Riparian Freshwater Lens Response to Flooding

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Abstract  The freshwater lenses (“lenses” hereafter) within saline floodplain aquifers are sensitive to river flooding events. However, the effects of extensive floodplain inundation on saline aquifers are rarely considered and have not been examined previously under controlled laboratory conditions. We conducted laboratory experiments within a two-dimensional (cross-section) sand tank (i.e., representing a saline floodplain aquifer) and built both laboratory- and field-scale numerical models to examine lens responses to flood events. Three sets of experiments were performed to explore different lateral extents of floodplain inundation. The temporal behavior of experimental lenses was quantified and compared to variable-density numerical models that adopted calibrated laboratory parameters, showing good agreement. Results show that more extensive floodplain inundation leads to larger lenses (as expected). The sensitivity analysis was performed based on field-scale numerical models, demonstrating that the floodplain inundation extent, hydraulic conductivity, and dispersivity are key factors controlling the post-flood recession in lens extent and volume. In field-scale simulations of floodplain inundation, the entire lens was significantly salinized during flood recession due to enhanced dispersion accompanying higher groundwater velocities, which may further split into several isolated freshwater bodies before eventually returning to steady-state conditions. Importantly, field-scale numerical results indicated that the salt load to the adjacent river increased immediately following the flood event, consistent with reporting of the River Murray (South Australia). These results provide critical new insights into relationships between flood events and the behavior of lenses, highlighting the significance of flooding events on both intermediate and long-term conditions of saline floodplains.

Plain Language Summary In semi-arid and arid regions, river-fed freshwater lenses within saline floodplain aquifers can sustain salt-sensitive riparian vegetation and the health of floodplain ecosystems, especially during periods of low river flow. The dynamics of these lenses may be significantly altered by the river flooding events that often cause widespread floodplain inundation. Thus, the quantitative analysis of how riparian lenses respond to river flooding events is crucial for the sustainable management of salt-affected floodplains. In this study, the lens behavior under flooding conditions was directly observed and quantified in laboratory experimentations for the first time. Flood-induced lens dynamics in real-world settings were further investigated numerically. The results indicate that the occurrence of floodplain inundation leads to a complex relationship between flood events and the behavior of lenses. The salt load to the adjacent river increased immediately following the flood event. These previously unarticulated outcomes are expected to broaden the understanding of riparian lens dynamics and river salinization associated with flooding events.

1. Introduction

In semi-arid and arid environments, freshwater lenses (“lenses” hereafter) overlying otherwise saline groundwater have been encountered within the riparian zones and floodplain aquifers adjacent to freshwater rivers (e.g., Cartwright et al., 2010; Werner & Laattoe, 2016; see Figure 1). These lenses are considered critical to the survival of salt-sensitive riparian vegetation and the health of floodplain ecosystems more broadly (Alaghmand et al., 2015; Bauer et al., 2006; Laattoe et al., 2017). In areas where saline groundwater discharge impacts river water quality (e.g., the River Murray, South Australia and the Colorado River, USA), lenses are also thought to buffer saline discharge, improving river water quality (e.g., Cartwright et al., 2011; Telfer et al., 2012; Woods et al., 2015).
The occurrence of lenses under both losing rivers (i.e., where river water flows into adjacent aquifers) and gaining rivers (i.e., rivers that receive groundwater influxes) has been documented. Lenses associated with losing river conditions (e.g., Bauer et al., 2006; Cendón et al., 2010) are expected, and extensive lenses have been observed where the groundwater hydraulic gradient slopes away from the river (Cartwright et al., 2011, 2010). Lenses under gaining river conditions are counterintuitive because these occur despite regional groundwater flow toward the river, but have nevertheless been encountered in geophysical surveys of the River Murray, South Australia (e.g., the Bookpurnong floodplain; Munday et al., 2006). Werner and Laattoe (2016) proposed a new conceptual model and analytical solution for stable lenses adjacent to fully penetrating (i.e., the riverbed and aquifer base

**Figure 1.** Conceptual model of a riparian aquifer system under: (a) normal river level, (b) river flood, and (c) flood recession conditions, where the bank topography on the left and right sides of the river represents two common scenarios, that is, with and without a low-lying floodplain, respectively. The black and blue arrows indicate the saltwater and freshwater flow directions, respectively. The gray and light blue areas represent the saline and fresh groundwater, respectively.

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coincide), gaining rivers. Their analytical solution, which presumed a sharp interface between fresh and saline groundwater, steady-state conditions, and a stagnant lens, illustrates the shape of lenses and allows for estimation of saline groundwater discharge to the river. They demonstrated that freshwater rivers with a water level slightly higher than the adjoining saline groundwater level may lose freshwater at the top of the aquifer due to the difference in water level, but gain saltwater at the base of the aquifer due to both water density-differences and hydraulic forces (i.e., losing freshwater and gaining saltwater simultaneously; Werner & Laattoe, 2016), thereby allowing freshwater lenses to appear under gaining river conditions.

Werner and Laattoe's (2016) conceptual model and the corresponding analytical solution were subsequently validated by the sand tank experiments conducted by Werner et al. (2016), who found that accurate analytical predictions can be achieved through parameter calibration based on lens measurements. Werner (2017a) introduced an empirical correction to the analytical solution of Werner and Laattoe (2016) to account for dispersive effects, which created freshwater circulation and less extensive lenses. Jazayeri, Werner, and Cartwright (2021), Jazayeri et al. (2020), and Jazayeri, Werner, Wu, et al. (2021) extended Werner and Laattoe's (2016) analytical solution by considering gaining rivers that partially penetrate the adjacent aquifer (i.e., the riverbed is above the aquifer base). Their analytical, experimental, and numerical results demonstrate that assuming a fully penetrating river significantly overestimates the extent of lenses adjacent to partially penetrating rivers.

Extensive human activities (e.g., irrigation practices, clearing of native vegetation) and extreme climate events (e.g., severe droughts) have increasingly affected floodplain environments. For example, agricultural irrigation along the River Murray (South Australia) raised the saline groundwater level, which enhanced saltwater discharge into the floodplain and river systems, resulting in reduced extents of fresh groundwater (Alaghmand et al., 2013). Higher floodplain groundwater levels may also lead to the salinization of floodplain soils due to evapo-concentration effects, which America et al. (2020) found may cause highly modified, complex lenses. Lower river water levels during drought conditions may also cause lenses to contract (Cartwright et al., 2010), while overbank flooding is expected to have a significant impact on the salinity stratification and the formation of lenses (e.g., Cartwright et al., 2011, 2019), although lens dynamics during river flooding remains rarely investigated and unclear.

Studies of the effects of floodplain inundation on lenses include the analysis of artificial flooding as an alternative to natural river flooding, which was tested as a technique to expand lenses by Berens et al. (2009). They conducted artificial inundation of the Clark floodplain adjacent to the River Murray (South Australia), demonstrating that artificial inundation can temporarily expand the lens. Holland et al. (2009) investigated the lateral extent of bank storage in response to artificial flooding in the Chowilla floodplain of the River Murray (South Australia). Results indicated that higher riverbanks and aquifer hydraulic conductivity caused more significant groundwater freshening (i.e., more extensive lenses). White et al. (2009) performed artificial flooding of depressions in the Clark floodplain (River Murray, South Australia) and reported improved soil conditions and tree health during the flooding period, although this was not sustained after flooding events.

Holland et al. (2013) compared the salinity of soil and groundwater at the Bookpurnong floodplain after natural and artificial floods. They showed that natural flooding causing more widespread inundation performed better than artificial flooding, in terms of the extent and degree of floodplain freshening (Holland et al., 2013). Alaghmand et al. (2016) modeled the impacts of artificial flooding of low-lying depressions on groundwater salinity within the same floodplain, albeit they neglected water density variations. They found that artificial flooding only temporarily caused lower-salinity soil and groundwater (for 4–6 months), mainly in flooded areas. Alaghmand et al. (2014) modeled transient lenses under periodic river flood events based on conditions typical of the Clark floodplain of the River Murray, considering hypothetical river flood events (short-term, instantaneous increases in river stages). The results indicated that the effectiveness of flood events in expanding lenses was limited spatially to the vicinity of the riverbank, probably due to the absence of floodplain inundation processes. The investigations of Alaghmand et al. (2014) neglected the buoyancy forces that are expected to play an important role in lens formation and the rate of groundwater discharge to the river. Alaghmand, Brunner, Graf, and Simmons (2016) demonstrated through numerical modeling of surface-subsurface water interactions that density effects (i.e., buoyancy forces) need to be taken into account where water density variations are significant (particularly in the vicinity of the riverbank); otherwise, the lens extent will be underestimated.

