actual impact of the allocated pumping rate can be expected to be either (a) roughly equal to the effect predicted by the model (if steady-state conditions are reached in the field); or (b) less than the effect predicted by the model (if steady-state conditions are not actually reached in the field). The following cases are considered, all of which assume heavy drought conditions (aquifer recharge set to zero).

- *Scenario A: Steady state, pristine conditions, new well.* A prospective groundwater user wishes to drill a new

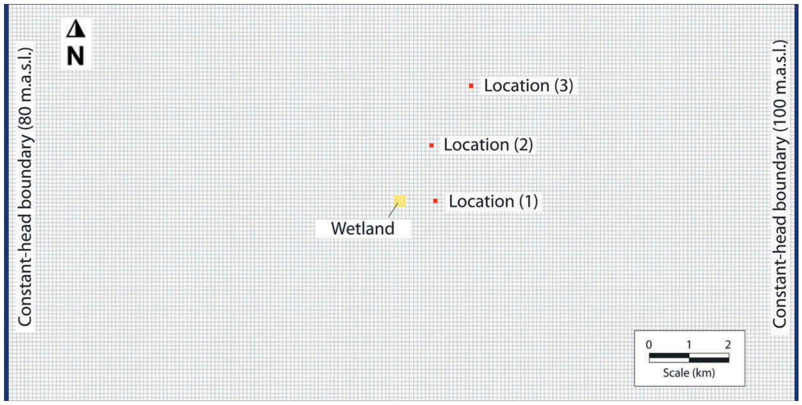

Figure 3. Hydrogeological setting of the numerical model.

Table 2. Summary of the six modelling scenarios.

Scenario	Flow regime	Objective	Comments
A	Steady-state	Establish whether a 10 L/s pumping rate is adequate. Well located 750 m to the east of the wetland (upgradient).	"Very dry" conditions. Recharge set to zero
B	Steady-state	Establish the optimal location for a 15 L/s well located to the northeast of the wetland (upgradient). The well of the previous scenario is pumping.	"Very dry" conditions. Recharge set to zero
C	Steady-state	Reduce a pumping allocation (or provide an alternative solution) for a well that is pumping 30 L/s at Location 1. No other well is pumping.	"Very dry" conditions. Recharge set to zero
D	Transient-state	Establish whether a 10 L/s pumping rate is adequate. Well located 750 m to the east of the wetland (upgradient).	Simulation runs for three "very dry" years, with recharge distributed over time
E	Transient-state	Establish the optimal location for a 15 L/s well located to the northeast of the wetland (upgradient). The well of the previous scenario is pumping.	Simulation runs for three "very dry" years, with recharge distributed over time
F	Transient-state	Reduce a pumping allocation (or provide an alternative solution) for a well that is pumping 30 L/s at Location 1. No other well is pumping.	Simulation runs for three "very dry" years, with recharge distributed over time

well approximately 750 meters upgradient (Location 1). The well is to pump 10 L/s. A CPR map is needed to establish whether this should be allowed.

- *Scenario B: Steady state, perturbed conditions, all ensuing wells*. Pumping rights were granted to the user of the previous case. Now the system is slightly perturbed by the existence of the well in Location 1. A second user wishes to drill a new well to pump 15 L/s. This may be done either in Location 2 or Location 3. The goal is to establish whether this would be acceptable.
- *Scenario C: Steady state, perturbed conditions, re-allocation pumping allowances*. The third case illustrates how to proceed when pumping rights have been over allocated and are causing an ongoing environmental damage. Scenario 1 conditions will hold, except that it will be assumed that the well in Location 1 had been given the right to pump 30 L/s under an older allocation system.

Transient-state scenarios (D, E and F) will be the same, except that the model will run for a number of years instead of running until equilibrium (Table 2). A suitable distribution of recharge over time will be set to illustrate how this influences the buffering process.

Processing Modflow Pro was used for modelling work (Chiang 2005). PMWin Pro is a three-dimensional groundwater flow and mass transport modelling package that provides a graphical user interface for the classic finite-difference Modflow code (McDonald and Harbaugh 1988), whose reliability and robustness have been tested extensively.

3. Results

3.1. Steady-state simulations

A first model run without wells reveals that the steady-state discharge through the wetland (drain) cells amounts to a little over 86 L/s. From demonstration purposes, it will be assumed that a 10% reduction of this figure is tolerable.

Figure 4 presents the CPR maps for scenarios A, B and C. The CRP contours are elliptical in shape, with a greater eccentricity in the vertical axis. The capture area around drain cells under natural conditions (i.e. prior to pumping) presents a similar arrangement (Fig. 5(a)). This configuration can be attributed to the regional flow pattern, constrained by the presence of the two constant-head boundaries.

Consider the outcomes of the first scenario. The well can be safely drilled at Location 1 because the requested pumping rate is 10 L/s and the critical pumping rate at this spot is 20 L/s. In other words, even if the well is allowed to pump until the system reaches a new steady-state, discharge through the wetland will remain above the minimum threshold. Since this well does not consume all the available resource (the required pumping rate is less than the critical rate), there will be room left for other users to drill new wells.

Scenario A assumes the hydrogeological system to be completely unperturbed. While useful for demonstration, such a context is relatively uncommon. Groundwater-dependent wetlands are often associated with a shallow water table, meaning that groundwater in these areas is easily accessible. Thus, wells can be expected to exist in most circumstances. This is

