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The magnitude and variability of lateral seepage in California rice fields

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ABSTRACT

Lateral seepage can be an important water loss pathway at the field level and a conduit for the discharge of pesticides and nutrients from rice fields. However, few studies have directly measured lateral seepage rates in flooded rice fields. This study sought to characterize the magnitude and variability of lateral seepage in California rice fields, and to explore the relationship between lateral seepage and soil properties or hydrologic conditions. Lateral seepage was measured during the growing season at 50 locations spread across six rice fields using a methodology that operates analogously to a double-ring infiltrometer. Lateral seepage rates varied over four orders of magnitude (0.05–33.11 $cm^2\,h^{-1}$ or 0.0011–1.05 $cm\,h^{-1}$), though even the highest rate measured was small compared to typical water inputs in California rice fields, and lateral seepage corresponded to only 1.0%–1.9% of water inputs at sites where irrigation inputs were measured. Lateral seepage was negatively correlated with levee width ($p = 0.025$) and the relative water height in the adjacent field, supply canal, or drainage ditch ($p = 0.045$), though this relationship explained little of the variation in lateral seepage rates (marginal $r^2 = 0.129$). Contrary to expectations, not all supply canals or higher flooded fields were a source for lateral seepage into fields, as unsaturated zones present in most levees served as a sink for lateral seepage from both sides of the levee. Future research should examine the prevalence of preferential flow pathways in rice field levees and the potential for transport of nutrients or agrochemicals through these flow pathways.

1. Introduction

Rice (*Oryza sativa*) accounts for only 10% of global cropland, yet rice fields are estimated to receive 23–43% of all irrigation water worldwide (Bouman et al., 2007; GRiSP, 2013; Mekonnen and Hoekstra, 2011). Evapotranspiration, which is the major outflow in non-rice cropping systems, has been estimated at 680 to 870 mm $season^{-1}$ for rice (Linquist et al., 2015; Montazar et al., 2017), comparable to many other crops. The high applied water footprint of rice production must therefore be explained by surface drainage from the field, which is controlled by the farmer, and percolation and lateral seepage, which are uncontrolled losses at the field level. Percolation is the downward movement of water to below the rice root zone, and lateral seepage is the subsurface movement of water through the levees (sometimes referred to as bunds) that border the rice fields (Bouman et al., 2007). Due to the influence of numerous hydrologic and edaphic factors, lateral seepage losses from rice fields are highly variable: for example, a single study observed lateral seepage losses that ranged from 2% to 75% of the water inputs to each field (Tsubo et al., 2007a). Lateral seepage losses at the field level are commonly recaptured and reused downstream and thus may not represent losses at the landscape level (Hafeez et al., 2007; Roost et al., 2008). Nonetheless, lateral seepage may be an important consideration for reducing applied water at the field level, as well as for controlling the off-site transport of pesticides and nutrients.

Lateral seepage is governed by Darcy's law (except in some cases of nonlaminar preferential flow), which states that this flow will be a product of the hydraulic head gradient and the saturated hydraulic conductivity of the soil (Hillel, 1998). The former is a function of the levee width and the relative water height on both sides of the levee (or the relative groundwater height in cases where lateral seepage flows to the groundwater). The latter, the saturated hydraulic conductivity, is an intrinsic property of each soil that depends on its total porosity and pore size distribution, which in turn depend on soil texture and structure (Hillel, 1998). Saturated hydraulic conductivity, bulk density, levee width, soil texture, and the relative difference in water height (or hydraulic head) all affect lateral seepage rates, especially as these values go to their extremes. These last three parameters are of particular interest as they affect the hydraulic head gradient and saturated hydraulic conductivity but can be measured in commercial rice fields without destructive sampling of the border levees.