Figure 1 shows a conceptual model of the riparian aquifer system, including normal river level conditions (Figure 1a), river flood conditions (Figure 1b), and flood recession conditions (Figure 1c), where different
riverbank topographies are illustrated. That is, the left and right sides of the river in Figure 1 illustrate conditions with and without a low-lying floodplain, respectively. As shown in Figures 1b and 1c, the expansion and contraction mechanisms of the lenses on the left and right sides of the river are different, depending on whether floodplain inundation occurs. To date, quantitative understanding of how river flood events (i.e., with and without floodplain inundation) may affect the lens transience remains unexplored. River regulation and diversions may alter water level rise, the duration of floods, and the extent of inundation (Bunn & Arthington, 2002; Rood et al., 1995; Shafroth et al., 2002). However, the lens responses to these variations have not been investigated. Analyses are warranted of the vulnerability of lenses to changes in the river flood regime, given their likely control of lens characteristics.

Direct observation and measurement of field-scale lenses are difficult and mostly lacking during natural river flood events, leading to significant uncertainty in the accompanying processes. As an alternative, laboratory experiments can assist in evaluating complex subsurface processes under simplified, controlled conditions that allow for rigorous observations and analysis of lens transience, which is challenging to characterize within field settings. Laboratory-scale physical models are commonly applied to various forms of lenses, including riparian lenses (e.g., Jazayeri, Werner, & Cartwright, 2021; Jazayeri, Werner, Wu, et al., 2021; Werner et al., 2016; Wu et al., 2020), as well as the lenses within coastal zones and oceanic islands (e.g., Lu et al., 2019; Stoeckl & Houben, 2012; Tang et al., 2021; Yan et al., 2021). More recently, Jazayeri et al. (2022) conducted laboratory experiments to study the transient response of lenses (adjacent to fully penetrating, gaining rivers) to instantaneous boundary head changes due to variations in the river water level or saltwater head at the inland boundary. They found that the lens response timescales are negatively correlated with the final riverward hydraulic gradient.

Previous artificial flooding investigations (e.g., Berens et al., 2009; Holland et al., 2009; White et al., 2009) have examined the effects of local inundation, whereas the effects of river flooding events, encompassing a wider region of inundation, are expected to have a more prolonged influence on floodplain conditions, but these are rarely characterized, and the associated lens responses have not been explored. To this end, the present study examines lens responses to a single river flood event under controlled laboratory conditions, which is the first attempt at investigating the effects of freshwater flooding on buoyant lenses, extending previous studies of both coastal and riparian regions. We treat the river as fully penetrating the riparian aquifer and under gaining conditions, at least prior to the flooding event. The river flood occurs in the form of a symmetric, trapezoidal water level event, consisting of three stages, that is, rising stage, high-level stage, and then falling stage. Losing-river conditions are expected during times when the freshwater head in the river is higher than the saltwater head at the landward boundary, whereas the river is likely to be gaining at other times. Two types of riverbank topographies are investigated, that is, with and without a low-lying floodplain (corresponding to the left and right riverbanks, respectively, in Figure 1). Temporal changes in the extent and volume of the lens are quantified. Sensitivity analysis based on numerical simulation of field-scale conditions is conducted to study the role of several physical attributes of the system (e.g., the duration of the flood event, the depth and lateral extent of floodplain inundation, and the aquifer properties) on the lens dynamics. The results of this study are expected to improve the understanding of lens dynamics under floodplain inundation, offering insights into the evolution and sustainability of lenses in semi-arid and arid riparian environments, at least for the simple physiographic conditions adopted here (e.g., homogeneous aquifer, etc.).

2. Methodology

2.1. Conceptual Model and Variables

Figure 2 shows the cross-sectional conceptual model and geometric variables of a saline, riparian aquifer containing a lens that is exposed to different river-level stages and floodplain topographies. As shown in Figure 2, the fully penetrating river normally operates at a water level ($H_{uw}$ [L]) that is lower than the saline groundwater level at the inland boundary ($H_{u}$ [L]). During high water levels ($H_{h}$ [L]), the river level exceeds that of the inland boundary. The riparian aquifer has dimensions of $D$ [L] (depth to the aquifer base) and $L$ [L] (distance to an inland boundary), and is connected to the river via a vertical “clogging layer” of thickness $B_{r}$ [L] and freshwater hydraulic conductivity $K_{r}$ [LT$^{-1}$]. The freshwater hydraulic conductivity of the aquifer is $K$ [LT$^{-1}$]. The density of freshwater and saltwater is $\rho_{f}$ and $\rho_{s}$ [ML$^{-3}$], respectively. $q_{s}$ [L$^{2}$T$^{-1}$] is the riverward saltwater volumetric discharge per unit width of the aquifer perpendicular to the cross-section. The thickness of the lens and the saltwater are designated $\eta_{t}$ and $\eta_{s}$ [L], respectively (Figure 2b). $\eta_{u}$ and $\eta_{uw}$ [L] indicate the freshwater and saltwater thickness.
adjacent to the riverbank, respectively. $x_L$ [L] is the lens extent in the horizontal direction (i.e., the location of the lens tip from the origin $O$; Figure 2b). The extent and thickness of the low-lying floodplain aquifer are $l$ [L] and $b$ [L], respectively (Figure 2c). The freshwater volume of the lens per unit width of the aquifer is designated $V_L$ [L$^2$] (shown as the hatched area in Figure 2c).

Figure 2a shows the system under steady-state, non-flooding conditions, where a stable lens develops next to the gaining river ($H_{nr} < H_L$) due to buoyancy effects. If the sharp-interface assumption is adopted, the water table within the lens area is presumed to be horizontal, of height equal to $H_{nr}$ (e.g., Jazayeri et al., 2020; Werner & Laattoe, 2016). Where solute dispersion (and therefore mixing between freshwater and saltwater) is considered, the lens water table tilts slightly downwards away from the river due to the resulting freshwater recirculation.
Figures 2b and 2c show high river-level ($H_{hr}$) scenarios without and with a low-lying floodplain, respectively, both of which are commonly encountered in real-world settings. For example, over much of the Murray River, one side of the river resembles Figure 2b due to high cliffs and limited floodplains, while the other riverbank contains extensive floodplains (e.g., Cartwright et al., 2011). In the current study, for simplicity, we ignored low-permeability soils that may occur over many floodplain areas (e.g., Woods et al., 2015), which is applicable where clay-rich soils are absent, thin, discontinuous or remain cracked during periods of extensive inundation.

2.2. Experimental Setup and Procedure

A schematic of the sand tank used in conducting two-dimensional cross-sectional experiments is illustrated in Figure 3. The tank has internal dimensions of 1.200 m long, 0.330 m high, and 0.030 m wide. The tank was packed with coarse sand (with $d_{10} = 1.22 \pm 0.05$ mm; where $d_{10}$ is the sand particle diameter at which 10% of a sample’s mass consists of smaller particles) to a depth of 0.310 ± 0.001 m using a wet-packing method (e.g., Jazayeri, Werner, & Cartwright, 2021; Jazayeri, Werner, Wu, et al., 2021). Where a low-lying floodplain was considered, its depth was 0.300 ± 0.001 m above the tank’s base. The aquifer-filled part of the tank was connected to freshwater and saltwater reservoirs (i.e., on riverward and landward sides, respectively) through plastic screens (embedded with a fine mesh to prevent clogging). The thickness of plastic screens was 0.005 ± 0.001 m, and these acted as clogging layers, exerting resistance to the flow between the aquifer and the river. The experimental setup was consistent with the conceptual model shown in Figure 2.