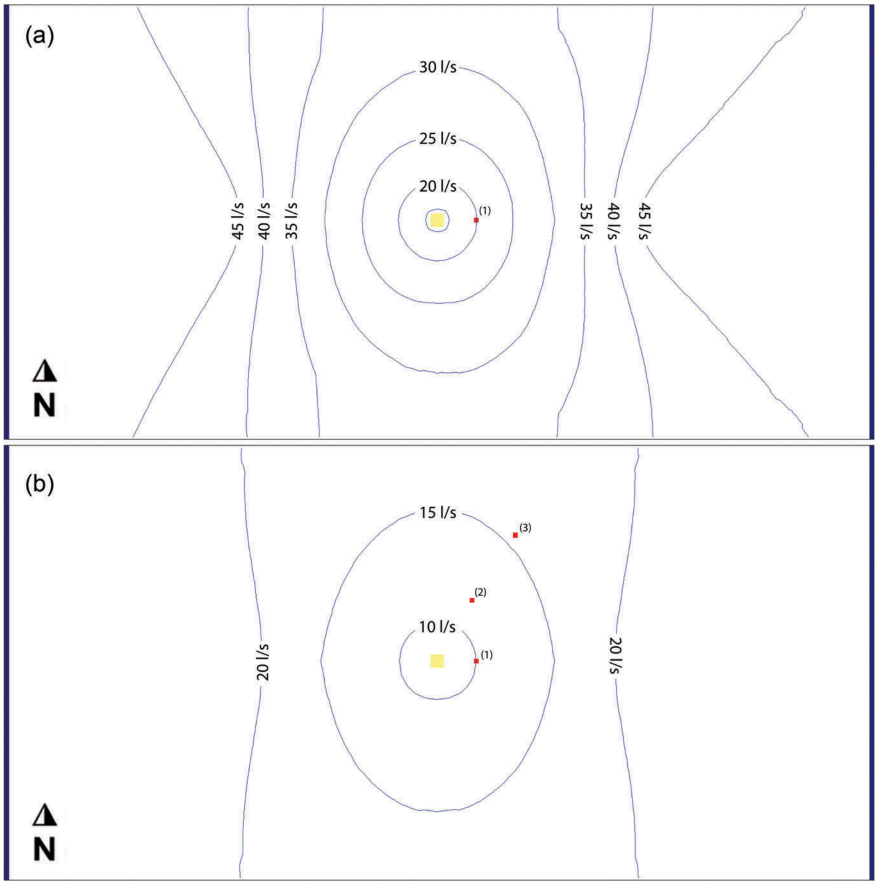

Figure 4. Spatial distribution of protection buffers under steady-state conditions. (a) Critical pumping rate map for scenarios A and C. (b) Critical pumping rate map for Scenario B.

the case in scenarios B and C. Under scenario B, the CPR map of Figure 4(a) is no longer valid because the well in Location 1 is already taking up some of the available resource. A second map needs to be developed to establish how much groundwater is left for prospective users to pump (Fig. 4(b)). In this second iteration, all contour values will necessarily be lower than the previous case. It is observed that Location 2 is inappropriate to pump 15 L/s because it falls in between the 10 and 15 L/s contour lines. In contrast, Location 3 may be considered suitable and will still leave the system open to newer users.

As more wells come into the picture, the critical pumping rate in the immediate vicinity of the wetland gradually becomes lower. Thus, locations close to the wetland cease to be attractive for users, who will naturally favour those located further away whenever possible.

Scenario C considers a situation where there is a need to moderate an existing allowance. Well 1, located 750 m to the east of the wetland, is the only pumping well in the area and is allowed to extract 30 L/s. Based on Figure 4(a), this exceeds the available rate for the spot where it was drilled. The map can be used to determine that this user should either reduce the pumping rate to 20 L/s or drill a new well beyond the 30 L/s contour line. In the latter case, the pumping rate could be split between the two, and a new iteration of the map could be developed to establish the most advantageous distribution.

Distance-extraction curves may also be computed. These represent the maximum amount of groundwater that can be pumped at a given distance from the wetland while simultaneously maintaining groundwater discharge above the minimum threshold. Distance-pumping curves may contribute to facilitate the process of determining the available pumping rate when contour lines in the CPR map are drawn far apart from each other. However, it must be kept in mind that pumping allowance presents a directional component, which means that a curve needs to be developed for each direction (Fig. 6).

The results can also be viewed in terms of capture zones (Fig. 5). A capture zone consists of the up-gradient and down-gradient areas that drain into an aquifer outlet (i.e. the wetland or the pumping well). Capture zones are primarily useful in assessing pollution risk. This is because those activities which take place within the capture zone are likely to modify groundwater quality, which will in turn translate into contamination at the outlet. However, the capture zone approach is of limited value for the purpose of assessing the impact on groundwater discharge. Under steady-state conditions, a well may reduce discharge through the wetland even if it is located outside the capture zone. Indeed, under a perturbed equilibrium, the drawdown cone will affect the hydrological balance of the aquifer, consuming a part of the water available for ecosystems. In addition, it will affect flow patterns and mitigate the difference in piezometric heads

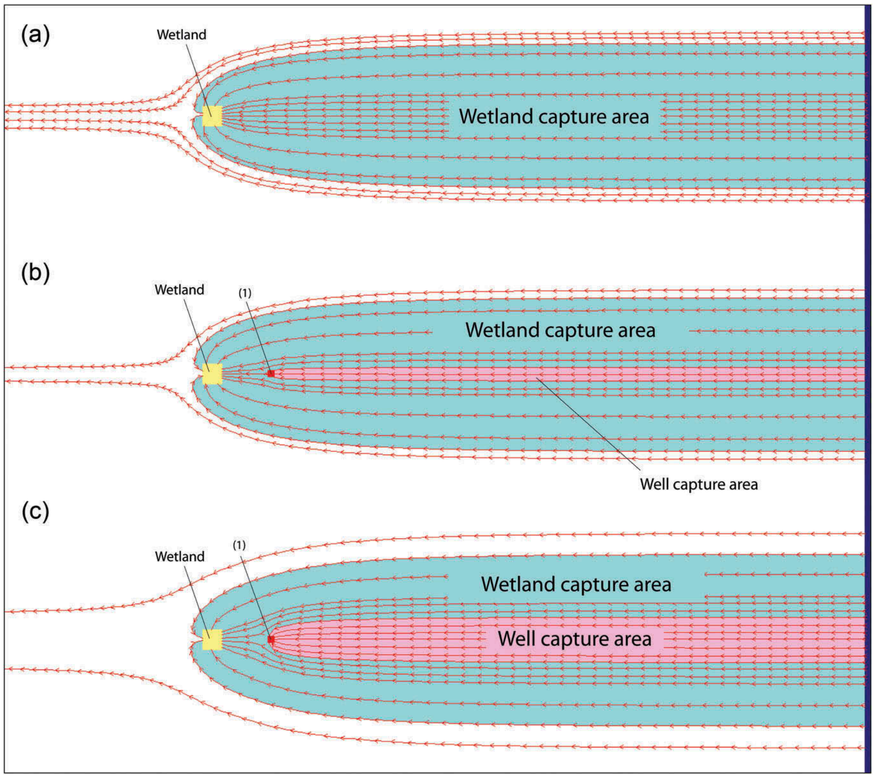

Figure 5. Wetland and well capture areas under natural conditions and scenarios A and C. (a) Wetland capture area under natural conditions. (b) Wetland and well capture area if the well at Location 1 pumps 10 L/s (i.e. below the critical pumping rate). (c) Wetland and well capture area if the well at Location 1 pumps 30 L/s (i.e. exceeding the critical pumping rate).

between the wetland and the aquifer. This explains why, in the case at hand, wells located several kilometres to the west, north and south of the wetland can be expected to cause a reduction in groundwater discharge without having a visible impact on its natural capture zone.