Quantifying the magnitude of lateral seepage losses is critical for

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understanding the potential for transport of agrochemicals and nutrients from rice fields. Lateral seepage has been studied through modeling efforts for its role in pesticide movement (Boulange et al., 2014; Phong et al., 2011) and through both modeling (Liang et al., 2007; Liang et al., 2014a) and physical studies (Liang et al., 2008; Liang et al., 2013; Xu et al., 2017) for its contribution to nutrient transport. Understanding lateral seepage is also critical to determining the potential impact of alternative irrigation practices that are designed to reduce applied water to rice fields. For example, alternate wetting and drying (AWD) has been extensively investigated worldwide (Carrijo et al. 2017), and field-level water savings associated with AWD are expected to come principally from reductions in percolation and lateral seepage (Lampayan et al., 2015). The percent of applied water lost as lateral seepage will depend on the field area and perimeter (Janssen and Lennartz, 2009), and given the small field size associated with many AWD studies (e.g. Abbasi and Sepaskhah, 2011; de Vries et al., 2010; Dunn and Gaydon, 2011; Feng et al., 2007), quantifying lateral seepage on commercial-scale rice fields should provide a better estimate of the potential for reducing applied water with novel irrigation management strategies. Despite the important role lateral seepage may play in field-level water losses and agrochemical movement, relatively few studies have directly measured lateral seepage from rice fields during the growing season (Janssen and Lennartz, 2008; Janssen and Lennartz, 2009; Liang et al., 2008; Liang et al., 2013) or used a water balance to estimate lateral seepage separately, rather than combined percolation and lateral seepage (Agrawal et al., 2004; Kukal and Aggarwal, 2002; Tsubo et al., 2007a; Wopereis et al., 1994).

There has been little research on lateral seepage in California rice production, even though rice is grown on over 200,000 ha and agricultural water use is frequently under scrutiny in the heavily irrigated and drought-prone state (USDA, 2017). Linquist et al. (2015) developed a water balance in commercial California rice fields and estimated combined percolation and lateral seepage (the residual term based on the difference method) at 27 cm or 15% of the total water input. The authors suggested that this combined loss was principally due to lateral seepage after comparing the combined loss with saturated hydraulic conductivity data from an earlier study (Liang et al., 2014b) and speculated that drainage ditches surrounding some fields may have been responsible for the relatively higher lateral seepage rates (Linquist et al., 2015). Given the increasing pressure on growers to reduce applied water and the need to avoid pesticide transport through rice field levees, it is important to understand the magnitude and variability of lateral seepage in California rice fields.

Our objectives in this study were to 1) quantify the variability in lateral seepage rates for levees typical of California rice fields, (2) situate field-level lateral seepage losses within the context of water inputs to rice fields, and 3) determine whether variability in lateral seepage rates was correlated with soil properties or hydrologic conditions that water managers could non-destructively measure in commercial rice fields.

2. Materials and methods

2.1. Study sites

Lateral seepage measurements were taken from border levees of five commercial rice fields spread throughout the Sacramento Valley and at the California Cooperative Rice Research Foundation's Rice Experiment Station in Biggs, CA (Fig. 1). Sites were chosen to be representative of California rice fields and to ensure adequate geographic representation (Table 1). A total of 50 direct measurements were made during the 2017 growing season, with four to twelve measurements at each site. Measurements were made at randomized locations on all border levees at three sites and at randomized locations on select levees at the other three sites (to ensure that the diversity of levees around California rice fields was appropriately captured). Levees may border supply canals, drainage ditches, fallow fields, or flooded fields with a higher or lower relative water height (Fig. 2a–2d). Border levees typically double as unpaved roads in California rice fields, and this was the case for all but four measurements in this study, which were made on smaller levees with no roads (Fig. 2e). All levees were composed of native soil and were constructed at least a decade prior to this study. Sacramento Valley soils on the valley floor generally have a high clay content and are dominated by smectitic clays, whereas soils on the eastern margin of the valley have a lower clay content and a mixed mineralogy (Table 1). The regional groundwater table is generally close to the soil surface (0.5–3.0 m) at the start of the growing season for most of the valley floor (State of California, 2018), though restrictive layers cemented with silica and carbonates are present approximately 1.0 m below the soil surface at some sites (Table 1) and may limit interaction between the regional groundwater and shallower groundwater.