The freshwater reservoir (i.e., the “river”) was connected to a 288 L freshwater storage tank through six silastic tubes with 25 mm internal diameter. The adjustable drain allowed for manual manipulation of the water level in the freshwater tank, which led to water level changes in the freshwater reservoir. A drainage pipe was connected to the bottom of the freshwater reservoir to drain brackish water (shown as the pink area in Figure 3) at a controlled rate, which ensured a relatively stable fluid density in the freshwater reservoir. The saltwater reservoir was recharged by a constant-flux pump through six silastic tubes with an internal diameter of 6 mm. The water level in the saltwater reservoir was constant, maintained by discharging excess saltwater through a free-drainage tube at a fixed elevation (i.e., the top tube on the landward side of the saltwater reservoir; Figure 3).

The freshwater and saltwater used in the experiments had densities of 998.0 ± 0.5 and 1,025 ± 0.5 kg/m$^3$ (measured with a calibrated pycnometer), respectively. Saltwater was produced by dissolving 35.0 g sodium chloride per liter of freshwater at 25°C. An additional 0.1 g of tracer dye (Allura Red AC) was dissolved per liter of saltwater for visualization and photography, which led to no measurable change in saltwater density. Jazayeri et al. (2022) demonstrated that under controlled laboratory conditions, adsorption of the dye tracer to sand grains made only a marginal difference in characterizing transient lenses and was therefore negligible, implying that different color shades of the dye tracer were a good proxy for salinity levels.

The effective porosity ($n_e$ [-]) of the sand was measured using the imbibition method (Collins, 1961), arriving at an average value of 0.38. The freshwater hydraulic conductivity of the sand, $K$, was obtained through
Table 1

<table>
<thead>
<tr>
<th>Laboratory parameter</th>
<th>Measured value</th>
<th>Calibrated value</th>
<th>Uncertainty range</th>
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<tbody>
<tr>
<td>Aquifer length, L [m]</td>
<td>1.200</td>
<td>1.200</td>
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<tr>
<td>Aquifer depth, D [m]</td>
<td>0.310</td>
<td>0.310</td>
<td>±0.001</td>
</tr>
<tr>
<td>Thickness of screen, B [m]</td>
<td>0.005</td>
<td>0.005</td>
<td>±0.001</td>
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<tr>
<td>Normal river level of freshwater reservoir, Hnr [m]</td>
<td>0.289</td>
<td>0.289</td>
<td>±0.001</td>
</tr>
<tr>
<td>High river level of freshwater reservoir, Hhr [m]</td>
<td>0.305</td>
<td>—</td>
<td>±0.001</td>
</tr>
<tr>
<td>Water level of saltwater reservoir, Hs [m]</td>
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<td>0.300</td>
<td>±0.001</td>
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<tr>
<td>Freshwater density, ρf [kg/m³]</td>
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<td>998</td>
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<td>Saltwater density, ρs [kg/m³]</td>
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<td>1,025</td>
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<tr>
<td>Hydraulic conductivity of sand, K [m/d]</td>
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<td>1,306</td>
<td>±144</td>
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<tr>
<td>Reduction ratio of screen, κ [-]</td>
<td>0.44</td>
<td>0.44</td>
<td>0.087</td>
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</table>

*Obtained from parameter calibration (see Section 2.3). Value that produced reasonable match between experimental measurements and numerical predictions. Value that produced reasonable match between experimental measurements and the analytical solution of Werner (2017a).

Darcy column testing and grain-size analysis based on the empirical equation proposed by Hazen (1911). Darcy column tests produced $K = 1,362 \pm 68$ m/d (based on repeated tests), while Hazen’s (1911) equation provided $K = 1,286$ m/d, with a possible range of 1,183 to 1,394 m/d, considering reasonable variability in input parameters (i.e., ±0.05 mm for $d_{50}$) and 1.0 for the Hazen’s empirical coefficient (the sand is well sorted). The measured value of $K$ was thus taken to be $1,286 \pm 144$ m/d. The equivalent freshwater hydraulic conductivity of the clogging layer (i.e., the plastic screens), $K_c$, can be calculated by $\kappa K$, where $\kappa$ [-] is the reduction ratio of the screen, that is, the ratio of the area of the holes in the screen to the cross-sectional area of the sand tank (e.g., Werner et al., 2016). Here, $\kappa$ was calculated as 0.44, with a possible range of 0.01–1 to account for uncertainty in estimating this parameter (e.g., Jazayeri et al., 2022). The normal and high river levels were $0.289 \pm 0.001$ m and $0.305 \pm 0.001$ m, respectively. The water level of the saltwater reservoir was $0.300 \pm 0.001$ m. The measured values of laboratory parameters and the corresponding allowable ranges (based on measurement errors) are listed in Table 1. An applicable range of 0–0.005 m was considered for the longitudinal dispersivity ($\alpha_L$ [L]), consistent with Fang et al. (2021), and the transverse dispersivity ($\alpha_T$ [L]) was set to $\alpha_L/10$.

To examine the impact of floodplain inundation, three different settings were adopted for the floodplain topography (i.e., sand surface) in the experiments: (a) no low-lying floodplain (i.e., experiment set A; Figure 2b), (b) with a low-lying floodplain of 0.600 m long (i.e., half the length of the sand tank) and 0.300 m high (i.e., experiment set B; Figure 2c), and (c) with a low-lying floodplain of 1.200 m long (i.e., covering the full length of the sand tank) and 0.300 m high (i.e., experiment set C). The low-lying floodplain was inundated by approximately 0.005 m during flooding events.

In all experiments, the sand tank was initially filled with freshwater, while the freshwater reservoir level was fixed at $H_{hr}$, causing saltwater to invade the sand aquifer. After 6 hr, a stable lens was observed by comparing photographs of consecutive lenses in 10 min intervals and showing no measurable change in the lens extent. Then, a single river flood event was imposed through manual manipulation of the freshwater tank level (Figure 3). The single flood event included three stages: (a) rising stage (i.e., the water level rose from $H_{nr}$ to $H_{hr}$), (b) high-level stage (i.e., constant water level at $H_{hr}$), and (c) falling stage (i.e., water level returned to $H_{nr}$). After the flood event, the water level of the freshwater reservoir was maintained at $H_{nr}$ until the lens restabilized. The durations of rising, high-level, and falling stages are designated as $t_1$, $t_2$, and $t_3$ [T], respectively. To examine the impact of floodplain inundation duration, each experiment set (i.e., A, B, and C) included two scenarios with short ($t_2 \approx 5$ min) and long ($t_2 \approx 10$ min) durations of the high-level stage. The floodplain geometry (i.e., L and b; Figure 2c) and stage durations (i.e., $t_1$, $t_2$, and $t_3$) for each experiment are listed in Table 2.

The stable lens obtained prior to the flood event was characterized in terms of the steady-state values of the horizontal extent of the lens ($L$), the lens thickness near the river ($E_r$), and the saltwater discharge ($q_s$). These were used in the calibration of experimental parameters (see Section 2.3). $q_s$ was calculated from the total saltwater influx to the saltwater reservoir, which was established using a peristaltic pump, minus the saltwater outflux through the reservoir drain (the top red pipe discharging from the landward side reservoir in Figure 3).
The temporal behavior of the lens was photographed in a dark room using a NIKON D300S digital camera at intervals of 5 s (during flooding) and 60 s (after flooding). Temporal changes in $x_L$ and $V_L$ were obtained through image processing of experimental photographs using OpenCV (Open Source Computer Vision Library; https://opencv.org/). The image processing performed here followed the procedure described in Jazayeri et al. (2022), which contains further details of the methodology.