3.2. Transient-state simulations

An aquifer subject to extractions may take a long time to reach a new steady-state. This means that, in reality, pumping might have stopped long before the cone of depression reaches the fringes of a groundwater-dependent ecosystem. A first transient-state simulation was carried out to establish how long the effects of pumping would take to reach the wetland for the case of scenario A. Figure 7 shows the time needed to reach a new steady state, which coincides with a reduction of 10% of the natural discharge ("tolerable discharge threshold"). The curves represent how discharge evolves when pumping the critical rate at distances of 50, 1500 and 5000 m from the wetland. It is observed that reaching the new steady-state, i.e. the moment of maximum decline, takes more than 10 years in all cases. It is however observed that most of the effect occurs in the early stages: about 75% of the allowed capture takes about one month, a year and a half and a little over two years, respectively.

Different authors explain that pumping effects may take hundreds or thousands of years to be fully felt (Balleau and Mayer 1988, Sophocleous 2000). This suggests that establishing pumping rules based on the assumption of a new steady-state may be excessively stringent on groundwater users. Transient-state buffering allows for a more versatile approximation to the problem, but require more data and a forecast of future conditions. Both recharge and pumping need not only be distributed in space, but also in time. Furthermore, the natural and acceptable discharge thresholds should refer to seasonal fluctuations under a worst-case scenario, i.e. a sufficiently long period with "very low" aquifer recharge. A conservative approach to establishing discharge fluctuations in natural conditions could be a run of the calibrated model with no wells and a recharge pattern equivalent to the driest period on record. Then, the tolerance threshold could be established based on the available information. With the previous scenarios, the benchmark will be a reduction of 10% of the natural discharge (Fig. 8).

Figure 9 shows the CRP maps for scenarios D, E and F. The allocation method and the conclusions for scenarios D and E are largely similar to scenarios A and B. However, the differences between Figures 4 and 9 are not only attributable to the flow regime, but also to the fact that transient-state scenarios include recharge.

In contrast, scenarios C and F highlight an essential difference of working with steady and transient-state conditions. Under the assumption of steady-state, users could only be assigned a constant pumping rate. Thus, Scenario C provided alternatives such as reducing the pumping rate altogether, or drilling a new well beyond the appropriate buffer line. By taking into account the time factor, transient-state conditions allow for the development of different pumping patterns. This renders solutions that are generally easier to implement in practice and

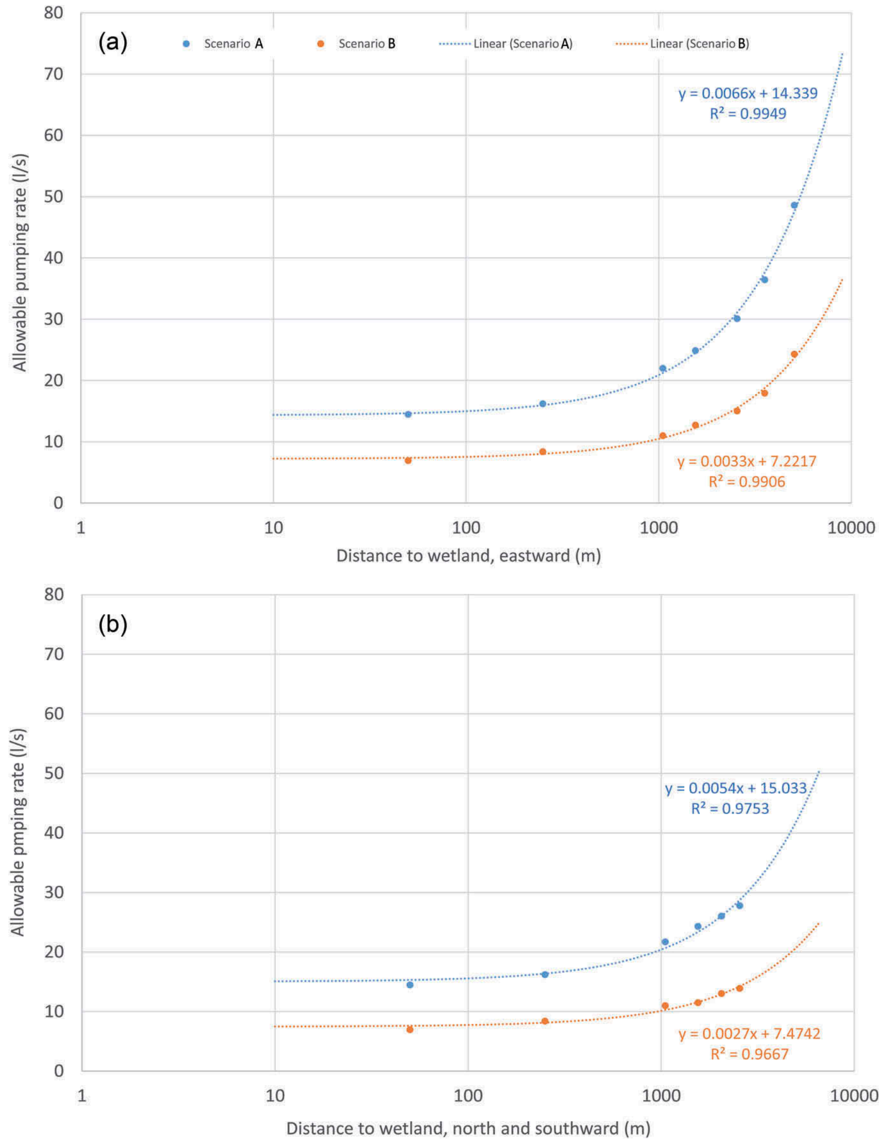

Figure 6. Allowable pumping rate expressed in terms of distance to the wetland for scenarios A and B. (a) East direction. (b) North and south directions. The acceptable reduction of the average groundwater discharge rate in the wetland in natural conditions is 10% in both cases. Linear trend lines have been fitted to the model results.

which facilitate agreements with groundwater users. It also means that the results are better expressed along a temporal line, rather than on a map. Take for instance outcomes of Scenario F, which successfully balance pumping requirements with a suitable rate of groundwater discharge through the wetland (Fig. 10). Thus, the user could keep pumping 30 L/s during 9 months each hydrological year (September–May, in this simulation), subject to the acceptance of a reduction to 20 L/s between June and August. Map-wise that would imply an average pumping rate of 27.5 L/s, consistent with the placement of the buffer lines on Figure 9. In other words, transient CPR maps are restricted to average pumping rates.