2.2. Lateral seepage measurements

Direct lateral seepage measurements were made using a modified version of the three-sided metal frames introduced by Janssen and Lennartz (2009). Frames were driven 25 cm into the soil at the intersection of the floodwater and the border levee, so that the floodwater covered approximately half of the area encompassed by the frame, and the open side of the frame was parallel with the levee (Fig. 3). Even though the fields were flooded for the measurements, nested frames were used to create a situation analogous to double-ring infiltrometers to minimize the effect of small fluctuations in field water height from wind or diurnal cycles of evapotranspiration (Janssen and Lennartz, 2009; Reynolds, 2007). A constant water height in both frames was maintained using Mariotte bottles, which were positioned to maintain the frame water height at the field water height at the onset of the measurement.

Frames were covered with reflective insulation to minimize evaporation, and the residual evaporation from a specimen cup inside the frame was measured and subtracted from lateral seepage rates. Similarly, percolation was measured at three locations in each field and the average percolation rate was subtracted from the lateral seepage rate. Percolation was measured using a methodology adapted from the International Rice Research Institute's water requirement meter (IRRI, 1987) and the seepage meters commonly used in stream hydrology, limnology, and oceanography (Lee, 1977). Briefly, 30-cm diameter PVC rings were inserted to 20–25 cm below the soil surface (5–15 cm into the plow pan) and covered with vented lids to minimize evaporation while allowing equilibration of air pressure. A flexible polyethylene bag attached to the ring's side allowed hydraulic head to equilibrate between the ring and the field. This bag was completely emptied into the ring for weekly ring water height measurements.

Although lateral seepage rates may change over time, measurements for each individual frame location were generally conducted in a single day (3–8 h or until a consistent measurement was obtained), as the limited number of nested frames (4) necessitated a choice between breadth and depth of measurement coverage, with the former more relevant to our research objectives. All lateral seepage measurements were taken at least six weeks after the fields were initially flooded, which allowed time for the levees to equilibrate with the flooded field.

Direct lateral seepage measurements have variably been presented as a volume flux per unit area (e.g. Liang et al. 2008) or as a volume flux per unit length of levee (e.g. Janssen and Lennartz, 2009). While the former is in the same form as Darcy's law, in practice the boundary between lateral seepage and vertical percolation (and thus the area over