### 2.3. Parameter Calibration

Parameter calibration was conducted by comparing steady-state (pre-flood) laboratory measurements to the analytical solution of Werner (2017a). The calibration process sought representative estimates of laboratory parameters (based on parameter ranges given in Table 1) that provided a reasonable match between laboratory measurements and analytical predictions (i.e., in terms of $x_L$, $\eta_{fr}$, and $q_s$). Regularization was applied within the calibration methodology to constrain the deviation of calibrated parameters from the measured parameters (i.e., $L$, $H_{nr}$, $H_s$, $\rho_f$, $\rho_s$, $B_r$, $K$, $\kappa$, $\alpha_L$). Consequently, the calibration objective function was defined as the weighted sum of "prediction error" (i.e., the squared deviation between analytical predictions and laboratory measurements) and "regularization mismatch" (i.e., the squared difference between the calibrated and measured parameter values; e.g., Jazayeri, Werner, & Cartwright, 2021; Jazayeri, Werner, Wu, et al., 2021; Werner et al., 2016). The Evolutionary Solving Method (ESM) in Microsoft Excel® was used to search for the representative parameter set (i.e., $L$, $H_{mr}$, $H_s$, $\rho_f$, $\rho_s$, $B_r$, $K$, $\kappa$, $\alpha_L$) that minimized the objective function. For the sake of brevity, the analytical solutions and objective function used for calibration, as well as the calibration procedure, are explained in the Supporting Information S1.

Values of calibrated laboratory parameters are listed in Table 1. Calibration (described in Section 2.4) produced $\alpha_T$ and $\alpha_L$ values of 0 m, which fall inside the expected range for the scale of the sand tank (i.e., 0–0.005 m; Fang et al., 2021). Nevertheless, a small amount of dispersion was added to the numerical models for numerical stability relative to the resolution of the model discretization (described below). Comparisons of analytical, numerical,
and experimental results (i.e., the values of $x_L$, $\eta_{fr}$, and $q_s$, and the interface shape) are summarized in Supporting Information S1 (i.e., Table S2 and Figure S1 in Supporting Information S1, respectively). Consistency between experimental, analytical, and numerical lens shapes (see Figure S1 in Supporting Information S1) builds confidence in the reliability of the calibrated parameter values.

### 2.4. Numerical Simulation

Both laboratory-scale and field-scale numerical models were constructed using SEAWAT (version 4; Langevin et al., 2008). The laboratory-scale numerical model was used to validate the experimental results. Figure 4 shows the numerical model domain and boundary conditions. The modeled domain of the sand tank (1.205 m long by 0.310 m high by 0.030 m wide) was discretized into 59,768 cells (2.5 mm long by 2.5 mm high, i.e., the cell size in $x$ and $z$ directions, $\Delta x$ [L] and $\Delta z$ [L], respectively). This model discretization achieved a balance between accuracy and computation times. Note that the length of the model domain (i.e., 1.205 m) was greater than the internal dimension of the sand tank (i.e., 1.200 m), because two extra columns were required to represent the freshwater reservoir and the plastic screen (“clogging layer”) on the riverward side of the model domain. Heads in the freshwater and saltwater reservoirs were assigned to the model as Dirichlet boundary conditions (Jazayeri & Werner, 2019) with the Time-Variant Specified-Head (CHD) package of SEAWAT used to represent river head variations. Solute conditions at the CHD and specified-head boundaries were represented by the Sink and Source Mixing (SSM) package of MT3DMS (Zheng & Wang, 1999) that allows inflows at a specified salinity (i.e., saltwater and freshwater with relative salt concentrations of 1 and 0, respectively) and outflows at the ambient groundwater salinity. The Block Centered Flow (BCF) package was applied to control the cell wet-dry conversions that arose during water table variations, similar to the approach of Jazayeri et al. (2022). Further details of the rewetting algorithms in the BCF package are given by Harbaugh et al. (2000).

To simulate overtopping of the floodplain surface, a “surface water” zone (covering the model domain above the low-lying floodplain surface) was included in the model (gray region in Figure 4). Cells in the surface water zone were assigned a high hydraulic conductivity ($K_{high}$ [LT$^{-1}$]), with $n_e = 1$. This method is referred to here as the “high-$K$” approach and has been applied successfully in previous studies to implicitly implement surface water in both fully saturated (e.g., Anderson et al., 2002; Yihdego & Becht, 2013) and variably saturated (Chui & Freyberg, 2008; Jazayeri, Werner, & Cartwright, 2021; Jazayeri, Werner, Wu, et al., 2021) groundwater models. The value of $K_{high}$ for the surface water zone was determined by trial-and-error, that is, repeatedly running the model (based on the calibrated parameter values) and modifying $K_{high}$ until lens tips ($x_L$) from numerical simulations were in agreement with experiment images, arriving at 77,760 and 328,320 m/d for experiment sets B and C, respectively. These values are largely arbitrary and difficult to correlate to physical processes. The different $K_{high}$ values obtained in experiment sets B and C are perhaps caused by differences in the extent and surface roughness of the low-lying floodplain. Table 1 describes other calibrated laboratory parameters. Other relevant
parameters include $\alpha_L$, $\alpha_T$, molecular diffusion ($D_m [L^2 T^{-1}]$), effective porosity ($n_e$), specific yield ($S_y [-]$), and specific storage ($S_s [L^{-1}]$), which were set to 0.0001, 0.00001 m, 0 m$^2$/d, 0.38, 0.3, 10$^{-6}$ m$^{-1}$, respectively.

Field-scale simulations adopted similar parameters to previous lens investigations of the River Murray (South Australia) by Werner and Laattoe (2016). Table 3 shows the relevant parameters. Values of $K$, $K_r/B_r$, $\rho_f$, and $\rho_s$ were taken from Werner and Laattoe (2016), while other parameters were chosen to reflect cross-sectional profiles of Lock 4 of the River Murray presented by Munday et al. (2006). The model dimensions were set to 1,000 m long by 30 m high, where the thickness of sediments within the floodplain segment was 27 m (i.e., the floodplain surface was 3 m below the regional highland surface; Figure 2). Three different floodplain extents (i.e., 0, 250, and 500 m) were simulated, resulting in three aquifer geometry scenarios (designated S1, S2, and S3, respectively; Table 3). Different values of $K$ and $\alpha_L$, typical of field conditions and previous modeling studies of River Murray floodplains (e.g., Alaghmand et al., 2016; America et al., 2020; Jolly et al., 2012; Woods

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base case value</th>
<th>Sensitivity values</th>
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<tr>
<td>Aquifer hydraulic conductivity, $K$ [m/d]</td>
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<td>10, 100</td>
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<td>Riverbank hydraulic conductivity, $K_r$ [m/d]</td>
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<td>Riverbed thickness, $B_r$ [m]</td>
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<td>Saltwater density, $\rho_s$ [kg/m$^3$]</td>
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<td>High river water level, $H_{hr}$ [m]</td>
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<td>Inland boundary saltwater level, $H_i$ [m]</td>
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<td>1, 5</td>
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<tr>
<td>Aquifer depth, $D$ [m]</td>
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<tr>
<td>Floodplain geometry, $(l, b)$ [m]</td>
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<td>Stage durations of river flood, $(t_1, t_2, t_3)$ [d]</td>
<td>T2: (58, 110, 58), T3: (58, 160, 58)</td>
<td></td>
</tr>
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</table>
et al., 2015) were also tested (Table 3). $K_{nh}$ of the floodplain region was set to 60,000 m/d in regional-scale models, which allowed overbank flow to rapidly cover the floodplain. $D_{sr}$, $n_{sr}$, $S_{sr}$, and $S_{1}$ were set to 0 m$^2$/d, 0.35, 0.25, $10^{-5}$ m$^{-1}$, respectively.