4. Case study

4.1. Study area

The buffering approach is illustrated through a practical application to the Timbique wetland, Colombia, a 300 m^2 aquatic ecosystem whose existence is currently threatened by groundwater extractions. Timbique is currently the object of a pilot wetland protection program in the Valle del Cauca region. Though small, it is an environmentally significant ecosystem subject to a number of conflicts between local organizations and irrigators. Furthermore, it provides an excellent example to illustrate the buffering method, as its conceptual functioning is relatively simple and its hydrological balance is known sufficiently accurately (Van Wachtendonk 2016).

Timbique is located approximately 15 km east of Santiago de Cali (Fig. 11). The region presents a tropical climate. Monthly maxima and minima may oscillate between 18 and 30°C, but the monthly average ranges between 23 and 24.5°C. Precipitation amounts to 1045 mm/year, following a bimodal distribution with peaks in April (143 mm) and October (140 mm). July is the driest month with 35 mm.

From a geological standpoint, it belongs within a narrow intramontane valley associated with a major fault that runs from the south to the north, traversing most of the country.

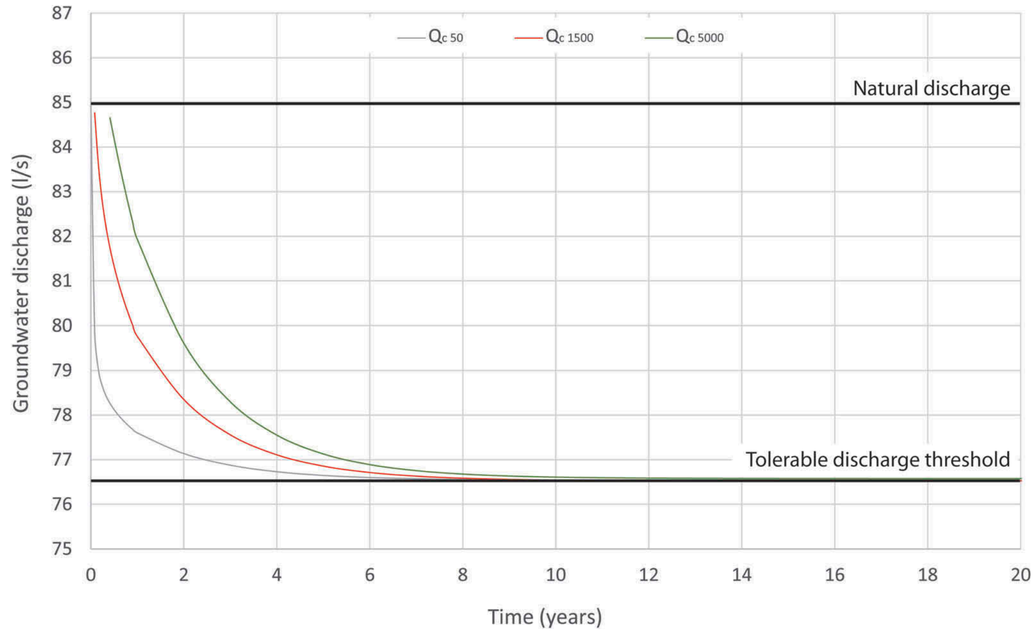

Figure 7. Time needed to reach a new steady state. The curves represent how discharge evolves when pumping the critical rate at distances of 50, 1500 and 5000 m from the wetland, respectively. The tolerable discharge threshold equals the new steady-state.

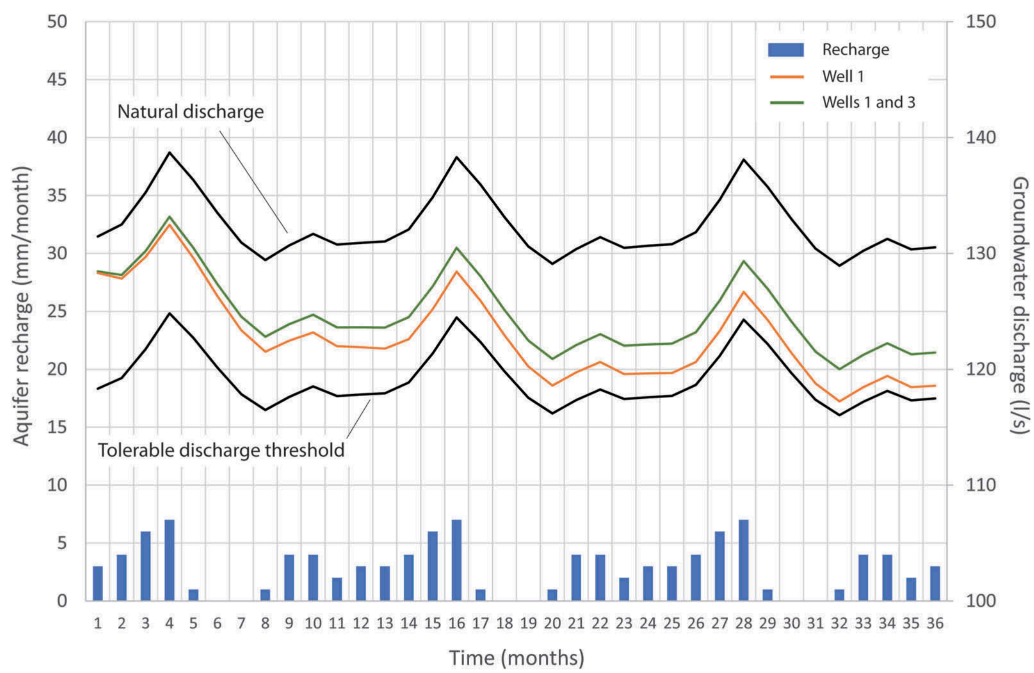

Figure 8. Wetland discharge under scenarios D and E in relation to the natural and tolerable discharge conditions. Scenario D assumes that Well 1 pumps at a continuous rate of 10 L/s, while Scenario E includes this together with a 10 L/s rate at Well 3. Recharge assumes a "very dry" sequence sustained over several years.

The geological basement is made up of igneous rocks, overlain by a sequence of tertiary sedimentary rocks. The main aquifer consists in a thick layer (several hundred metres) of quaternary deposits. The central part of the valley, where Timbique is located, is predominantly flat and presents a poorly-defined drainage network. Since the water table is shallow (typically less than 5 m) there is a strong interrelation between surface water and groundwater. This gives rise to a series of springs and wetlands which are often in association with fluvial dynamics. These are characterized by intermittent links to floodplains and branching streams and rivers. Thus, their behaviour alternates between lentic (still) and lotic (flowing), depending on groundwater discharge, recent rainfall and surface run-off.