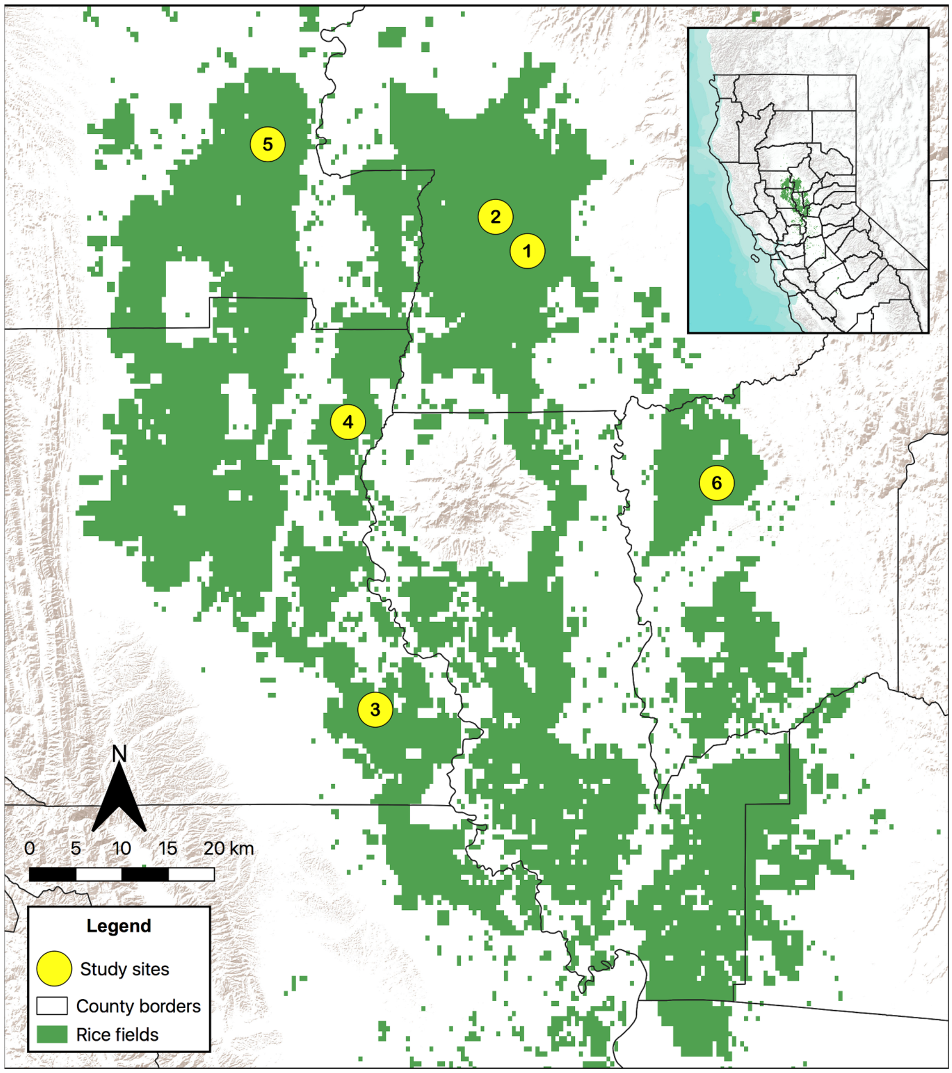

Fig. 1. Map of study site locations and the rice growing area in the Sacramento Valley, California. The rice cropping area is from the National Agricultural Statistics Service (2016), county boundaries are from the State of California (2016), and the base imagery is from Esri (2009). The map was produced with QGIS Version 3.0 (QGIS Development Team, 2018).

which a volume water flux is measured) is difficult to determine. For this reason and other reasons discussed by Janssen and Lennartz (2009), we chose to use the latter units and treat lateral seepage as an "edge effect" dependent on the length of levee measured. That is, the average percolation rate measured elsewhere in the field was subtracted out, and the resultant measurement was considered lateral seepage. However, we also provide units of volume flux per unit area for ease of comparison, by considering the area of the open face of the metal frame below the field water level.

Table 1
Study site locations and soil characteristics.

Site	County	Soil order	Soil taxonomy	Clay (%)[1]	Sand (%)	Border[4]
1	Butte	Vertisols	fine, smectitic, thermic, Xeric Epiaquerts fine, smectitic, thermic, Xeric Duraquerts	54.4 (1.5)[2]	21.2 (1.4)	b,c,d,e
2	Butte	Vertisols	very-fine, smectitic, thermic, Xeric Epiaquerts very-fine, smectitic, thermic, Xeric Duraquerts	69.5 (2.1)[2]	8.3 (0.5)	a,c,d,e
3	Colusa	Vertisols	fine, smectitic, thermic, Xeric Endoaquerts	56.1 (2.1)[3]	4.3 (1.4)	a,b
4	Colusa	Vertisols	fine, smectitic, thermic, Sodic Endoaquerts	37.7 (3.2)[3]	5.5 (0.9)	a,b
5	Glenn	Mollisols	fine, thermic Typic Calciaquolls	55.1 (6.1)[3]	22.2 (1.8)	b,d
6	Yuba	Alfisols	fine, mixed, thermic, Abruptic Durixeralfs	19.3 (1.3)[3]	38.1 (2.7)	a,b

[1] Values are the mean (and standard error) for all locations and horizons sampled at each site
[2] Soil samples collected down to the top of a restrictive layer
[3] Soil samples collected down to one auger bucket-length below the depth at which free water was found
[4] Levees may be bordered by a: a) supply canal, b) drainage ditch, c) fallow field, d) flooded field with a higher or lower relative water height, or e) drainage ditch with no access road (see Fig. 2)