Three different values of $t_2$ (i.e., 60, 110, and 160 d) were considered, producing three flood stage duration scenarios (designated T1, T2, and T3, respectively; Table 3), each with a constant $t_1$ and $t_3$ (i.e., 58 d). The stage durations and heights of river flood events (i.e., $H_{ut}$, $H_{hr}$, $t_1$, $t_2$, and $t_3$; Table 3) were adapted from measured time series of river water levels downstream of Lock 4, River Murray (from River Murray Data: https://riverdata.mdba.gov.au/lock-4-downstream). That is, $H_{ut}$ approximates the average river water level downstream of Lock 4 from 1 October 2007 to 1 October 2021, excluding data during periods of flooding. Figure S2 in Supporting Information S1 depicts river levels for this period. Four flooding events evident in the data set were reproduced as simplified representations of constant flood water levels, as shown in Figure S2 in Supporting Information S1, and these were applied in field-scale numerical simulations (see Table S2 in Supporting Information S1).

2.5. Quantitative Indicators

The quantification of lens responses to a single river flood event, within laboratory experiments and numerical models, was based on the temporal changes in $x_h$ and $V_c$. In numerical simulations, the 0.5 relative salinity isochlor was tracked as an approximation of the freshwater-saltwater interface (e.g., Jazayeri et al., 2022). In addition, to examine the salt load to the adjacent river, temporal changes in $q_{sr}$ [L$^2$T$^{-1}$] (defined as the saltwater flux per unit width discharged into the river) were quantified and analyzed.

3. Results

3.1. Laboratory Experiments

Lenses obtained from laboratory experiments and numerical simulations of experiments A−S, B−S, and C−S (i.e., 5 min flooding event with no floodplain, 0.6 m wide floodplain, and 1.2 m wide floodplain, respectively; see Table 2 for scenario definitions) are compared in Figure 5. Results also include water table and flow vector distributions obtained from numerical models. Figure 5 shows that numerical simulations well reproduced the experimental observations in terms of the freshwater-saltwater interface. The experimental water table cannot be depicted by the red dye tracer due to capillary effects, and thus the water table was shown only from the numerical simulation (i.e., the cyan line).

Figure 5 shows that more expansive lenses are apparent in the experiments with a larger floodplain inundation extent (e.g., panels (b3–b4) and (c3–c4)), as expected. The flow vectors shown in Figure 5 reveal the lens and saltwater dynamics, whereby the lens was replenished during the rising and high-level stages, while freshwater returned to the river as the lens shrank during the falling stage. Expansion of the lens in experiment A−S was driven by freshwater infiltration through the vertical riverbank (i.e., the lens shows primarily horizontal flow), whereas in experiments B−S and C−S, freshwater infiltration through the floodplain surface caused the horizontal displacement of the lens tip away from the riverbank, as reflected by mainly vertical flow within the lens. Overtopping caused rapid freshening and a relatively elongated lens during early times (e.g., Figure 5 (b3–b4) and (c3–c4)).

The river gained saltwater during all stages of the flood event, indicated by flow vectors within the saltwater region have a component of flow toward the river (i.e., adjacent to the riverbank; Figure 5). During the falling and final re-stabilization stages (i.e., Figure 5 (a4–c4) and (a5–c5), respectively), groundwater flow in the saltwater region was toward the river throughout the entire model domain, as expected. However, during the rising and high-level stages (i.e., Figure 5 (a2–c2) and (a3–c3), respectively), a groundwater flow divide was apparent in the saltwater zone, leading to riverward saltwater flow in the vicinity of the river and otherwise landward flow in the remaining areas. This outcome indicates a situation analogous to the simultaneous occurrence of both active (i.e., saltwater and freshwater flowing in the same direction) and passive (i.e., saltwater and freshwater flowing in opposite directions) seawater intrusion in coastal aquifers (e.g., Werner, 2017b). That is, the lens is buoyancy-controlled near the river (with saltwater and freshwater passively flowing in opposite directions) but advances with the regional groundwater flow direction (i.e., saltwater and freshwater actively flowing in the same direction) at larger distances from the river. This is best illustrated in (c3) of Figure 5.
In experiment sets B and C, mismatch between the experimental mixing zone and numerical interfaces is apparent around $x = 0.2$ m at the end of the rising and falling stages (Figure 5). This deviation may be attributable to the uniform floodplain surface elevation of 0.3 m adopted in the numerical model, ignoring the micro-topographic variation of the experimental floodplain. To evaluate this hypothesis, the floodplain topography in experiment B–S was corrected by accurately depicting the sand surface with a polyline. The freshwater-saltwater interface and flow vector distribution arising from the numerical simulation that adopts the corrected floodplain topography (i.e., “modified” case) are compared with the corresponding numerical simulation without correction (the floodplain surface elevation is fixed at 0.3 m, i.e., “unmodified” case) in Figure S3 in Supporting Information S1. The results demonstrate that, during the high-level stage of the modified case, small variations in the sand surface adjacent to the freshwater reservoir blocked the overtopping flow, and rather, the water overlying the low-lying sand surface ($0.2 < x < 0.6$ m) originated from the water table, which rose above the sand surface in response to the river level rise. Thus, some of the surface water was in fact groundwater discharge derived from flow through the lens (Figure S3a in Supporting Information S1). Consequently, where $x < 0.2$ m, flow vectors within the lens of the modified case show a clear upward trajectory, with greater velocity magnitudes compared to the unmodified case (Figure S3a in Supporting Information S1). The modified case more accurately captured the characteristics of the mixing zone in experiment B–S compared to the unmodified case (Figure S3 in Supporting Information S1). The same improved representation of the surface topography can be expected to improve the model results for other experiments.

Figure 5. Experimental and numerical results for experiments A–S (a1–a5), B–S (b1–b5), and C–S (c1–c5). Experimental images at different times are shown, and the corresponding river stages are given in the panels of the top row. The freshwater-saltwater interface (i.e., 0.5 isochlor; blue dashed line), water table (cyan solid line), and flow vectors (white arrows; only 0.42% of vectors shown) obtained from numerical simulations are included in each panel, where vector magnitudes (indicated by vector length) adopt consistent scaling across the panels. The black dotted lines in panels (b2–b3 and c2–c3) represent the water divide separating riverward and landward saline groundwater flow.

Figure 6 shows the temporal changes of $x_L$ and $V_L$ obtained from the experimental and numerical results of experiments A–S, B–S and C–S. Figure 6 indicates that the experimental values of $x_L$ and $V_L$ (obtained from image
processing of the experiments' photos) are reasonably matched to the numerical predictions. A sudden increase in $x_L$ was observed in both experiments B−S and C−S due to the presence of floodplain inundation. The maximum $x_L$ and $V_L$ for the three experiments (i.e., A−S, B−S, and C−S) were achieved during the falling stage, indicating a time lag between flooding and the lens response (i.e., time from the end of the high-level stage to peak $x_L$ and $V_L$), except for $x_L$ in experiment C−S, for which the maximum $x_L$ was obtained during the high-level stage (i.e., when the freshwater lens tip reached the landward boundary). The time lags, in terms of $V_L$, for experiments A−S, B−S, and C−S were 30, 85, and 135 s, respectively. Clearly, steady-state conditions were not reached during the high-level stage.

For experiment B−S, the maximum values of $x_L$ (0.71 m) and $V_L$ (0.021 m$^2$) were larger than those of experiment A−S by 61.4% and 23.5%, respectively. For experiment C−S (where floodplain inundation extent was twice that of experiment B−S), the maximum values of $x_L$ (1.20 m) and $V_L$ (0.027 m$^2$) were 173% and 58.8% larger, respectively, compared with experiment A−S.

Experimental and numerical lenses from experiments A−L, B−L, and C−L (i.e., scenarios with longer flooding durations; $t_2 \approx 10$ min) are shown in Figure S4 in Supporting Information S1. Figure S4 in Supporting Information S1 shows that numerical results again reasonably reproduce the experimental observations in terms of the freshwater-saltwater interface. The lens responded to changes in the inundation extent in a similar manner to that illustrated in Figure 5 (i.e., for a floodplain of half the landward extent). For example, the flow divide in the saltwater region was again apparent, along with other phenomena apparent in Figure 5. Figure S5 in Supporting Information S1 quantitatively compares $x_L$ and $V_L$ of experiments A−L, B−L, and C−L with those obtained from numerical simulations. The results show that the experimental $x_L$ and $V_L$ are again in reasonable agreement with the numerical predictions. Also, the period of flooding does not lead to a steady-state flood condition, as

![Figure 6](image_url)
previously. $x_L$ in experiments A–L, B–L, and C–L reached 0.55, 0.82, and 1.20 m, respectively, and the corresponding peak values of $V_L$ were 0.023, 0.029, and 0.035 m$^3$. Compared to experiment A–L, $x_L$ of experiments B–L and C–L increased by 49.1% and 118%, respectively, and $V_L$ of experiments B–L and C–L increased by 26.1% and 52.2%, respectively.