4.2. Model development and calibration

The model spans a surface of approximately 200 km^2 and considers a single layer. Cell size ranges from 10 × 10 m in the vicinity of the wetland to 100 m × 100 m in areas located further away. A calibrated regional model (Faneca *et al.* 2016) was used to establish both the hydrogeological parameters

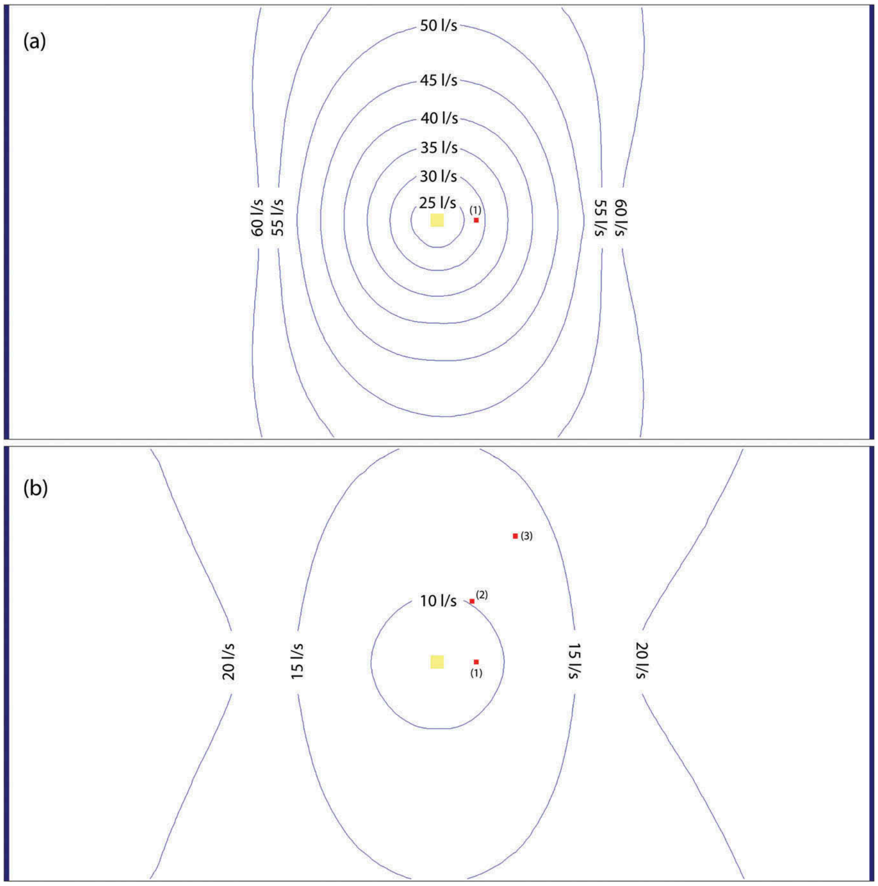

Figure 9. Spatial distribution of protection buffers under transient-state conditions. Critical pumping rate maps for (a) scenarios D and F, and (b) Scenario E.

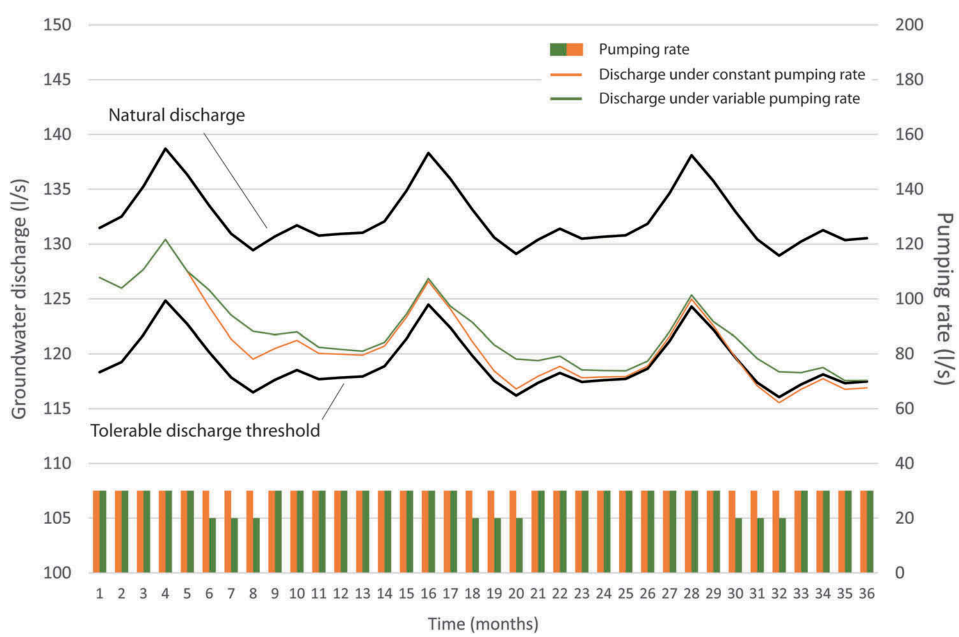

Figure 10. Wetland discharge under Scenario F in relation to the natural and tolerable discharge conditions. Two pumping patterns are considered, the original one (constant rate of 30 L/s) and the reduced one (30 L/s all year with a reduction to 20 L/s during the June-August period). Recharge conditions are identical to those in Figure 8.

and the boundary conditions. The northern, southern and eastern boundaries are thus delimited by the Bolo and Palmira rivers and represented by means of Cauchy conditions, whereas the western boundary is the Central Range (Neumann condition, impervious). Additional boundary conditions include drain cells to represent all springs and