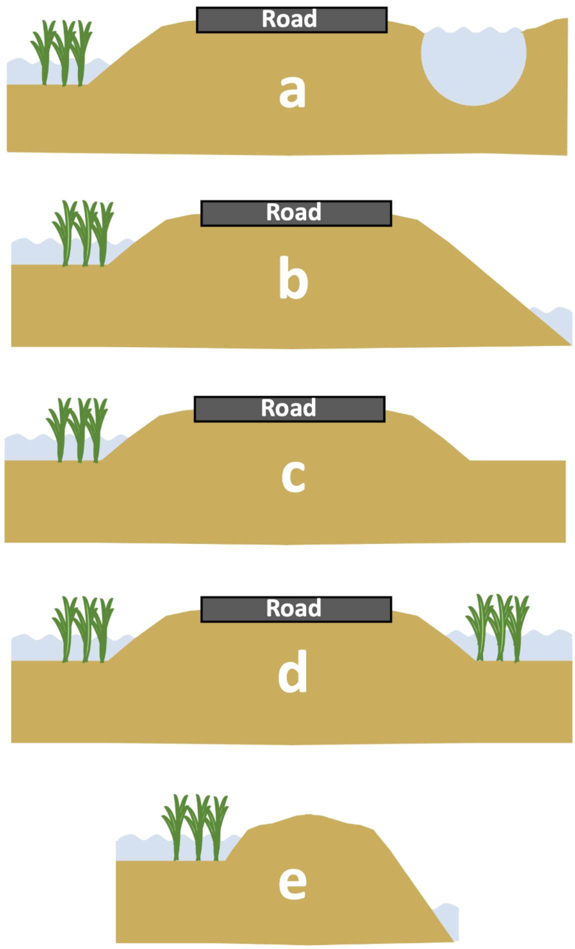

Fig. 2. Cross-section diagrams of common levees in California rice fields, separated based on the features they border. These include levees with unpaved access roads bordering a) supply canals, b) drainage ditches, c) fallow fields, and d) flooded fields with a higher or lower relative water height. Some levees also bordered a drainage ditch but were narrower with no access road (e).

2.3. Lateral seepage measurement quality control

Janssen and Lennartz (2008, 2009) validated the seepage measurement methodology used in this study with dye tracers and levee dissection. Repeating this work was not feasible given the number of levees we investigated and that it required the levees to be deconstructed, which was not possible in commercial fields. However, every effort was made to ensure the accuracy of measurements and to verify that any water lost from the frames entered the levee rather than the field. Water exchange between the frame and the field was restricted by: (1) maintaining the water height in both frames at the field water height to prevent a hydraulic head gradient from forming, and (2) ensuring good contact between the frame and the soil by adding and compacting soil into any cracks between the soil and the frame (as this was done only in the area immediately adjacent to the frame ($<$ 10% of the frame length), the effect on lateral seepage rates should be negligible). A potassium chloride (KCl) tracer, chosen for its lack of toxicity, ease of use, and availability (Leibundgut and Seibert, 2011; Mastrocicco et al., 2011), was applied to one frame per site to verify the absence of significant water exchange between the field and the frame by monitoring the electrical conductivity (EC) in the outer frame and the immediately adjacent field floodwater. No increase in EC relative to a control frame (not spiked with KCl) was observed in either the field or the outer frame. Auger holes were also cored into the levee at one site and the EC of the water in the holes was measured directly in front of the frame and at progressive distances from the frame along the levee to confirm that water from the frame was moving into the levee. Auger holes in front of the outer frame (which was not spiked with KCl) and the immediately adjacent field showed no increase in EC compared to a random location along the levee. As expected, auger holes in front of the inner frame showed an increase in EC, especially closer to the