A comparison of Figure 6 and Figure S5 in Supporting Information S1 reveals the impact of $t_2$ on lens behavior, which is quantified in Table S4 in Supporting Information S1. The larger $t_2$ of A–L, B–L, and C–L produced a more extensive lens in terms of $x_L$ and $V_L$, except for $x_L$ in experiment set C, which had the same maximum value (i.e., 1.20 m) for both experiments C–S and C–L. This was caused by the constraint of the sand tank length. Doubling $t_2$ led to a similar increase in $x_L$ (i.e., ~0.11 m) for both experiments A–L and B–L (with respect to A–S and B–S, respectively), while the increase in $V_L$ (i.e., ~0.008 m$^3$) for experiment set B was greater than that of experiment set A (i.e., ~0.006 m$^3$; Table S4 in Supporting Information S1).

### 3.2. Sensitivity Analysis

The sensitivity analysis was conducted based on the field-scale numerical simulations using the ranges of $H_w$, $t_2$, $K$, and $\alpha_t$ given in Table 3. Three floodplain geometry scenarios, S1, S2, and S3 (i.e., floodplains with different lateral extents), were considered for each parameter combination. Temporal changes of $x_L$, $V_L$, and $q_w$ were quantified and analyzed.

Figure 7 shows the sensitivity of temporal changes in $x_L$, $V_L$, and $q_w$ to the variations of $H_w$ (i.e., 28, 28.5, and 29 m) and $t_2$ (i.e., 60, 110, and 160 d) in scenarios S1, S2, and S3, with other field-scale parameters listed in Table 3. The results are largely intuitive. For example, for a given scenario (i.e., S1, S2, or S3), a more extensive lens (in terms of $x_L$ and $V_L$) was obtained with a greater $H_w$ or $t_2$. Where $H_w$ and $t_2$ were fixed, a greater inundation extent (i.e., scenarios S1 < S2 < S3) led to larger peak values of $x_L$ and $V_L$ (Figure 7).

The results in Figure 7 reveal the lens and saltwater dynamics in different scenarios (i.e., S1, S2, and S3). In all scenarios, both $x_L$ and $V_L$ increased over time during the rising and high-level stages, as expected. A sharp increase in $x_L$ was observed in scenarios S2 and S3 due to the occurrence of floodplain inundation during the rising stage (Figures 7a and 7d). During the falling and re-stabilization stages, a downward trend in both $x_L$ and $V_L$ was apparent in scenario S1, whereas in scenarios S2 and S3, temporal changes in $x_L$ and $V_L$ were more complex. For example, in the base case (i.e., $H_w = 28.5$ m and $t_2 = 110$ d) of scenario S3, both $x_L$ and $V_L$ were stable or continued to increase, albeit slightly, during the falling stage (the red dotted lines in Figures 7a and 7b, respectively), indicating an important time lag between the flood event and the lens response (further explained in Figure 8).

Figure 7 shows that in scenario S3, both $x_L$ and $V_L$ (the dotted lines) abruptly dropped after a period of minimal change during the re-stabilization stage. These vertical drops in $x_L$ and $V_L$ occurred because the lens split into two parts during the recession period. That is, one part was in hydraulic connection with the adjacent river and the other part was relatively isolated, floating on saline groundwater. This lens splitting behavior is further explained in Figure 8. Only the extent and volume of the part of the lens connected to the river were considered in $x_L$ and $V_L$ estimations, respectively, thus causing rapid drops in $x_L$ and $V_L$ when part of the lens became detached. After the lens split, $x_L$ and $V_L$ values from scenario S3 (the dotted lines) were lower than the corresponding values of scenario S2 (the solid lines without vertical drops; Figure 7).

Figures 7a and 7d show that in the final re-stabilization stages of scenarios S2 and S3, $x_L$ may reduce to a value (e.g., 83.2 m < $x_L$ < 97.5 m at $t = 1,600$ d) lower than the steady-state value (i.e., $x_L = 106.8$ m at steady state), instead of stabilizing at the steady-state value obtained prior to the flooding event. This lens extent variation after flood recession suggests an “overshoot” behavior of the lens (further explained in Figure 8), which is similar to seawater intrusion overshoot encountered in coastal aquifers (e.g., Morgan et al., 2013).

The temporal behavior of $q_w$ in Figure 7 (i.e., (c1–c3) and (f1–f3)) indicates that the saltwater discharge to the adjacent river was highly modified by the flood event. In scenario S1, $q_w$ decreased significantly during the rising stage, then increased slightly during the high-level stage, rose sharply to a peak value during the falling stage and eventually dropped and approached a constant value equal to the pre-flood steady-state value. Temporal changes of $q_w$ in scenarios S2 and S3 showed a different trend to that of scenario S1. During the rising stage of scenarios S2 and S3, $q_w$ first decreased significantly, but then sharply increased to a value slightly larger than the initial
Figure 7. Numerical results of the sensitivity of $x_L$, $V_L$, and $q_s$ (saltwater flux into the river per unit width) to changes in $H_{hr}$ (panels (a, b, and c1–c3), respectively) and $t_2$ (panels (d, e, and f1–f3), respectively) for scenarios S1, S2, and S3 (see “floodplain geometry” in Table 3). Note that the light pink, light yellow, and light blue areas represent the rising, high-level, and falling stages of the base case (i.e., T2 given in Table 3), respectively.
(pre-flood, steady-state) value of $q_{sr}$ due to the occurrence of inundation (Figure 7 (c2–c3) and (f2–f3)). This outcome can be attributed to the complex dynamics of saltwater flow under floodplain inundation, whereby a saltwater divide occurs below the lens, as previously described in Figure 5. For all cases, $q_{sr}$ peaked near the end of the falling stage, indicating that saltwater discharge to the adjacent river may increase immediately following flood recession. For a given scenario (i.e., S1, S2, or S3), a slightly greater peak value of $q_{sr}$ was obtained in the case with a larger $H_{hr}$ or a lower $t_2$. Compared with scenarios S2 and S3, the no inundation scenario (i.e., S1) involved a smaller increase in the saltwater discharge to the adjacent rivers during the period of high-water levels.

Figure 8 shows the lens dynamics at different times in the base case (i.e., $H_{hr} = 28.5$ m and $t_2 = 110$ d) of scenarios S2 and S3. As shown in Figure 8 (a2) and (b2) (i.e., at the end of the high-level stage, 168 d), the interface below the landward edge of the floodplain bulges downward, indicating the occurrence of preferential freshwater infiltration. That is, during the high-level stages, the entire floodplain has the same hydraulic head (i.e., equal to the river stage), whereas the landward edge of floodplain is closer to the inland constant-head boundary, thereby producing a large hydraulic gradient toward the inland (according to the Darcy’s law). Whether this effect is likely to occur in real-world conditions will depend on the nature of the inland boundary and the contribution of buoyancy-driven flow to this phenomenon. We expect the inland boundary to rise as floodwater recharges the aquifer in real-world settings, which is likely to reduce the preferential infiltration near the landward edge of the floodplain that was observed in the numerical results.

Figure 8 reveals the mechanism for the time lag between the flood recession and the lens extent response in scenarios S2 and S3 that is shown in Figures 7a and 7d. For example, Figure 8 (a2–a4) and (b2–b4) indicate that
there was no significant reduction in lens extents during the falling stage (i.e., 168 d ≤ t ≤ 226 d), even though the lens thinned and showed other complex behavior during that time. During the falling stage of scenario S3 (Figure 8 (b8)), the lens thinned (through downward movement of the freshwater-saltwater interface) over the region ∼440 m ≤ x ≤ ∼520 m, while the lens thickened in other locations (e.g., x ≤ ∼440 m and x ≥ ∼520 m), leading to an overall increase in $x_L$ and $V_L$. Similar complex motion in the interface also influenced the $V_L$ variation during the falling stage of scenarios S2 and S3 (Figures 7b and 7c).