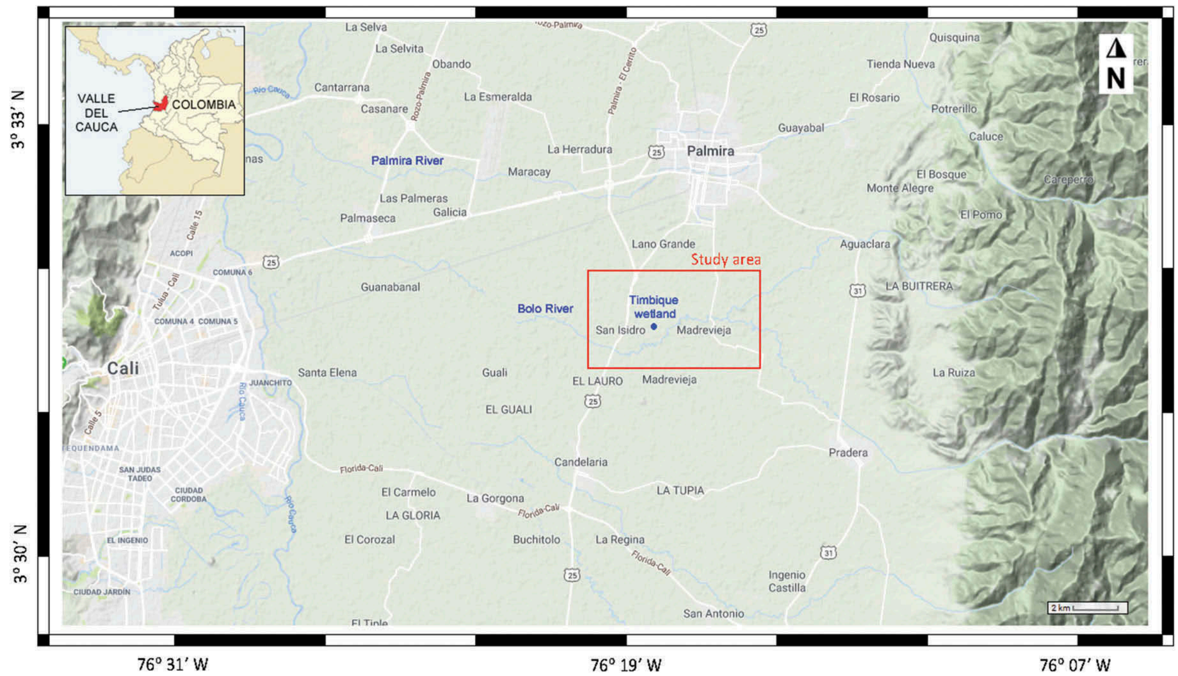

Figure 11. Geographical setting. (Source: Corporación Autónoma Regional del Valle del Cauca, online SIG, http://geo.cvc.gov.co/visor/).
Corporación Autónoma Regional del Valle del Cauca, online SIG, http://geo.cvc.gov.co/visor/).

wetlands, including Timbique (Cauchy condition), aquifer recharge and groundwater pumping.

At the regional scale, the transmissivity of the aquifer ranges between 300 and 2200 m^3/d, while the horizontal hydraulic conductivity is 5 to 55 m/d. In the study area, however, these values are further constrained to 1000–2000 m^2/d and 5–15 m/d, respectively. The storage coefficient is estimated at 10^{-3} to 10^{-2}. Recharge ranges between 10 in the less permeable areas to 830 mm/year (Faneca *et al.* 2016).

The model was re-calibrated under steady- and transient-state conditions. In particular, drain conductance was further adjusted to better reproduce the conditions around the wetland. The steady-state calibration assumes a semi-perturbed state. This model run incorporates existing pumping wells and was used to determine the initial heads for transient calibration. Steady-state calibration uses piezometric data recorded at the existing wells in September 2017, whereas the transient-state model was calibrated on pumping test records (Fig. 12).

4.3. Delineation of protection buffers

To estimate wetland discharge, the calibrated model was run under steady-state conditions without the pumping wells. This led to a discharge estimate of 0.5 m^3/d, consistent with the wetland water balance characterized by Van Wachtendonk (2016). Two thresholds were established for the purpose of demonstrating the application of the buffering methodology to this case study. These represent a wetland discharge reduction of 10% and 50%, respectively. Figure 13 shows the steady-state outcomes in terms of acceptable pumping rates (L/s). The outcomes suggest that there may still be room for further groundwater development in the area, even though the system is not far from reaching the pumping limit.

Figure 14 presents a comparison between the results of steady- and transient-state simulations carried out to determine whether Well vp-789 should be allowed to increase its pumping allowance to 15 L/s. The answer would be negative (consistent with maps of Figure 13) for a continuous pumping rate (steady-state). However, an extraction pattern of 12 h per day for six days a week could be acceptable under the 50% discharge reduction threshold. This highlights the limitations proper to steady-state simulation, which tend to lead to more restrictive results.

5. Discussion

Wetlands are intricate ecosystems whose functionality relies on complex interactions between biotic and abiotic factors. Buffer protection zones need to take into account a variety of indicators based on wetland functionality, values, and sensitivity to disturbance (Macfarlane *et al.* 2009, Aldous and Bach 2011). This recognizes the different degree of perturbation that each activity causes to fauna and flora, and suggests that each buffer can be expected to be partial in scope. Our methodology is specifically designed for the purpose of limiting the amount of water diverted from the wetland by pumping wells. Thus, the CPR maps should be combined with other buffering methods, ideally in a GIS context, prioritizing the more stringent criteria whenever possible.

Clear quantitative thresholds need to be defined as indicators of hydro-ecological relations. While basing management decisions on a numerical model is both sophisticated and straightforward enough, determining the key indicator may pose a significant practical challenge. Wetland discharge may be replaced by the maximum allowable water table depletion.