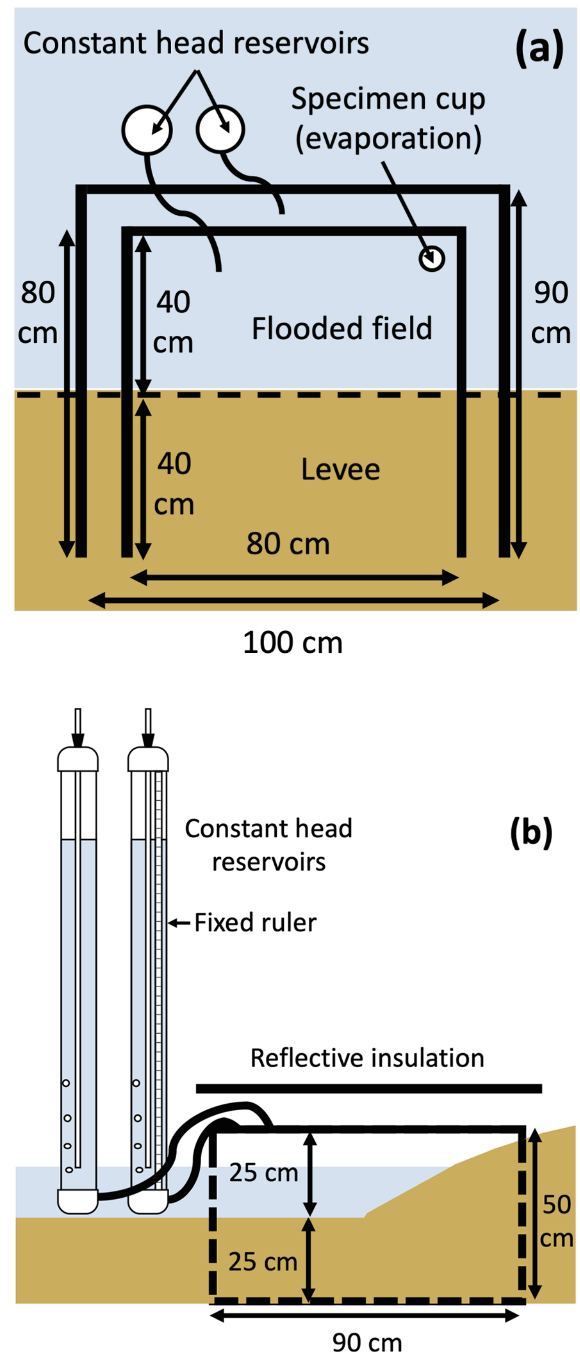

Fig. 3. Top (a) and side (b) views of nested three-sided frames used for lateral seepage measurements at 50 locations and six field sites in the Sacramento Valley of California during the 2017 rice growing season. Frames were covered with reflective insulation to minimize evaporation and residual evaporation from a specimen cup was measured. Constant-head reservoirs were used to maintain a constant water height in the frames equivalent to the field water height, and the rate of water loss from these reservoirs was taken to be the lateral seepage rate after subtracting out percolation and residual evaporation. For more details, the reader is referred to the original source that developed this methodology (Janssen and Lennartz, 2009).

intersection of the levee and the field floodwater.

2.4. Soil sampling and field measurements

Levee width, field water depth, groundwater elevation, and the relative water height in the adjacent supply canal, drainage ditch, or field (hereafter referred to as adjacent water height) were measured in the field at each location where a lateral seepage measurement was made. The water height in the adjacent supply canal, flooded field, or drainage ditch was measured using a NSL100B builder's level, tripod, and rod (Northwest Instrument, Mt. Olive, NJ). For adjacent fallow fields, the depth to reach groundwater (as determined by free water in soil cores pulled from an auger hole in the fallow field) was added to the soil surface elevation. Levee width was measured as the horizontal distance between the field water-levee interface and the adjacent water-levee interface. Field water depth was measured at three points 30–40 cm from the back of the lateral seepage frame. A 6-cm wide Dutch auger was used to core into the center of the levee until free water was observed in the soil removed from the auger bucket or until a confining layer (e.g. a duripan or chemically cemented layer) was reached. The depth at which free water was observed in soil samples was recorded as the groundwater height. Any soil from the auger hole above the elevation of the water on either side of the levee was discarded, the complete soil sample was divided into horizons based on defining visual features (such as consistence, soil texture, soil color, water content, etc.), and samples were taken at the midpoint of each horizon. Intact cores at depth could not be obtained, as this would require destructive sampling of the levees in commercial rice fields, and therefore saturated hydraulic conductivity and bulk density could not be measured.