The results in Figure 8 also highlight some differences in lens contraction processes between scenarios S2 and S3. For example, the lens splitting behavior in scenario S3 (Figure 8 (b5–b6)) was not observed in scenario S2 (Figure 8 (a5–a6)). In scenario S3, the lens that formed during the flood period was relatively thin over the middle part of the floodplain (i.e., 250 m < x < 350 m; Figure 8 (b2–b4)). This feature was more obvious as the flood receded (due to the combination of lowering water tables and enhanced freshwater-saltwater mixing), and eventually resulted in the lens bifurcation (or “splitting behavior”) (Figure 8 (b2–b6)). However, the lens in scenario S2 was thicker over the middle region of the lens than in scenario S3, which precluded lens splitting, allowing the lens to remain as a single body of freshwater through the recession period (Figure 8 (a2–a6)).

Figure 8 (a8 and b8) also shows that differences occurred between the pre-flood ((a1) and (b1)) and post-flood lens shapes ((a7) and (b7), respectively). We attribute this to overshoot behavior, whereby the lens temporarily shrank to a smaller size before growing to the eventual steady-state condition that was observed prior to the flooding event. For example, in scenario S3 (Figure 8 (b8)), the post-flood lens tip location at $t = 1,600$ d (i.e., 85.9 m) was apparently riverward of the steady-state tip location (i.e., 106.8 m). Due to the presence of extensive diluted saltwater on the landward side of the interface (Figure 8 (a7 and b7)), overshoot lenses may take a long time to return to the pre-flood, steady-state conditions. To explore this, a selection of long-time simulations was developed, although long computer run-times limited the number and duration of those models. Figure S6 in Supporting Information shows the comparison of transient (i.e., the base case of scenarios S1, S2, and S3; Table 3) and steady-state lens characteristics (i.e., $x_L$ and $V_L$) for a long simulation time (i.e., 8,000 d). The results indicate that the overshoot behavior was generally observed in scenarios involving inundation (i.e., scenarios S2 and S3) and was more pronounced in the scenario of larger inundation extent. It took a considerable amount of time (i.e., >4,000 d) for the overshoot lens in scenario S3 to return to steady-state conditions, indicating an unintuitive, adverse effect (i.e., “overshoot” here involves a small lens than the final steady-state condition) of extensive inundation.

Figure 9 shows the sensitivity of the temporal changes in $x_L$, $V_L$, and $q_{sw}$ to variations of $K$ (i.e., 10, 20, and 100 m/d) and $\alpha_L$ (i.e., 1.0, 2.5, and 5.0 m) in scenarios S1, S2, and S3. Other field-scale parameters are listed in Table 3. As shown in Figure 9, for a given scenario (i.e., S1, S2, or S3), a more extensive lens (in terms of the maximum values of $x_L$ and $V_L$) was observed in the cases of greater $K$ or lower $\alpha_L$. Where $K$ and $\alpha_L$ were fixed, larger peak values of $x_L$ and $V_L$ were again obtained in the scenario with greater inundation extent (i.e., scenarios S1 < S2 < S3), as expected.

Figures 9a and 9b show that trends in $x_L$ and $V_L$ for $K = 100$ m/d (i.e., scenario S3; green lines) deviated significantly from those for $K = 10$ and 20 m/d (i.e., red and blue lines, respectively). The lens for $K = 100$ m/d expanded faster (in terms of $x_L$ and $V_L$) during the river flood event and shrank more rapidly after the flood event (Figure 9b), compared to those of $K = 10$ and 20 m/d; an expected consequence of the higher permeability. This was accompanied by a delay (by > 220 d relative to S1 and S2) in the occurrence of lens splitting in scenario S3 (during flood recession)—indicated by the sharp change in $x_L$ in Figure 9a.

The results in Figures 9d and 9e show that, in scenarios S2 and S3, the trends of $x_L$ and $V_L$ were more complex for $\alpha_L = 5.0$ m compared to $\alpha_L = 1.0$ and 2.5 m. When $\alpha_L = 5.0$ m, two vertical drops in $x_L$ of scenario S3 (the green dotted line in Figure 9d) were observed, indicating two lens splitting events. Salinity distributions confirm this phenomenon, as shown in Figure S7 in Supporting Information S1. However, only one vertical drop in $x_L$ was observed for scenario S3 with $\alpha_L = 1.0$ and 2.5 m (i.e., the blue and red dotted lines in Figure 9d, respectively). This outcome highlights the controlling effect of $\alpha_L$ on lens splitting. It follows that aquifer heterogeneities (for which $\alpha_L$ is a common surrogate; Rajaram & Gelhar, 1995) are likely to also play an important role in lens splitting in real-world settings.

The temporal behavior of $q_{sw}$ in Figures 9c and 9f is generally similar to that shown in Figures 7c and 7f. For all cases, the peak value of $q_{sw}$ occurred at around the end of the falling stage. A higher peak value of $q_{sw}$ for a given
Figure 9. Numerical results of the sensitivity of $x_L$, $V_L$, and $q_{sr}$ (saltwater flux into the river per unit width) to changes in $K$ (panels (a, b, and c1–c3), respectively) and $\alpha_L$ (panels (d, e, and f1–f3), respectively) for scenarios S1, S2, and S3 (see “floodplain geometry” in Table 3). The light pink, light yellow, and light blue areas represent the rising, high-level, and falling stages of the base case (i.e., T2 given in Table 3), respectively.
4. Discussion

4.1. Laboratory Versus Field-Scale Conditions

The dimensionless variables of $x_L^*$ [-] (lens extent), $a^*$ [-] (saltwater flux), and $b^*$ [-] (stream-aquifer conductivity) proposed by Werner et al. (2016) were introduced for the comparison of lenses under the laboratory and field-scale conditions. Expressions of dimensionless variables and the corresponding values for the laboratory setup and field-scale conditions (i.e., the River Murray) are given in Table 4.

The results in Table 4 show that $x_L^*$ had a range of 0.013–0.020 for the field conditions adopted in the current study. $x_L^*$ for the base case laboratory experiment ($=0.022$) was slightly higher than the upper limit of $x_L^*$ from field conditions. In contrast, $a^*$ was an order-of-magnitude higher while $b^*$ was lower in laboratory experiments compared to the ranges obtained for field conditions. The higher value of $a^*$ indicates larger saltwater fluxes relative to the buoyancy force in laboratory experiments (Werner et al., 2016). The laboratory experiment involved relatively weak streambed resistance (i.e., the plastic screen) compared to field conditions, on the basis of $b^*$. The field case adopting the lowest $\alpha_L^* (=1\ \text{m})$ led to $x_L^*$ closer to the experiment. This outcome reveals that the dispersion effect in the laboratory experiment was also relatively weak.

The representative value (i.e., 0.5 isochlor) for tracking the lens shape had little effect on the experimental result (e.g., $x_L$ and $V_L$), because the mixing zone within experiments was thin. However, as the field-scale models involved higher dispersion values (e.g., $\alpha_L = 1.0$–5.0 m), it follows that the use of alternative solute concentrations for representing the freshwater-saltwater interface would likely modify the results, in terms of $x_L$ and $V_L$ (see Figure S8 in Supporting Information S1 showing the comparison of numerical results calculated using 0.1 and 0.5 isochlor, respectively). The result in Figure S8 in Supporting Information S1 indicates significant expansion of lens mixing zones in scenarios S2 and S3, which reflects greater mixing during flood recession. This is evident in Figure 8 (a4–a7) and (b4–b7), which shows that saltwater movement and groundwater flow are in the same direction during the falling stage, favoring the formation of a broad mixing zone (e.g., Badaruddin et al., 2017; Werner, 2017b).