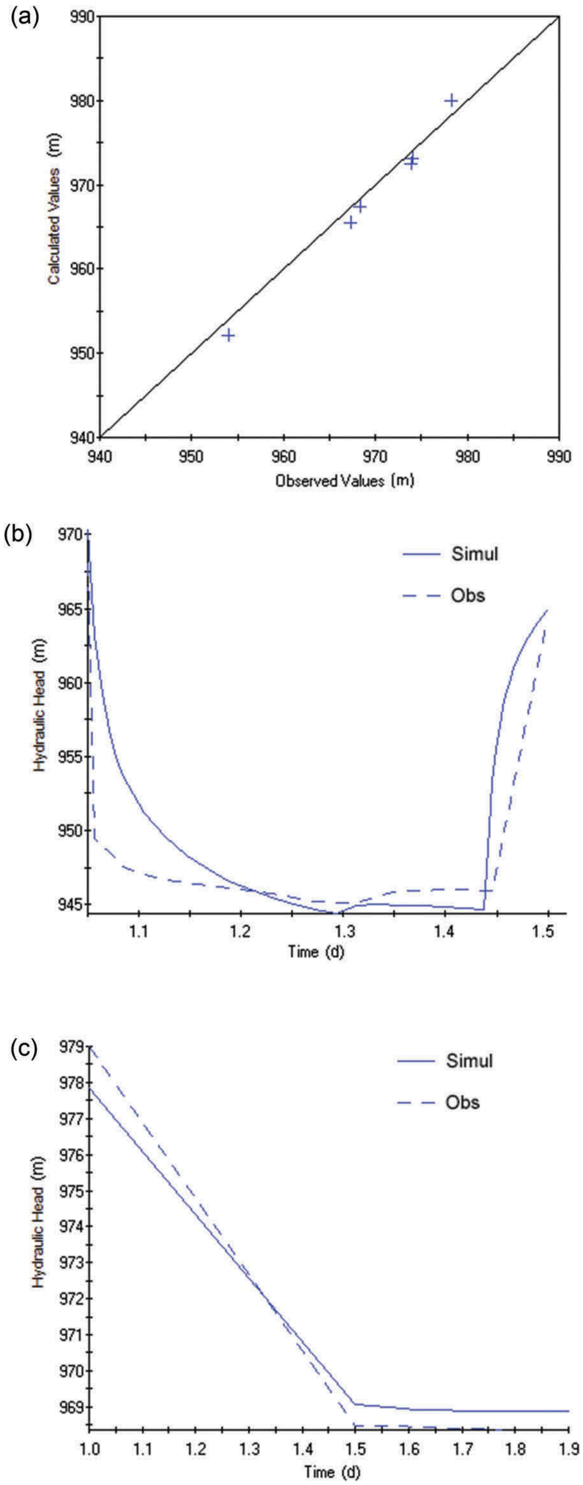

Figure 12. Model calibration. (a) Steady-state conditions. (b) Transient-state conditions (pumping well vp-779). (c) Transient-state conditions (pumping well vp-507). The location of both pumping wells is depicted in Figure 13.

This indicator is often seen in the wetland literature due to the ease with which it is measured in the field (Williams *et al.* 1995, Aldous and Bach 2014). Using groundwater levels instead of discharge will not substantially change the modelling approach or the outcomes, but will incorporate some difficulties of its own. This is due to the likely presence of vertical flows at the local scale (Custodio 2010), which may yield different piezometric heads at the same point depending on the depth of the monitoring well (Conant 2004, Martínez-Santos *et al.* 2013). Moreover, local conditions can be expected to be highly heterogeneous. Hence, a sufficiently dense and well-designed piezometric network will be needed for optimal results.

Provided that enough information is available, CRP maps are applicable to any kind of groundwater-dependent ecosystem, be it a wetland, an underground cave, or a surface ecosystem sustained by shallow water table. In the case of the latter, drain or river cells will most likely need to be replaced with evapotranspiration cells, and discharge thresholds established accordingly. Nevertheless, there are some precautions that stem both from the nature of subsurface flow and from some of the basic modelling assumptions. For one, numerical codes generally assume Darcy's law to hold. This implies that methods such as the one at hand are better suited to intergranular systems. As Kimberley and Coxon (2013) note, differences in specific yield mean that the same groundwater abstraction can cause a greater drawdown when conduit flow predominates over diffuse flow. Thus, assessing the impact of pumping on discharge thresholds would require more conservative methods in the case of groundwater-dependent wetlands associated with karstic and fissured aquifers.

Modelling work is simpler under steady-state conditions. These can be expected to yield more conservative outcomes than a transient-state regime, thus favouring environmental protection. From that point of view, the assumption of steady-state can be seen as an advantage. Furthermore, delineating buffer protection zones in transient-state conditions is potentially unfeasible if there is a large number of wells subject to different pumping patterns. On the other hand, a steady-state model runs, by definition, until it reaches the equilibrium between inflows and outflows. Thus, it provides no information on the temporal variation of piezometric heads, capture zones or groundwater discharge. Moreover, it only allows the user to work with average values and towards a single discharge benchmark at a time. These limitations may be overcome by establishing the most stringent threshold in all simulations (for instance, by referring the tolerance value to wetland discharge during the dry season). However, this can be problematic in those cases where wetlands alternate seasonally between gaining and losing behaviour. It may also lead to impractical solutions from the point of view of groundwater users.

On a final note, it must be recognized that managing groundwater-dependent wetlands in a context of intensive pumping goes way beyond quantifying or modelling hydro-ecological interactions. Technical approaches such as the one at hand will always need to be complemented by robust institutional and legal frameworks. Given the high degree of vulnerability of wetlands, additional policy instruments should be available. These may include mechanisms for stakeholder participation, sanctions, economic compensation or the exchange of extraction rights among users. Only thus regulations will be adequately enforced and wetlands protected effectively.

6. Conclusions

Groundwater-dependent wetlands are characterized by a delicate equilibrium of hydrological, geomorphological and ecological variables. Wetlands have drawn considerable