2.5. Soil particle size analysis

Soil samples were air-dried, ground, and passed through a 2-mm sieve. For textural analysis, 5.00 g of the sample was weighed into a 50-ml centrifuge tube, mixed with 5 g L^{-1} sodium metaphosphate (NaO_3P), and shaken overnight on a mechanical shaker. The presence of significant carbonates was evaluated visually with 1 M hydrochloric acid (HCl) and samples were pre-treated with 1 M sodium acetate ($C_2H_3O_2Na$) adjusted to pH 5 to remove carbonates as necessary. The percent clay was determined using the micro-pipette method (Miller and Miller, 1987), with laboratory duplicates for each soil sample. The percent sand was determined by wet-sieving the dispersed soil sample through a 53 µm sieve. Finally, a depth-weighted average was calculated for percent sand and percent clay based on the estimated thickness of the soil horizons in the field.

2.6. Data analysis

All data analysis was done in R Version 3.5.0 (R Core Team, 2018) and data visualization was performed using the "ggplot2" package (Wickham, 2009). To investigate the relationship between variation in lateral seepage rates and measured soil properties or hydrologic conditions, the "lme" function of the "nlme" package was used for a linear mixed effects model (Pinheiro et al., 2018). As percent sand, percent clay, or both could be used to represent soil texture and the two variables were correlated, only percent clay was considered in the analysis due to its greater range of variation and the nature of its relationship with lateral seepage. As the model residuals did not satisfy the assumption of normality due to leptokurtosis (Shapiro-Wilk: $W = 0.927$, $p = 0.005$), a Lambert W transformation was applied to the lateral seepage data (Goerg, 2011), at which point the residuals satisfied the assumption (Shapiro-Wilk: $W = 0.970$, $p = 0.243$). However, the models with the original and transformed data yielded nearly identical results, so the original data is used to simplify the interpretation of results.

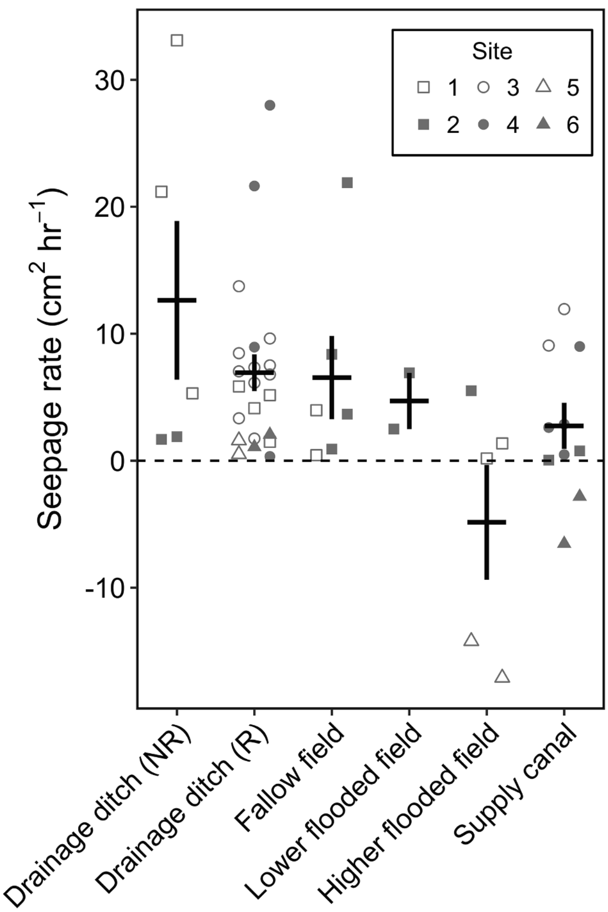

Fig. 4. Seepage rates for levees bordering common features in California rice fields (defined in Fig. 2), based on 50 seepage measurements taken at six field sites in the Sacramento Valley of California during the 2017 rice growing season. All levees double as access roads (except for five narrower levees bordered by drainage ditches, which are indicated by "NR" for "No Road"). Points represent individual observations with symbols corresponding to the site at which the measurement was taken (Fig. 1; Table 1). Horizontal lines are the mean lateral seepage rate for each category and vertical lines are the standard error of the mean. Note that 10 cm^2 hr^{-1} is approximately equal to 0.3 cm hr^{-1} based on the dimensions of the seepage frame and the average field water height.