The current laboratory experiment failed to reproduce the lens splitting behavior that was encountered in field-scale simulations. The reason for this outcome can be inferred from the sensitivity analysis based on the field-scale conditions. The results in Figure 9 indicate that $K$ and $\alpha_L$ exert opposite effects on the integrity of the shrinking lens. That is, high $K$ may delay and weaken the lens splitting behavior, while larger $\alpha_L$ is more likely to cause the lens to split (Figure 9). Compared to the field conditions, the current laboratory experimental setup involved a higher $K$ and lower dispersion effect (as described above), and thus lens splitting was less likely to occur.

4.2. Implications for Natural Rivers

An important consideration for river salinization management is to reduce subsurface salt load. Previous studies have investigated a series of interventions to reduce the saline groundwater discharge to the adjacent river,
including extraction of saline groundwater, injection of freshwater, artificial flooding, and construction of low-permeability barriers (e.g., Alaghmand et al., 2016; Berens et al., 2009; Wu et al., 2020). However, our analysis reveals a high peak saltwater influx to the adjacent river following the flood event (Figures 7 and 9), potentially exacerbating the river salinity in the short term, albeit the river discharge may still be quite high during recession periods allowing for dilution of saltwater discharge. This outcome is consistent with reporting of the River Murray, South Australia (Telfer et al., 2012), which suggested that a high salt load to the river may persist for more than 12 months (i.e., post-flood). Our modeling results show that extending the falling stage duration of the flood event can reduce the peak saltwater influx (see Figures S9a–S9c in Supporting Information S1, which shows the comparison of the field-scale cases considering different durations (i.e., 58 and 116 d) of the falling stage). This should be considered in designing artificial flooding or river stage manipulation where salinity impacts on the river are an issue.

Although we excluded the extent and volume of the isolated lens that arose from the splitting of the main body of the lens from the analyses of the current study, the extent and volume of the isolated lens can be substantial. For example, in the base case of scenario S3, the isolated lens had a maximum extent of 286.8 m and a maximum volume (per unit width of the aquifer) of 178.0 m³. From an ecological point of view, these isolated lenses may play an important role in sustaining the overlying vegetation communities relatively far from the river regime. Cross-sectional airborne electromagnetic (AEM) results for the Clark Floodplain (River Murray, South Australia) indicate the occurrence of low-salinity groundwater lenses that seemed to be isolated from the lens adjacent to the river (i.e., Munday & Soerensen, 2018). Those isolated lenses, observed in 2006, had disappeared by 2015 according to cross-sectional AEM results, which was attributed in part to the absence of flooding recharge (Munday & Soerensen, 2018).

Our study found that the lens response to flooding is sensitive to the floodplain microtopography. Results in Figure S3 in Supporting Information S1 show that small changes in floodplain topography can significantly modify the saltwater-freshwater interface. Surface microtopography can spatially and temporally alter flood-induced lens dynamics. Depressions within the topographic surface trigger puddle filling and spilling behavior, and interrupt overland flow, thereby increasing infiltration at water-ponding sites (Yang & Chu, 2015). Floodplain microtopography may delay the initiation of overbank flow and the recession of floodwater, thereby controlling the expansion or contraction of freshwater lenses. These microtopographic controls may also cause isolated lenses observed in the field (e.g., AEM results of Munday & Soerensen, 2018), especially following flood events.

Previous investigations of lenses have emphasized the role of inland boundary conditions (e.g., Werner & Laattoe, 2016; Wu et al., 2020). It can be expected that the landward boundary condition will also modify the lens response to the river flood. The comparison of field-scale cases considering different inland boundary conditions (i.e., constant-head or constant-flux) is shown in Figures S9d–S9f in Supporting Information S1. The results in Figures S9d–S9f in Supporting Information S1 show that, in the case of constant-flux inland boundary conditions, the extent and volume of the lenses were sharply reduced immediately after the river flood receded, and a higher peak saltwater influx (i.e., around the end of the river flood) was observed, compared to that under the constant-head condition. That is, lenses had a greater extent and volume under constant-head rather than constant-flux boundary conditions.

Real-world river-aquifer systems in semi-arid and arid regions are episodic and therefore highly dynamic (Woods et al., 2015). Processes or factors not considered here but often encountered in real-world environments can also change the behavior of lenses. For example, Figure S2 in Supporting Information S1 shows that multiple flooding events were experienced over several years. These successive floods can prevent the lens from experiencing long-term decay, thereby maintaining a sizable lens. In contrast, drought conditions may increase the risk of salinization of post-flood lenses with shallow water table depths, potentially leading to highly modified, complex lenses (e.g., America et al., 2020). Thus, future work should consider multiple flooding events of differing duration in exploring the resilience of riparian freshwater lenses.

The saltwater densities considered in the current study (i.e., 1,025 and 1,037 kg/m³ under laboratory- and field-scale conditions, respectively) fall within the typical range (i.e., from 1,012 to 1,042 kg/m³) reported by Werner and Laattoe (2016). Nonetheless, the lens response to flooding may change for alternative density contrasts between freshwater and saltwater. In floodplains with lower-density contrasts, smaller lenses are expected under steady-state conditions (Werner & Laattoe, 2016). However, the effect of the density contrast on the lens response to flooding is unclear and remains an area for further investigation.
Holland et al. (2009) found in the field survey of the floodplain of the lower Murray River that the upper floodplain soil may consist of clay deposits, while the underlying aquifer was comprised of sand. Heterogeneity of riparian aquifers is likely to reduce or prevent vertical floodwater infiltration through the floodplain surface in some locations, while allowing it to occur at high rates (e.g., through clay cracking) in others. The effect of heterogeneity on the lens response to floodplain inundation should be assessed further, including where clay-rich soils are absent or discontinuous, to assess the implications for flooding-induced lens formation and decay.

Furthermore, in the current study, the lens response to flooding was examined through a fully saturated method (i.e., based on SEAWAT), which ignored the effect of the unsaturated zone. This method is considered applicable to floodplain systems where the water table is relatively shallow (avoiding lag times in the flood-recharge response). We were able to simulate the rapid response of the water table to flooding using the cell wet-dry conversions of SEAWAT (i.e., using BCF package). Nonetheless, unsaturated models are recommended to examine the response of lenses to flooding in floodplains with deep water tables or where evapoconcentration of soil salinity between flooding events (e.g., America et al., 2020) is considered.

5. Conclusions

The sensitivity analysis based on field-scale simulations indicates that for a given floodplain geometry, greater river level rise, longer high-level stage duration, a lower dispersivity, or a higher hydraulic conductivity produced larger lens extent and volume during the river flood period. When comparing the impact of floodplain inundation, the largest lens extent and volume were observed in the scenario with the greatest floodplain inundation. However, during flood recession, the lens may split into multiple parts by riverward saltwater flow, depending on the floodplain geometry and hydrogeological parameter values. Dispersion effects can be significant during flood recession where floodplain inundation occurs, potentially causing lens thinning over its entire length as the flood recedes. In particular, floodplain micro-topography can significantly modify the lens shape response to flooding. Numerical estimates of lens shapes observed in sand tank experiments involving floodplain inundation were improved by considering micro-topographic changes in the experimental floodplain.

The peak saltwater discharge to the river generally occurred around the end of the falling stage, potentially causing post-flood salinization of the river. However, this peak can be reduced by extending the flood recession period, which may be possible where flooding is induced by artificial river level manipulation. The analyses presented herein describe new observations of lens behavior and saltwater discharge under flooding and recession conditions. In order to better inform the assessment and management of lenses in semi-arid or arid regions, future work should consider more complex conditions, including multiple flood cycles, sediment heterogeneity (including low-permeability floodplain soils and cracking clays), and the effects of evapotranspiration, to build on the results presented here for relatively simple conditions. Additionally, field sites where flooding effects can be observed and modeled are needed to validate the overall conclusions drawn from experimental findings and models with simplified representations of field conditions.

Data Availability Statement

No data was used, as the paper is theoretical.

References