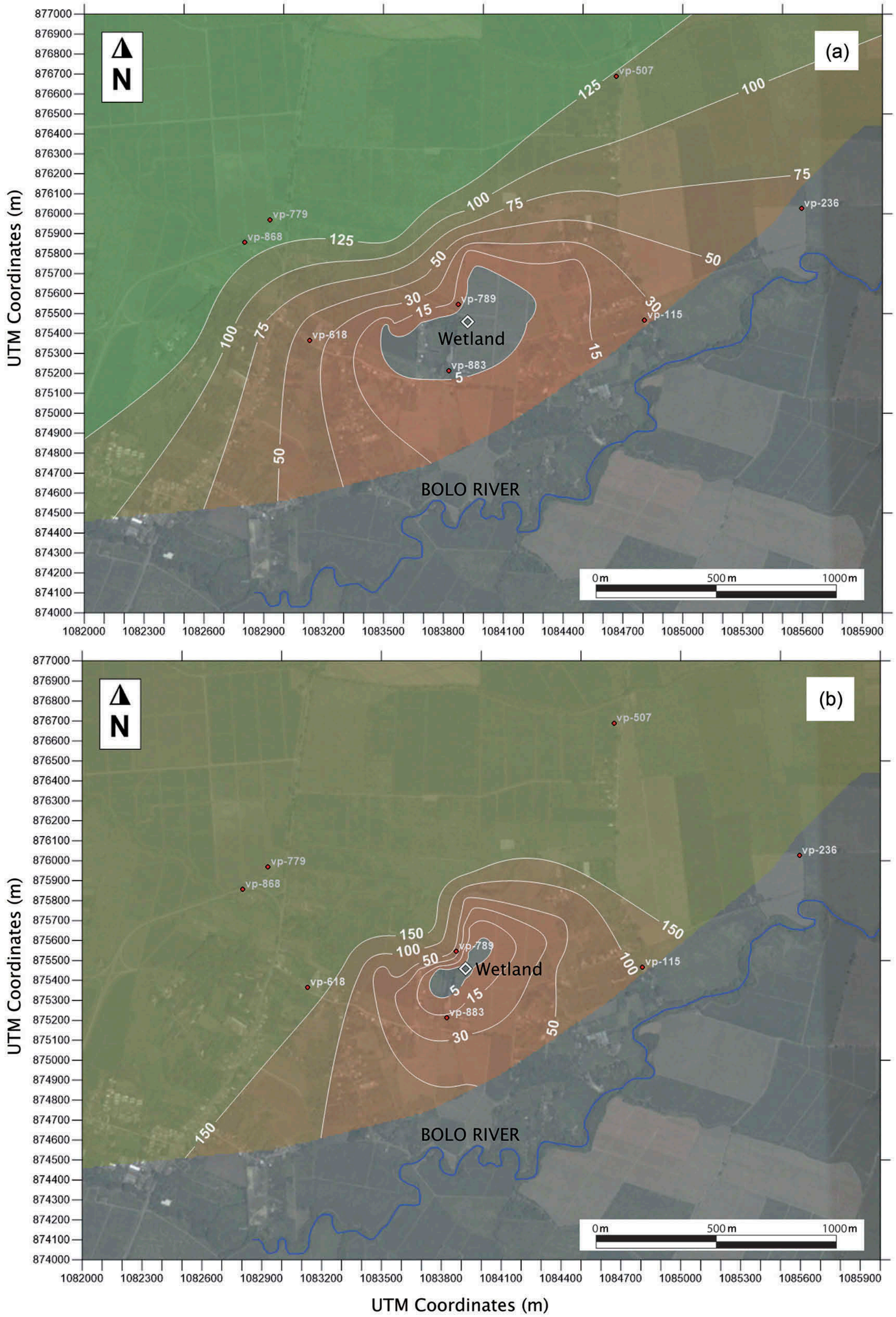

Figure 13. Acceptable groundwater extraction rates around the Timbique wetland. The isolines represent the maximum allowable pumping rate (L/s) at each point in the map. (a) if a 10% wetland discharge reduction is acceptable (wetland discharge drops to 0.45 m3/d); (b) if a 50% wetland discharge reduction is acceptable (wetland discharge drops to 0.25 m3/d). Coordinates: EPSG Projection 32,618 – WGS 84/UTM zone 18N.

attention from the academic community in the last two decades, largely because understanding their complexity remains a major scientific challenge. Since wetlands are often at the core of conflicts between environmental conservation and socio-economic development in regions subject to intensive groundwater pumping, environmental practitioners need to

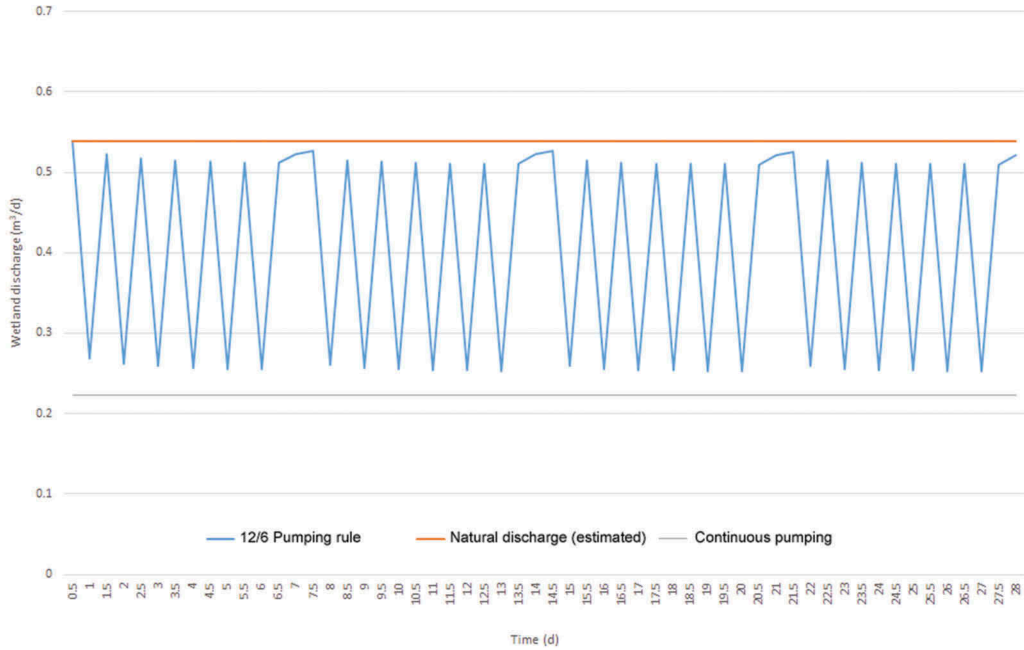

Figure 14. Wetland discharge rate for a 28-day interval based on two different pumping rules. The "12/6 pumping rule" curve (transient-state conditions) represents how wetland discharge could be expected to vary while pumping 15 L/s from Well vp-789 for 12 hours a day during six days each week. The "continuous pumping" curve represents wetland discharge if the well were to pump non-stop (steady-state conditions). In this case, the 12/6 pumping rate could be acceptable under the 50% reduction scenario, as wetland discharge never drops below 0.25 m3/d.

be endowed with tools that are straightforward and versatile enough to deal with everyday management issues.

This paper has presented a novel technique to delineate wetland protection buffers in regions subject to groundwater pumping. Critical pumping rate maps have been developed for a series of scenarios with a calibrated numerical model. These provide a clear rule of thumb as to how much water can be extracted at any given point in the aquifer without causing major disturbances to wetland functionality, both under steady- and transient-state conditions. The iterative outlook favours placement of wells as far as possible from the wetlands while ensuring that pumping rights are allocated in order of precedence. As exemplified by the case study, this method is applicable under a wide range of conditions, provided (a) that there is enough information regarding the main hydrogeological variables, including pumping; (b) that a sufficiently clear wetland discharge threshold may be established; and (c), that groundwater extraction is still at an incipient stage (i.e. there is a manageable number of wells in the system). This procedure may allow practitioners to establish hydrogeological protection buffers with relative ease, and should be applied in the context of multidisciplinary studies for optimal outcomes.

Acknowledgments

This research has been funded by the Corporación Autónoma Regional del Valle del Cauca, Colombia, under project CVC-ESCACES 2, and has been carried out under a contractual agreement involving this institution, Stichting Deltares and the Universidad Complutense de Madrid. The authors would like to thank all those people who have facilitated our task in any way. This paper compiles some of the main findings of the first author's PhD Thesis.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Corporación Autónoma Regional del Valle del Cauca [CVC-ESCACES 2].

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