3. Results and discussion

3.1. Lateral seepage magnitude and variability in California rice fields

Lateral seepage measurements at the 50 locations in six California rice fields varied over four orders of magnitude (Fig. 4) with the highest value (33.11 cm^2 hr^{-1} or 1.05 cm hr^{-1}) recorded for a narrow levee with no road bordering a drainage ditch (Fig. 2e), the lowest positive value (0.05 cm^2 hr^{-1} or 1.1×10^{-3} cm hr^{-1}) recorded for a levee with a dirt road bordered by a supply canal (Fig. 2a), and the overall lowest value (-17.10 cm^2 hr^{-1} or -0.48 cm hr^{-1}) showing an influx of water to the field for a levee with a gravel road bordered by a higher flooded field (Fig. 2d). Despite this variability, all measured lateral seepage rates were low relative to total water inputs or evapotranspiration losses. For example, the highest lateral seepage rate measured corresponds to 7.3 cm per season for a hypothetical square 25-ha field that is bordered by drainage ditches on all sides and flooded for 115 days. In contrast, applied water to California rice fields averages 137 cm (Johnson and Cody, 2015). The mean lateral seepage rate across all sites and locations was 5.35 cm^2 hr^{-1} (or 0.16 cm hr^{-1}), which can be interpreted as 5.35 cm^3 or ml of water passing through each cm of perimeter levee length per hour (Std. Dev. = 8.70 cm^2 hr^{-1}; Std. Error = 1.23 cm^2 hr^{-1}). Directly measured lateral seepage rates in other studies ranged from 0.017 to 4.3 cm^2 hr^{-1} for a levee bordered by a drainage ditch in a clay loam soil (Liang et al., 2008; Liang et al., 2013), and from 10.8 to 43.7 cm^2 hr^{-1} for a levee with a loam and clay loam soil texture bordered by a lower flooded field (Janssen and Lennartz, 2009). Despite these measurements being made at a single site in each study, the ranges are consistent with the 0.34–33.11 cm^2 hr^{-1} range of lateral seepage measurements on levees bordered by drainage ditches in this study.

Most water balance studies report combined percolation and lateral seepage losses rather than each component individually due to the difficulty in quantifying them separately (Bouman et al., 2005; Devkota et al., 2013; McDonald et al., 2006; Mohanty et al., 2004; Linquist et al., 2015). Even in those water balance studies that do report lateral seepage separately from percolation, lateral seepage is frequently given in a single dimension that is based on the area and perimeter of the field, but these dimensions are often not reported (as discussed in Janssen and Lennartz, 2009). However, for the few water balance studies that reported lateral seepage and field dimensions, lateral seepage rates were 0.17–1.98 cm^2 hr^{-1} (Kukal and Aggarwal, 2002) and 67 cm^2 hr^{-1} (Wopereis et al., 1994), which is generally consistent with the rates reported in this study.

While reporting seasonal lateral seepage losses as an equivalent height of water in the field can make it difficult to compare across locations (as it depends on the field area and perimeter), it is still useful to situate lateral seepage within the context of other water balance components. Field-level lateral seepage losses extrapolated for the entire growing season were only 1.4 cm, 1.5 cm, and 2.3 cm at Sites 2, 3, and 4, respectively, the three fields where districts measured irrigation inputs and at least two measurements were taken in all four border levees (Table 2). Using this irrigation input data, outflow from lateral seepage corresponds to 1.2%, 1.0%, and 1.9% of the total season-long water inputs at Sites 2, 3, and 4, respectively (Table 2). This small contribution to the rice field water balance in California stands in contrast to the substantial field-level water losses from lateral seepage in many rice-growing regions, likely due in part to differences in field size and soil texture. Whereas large fields (14–46 ha; Table 2) and clay-rich soils (38–70%; Figure S2; Table 1) are typical of California's Sacramento Valley, 90% of global rice production comes from $<$ 1 ha fields (Tonini and Cabrera, 2011), and rice is grown on 14.4 million ha with coarse-textured soils worldwide (Haefele et al., 2014). Yadav et al. (2011) reported lateral seepage rates corresponding to 16–38% of total water inputs in India, attributable largely to small plot size and the resulting high perimeter-to-area ratio. Similarly, high losses from lateral seepage have been observed in India (Kukal and Aggarwal, 2002) and the Philippines (Wopereis et al., 1994), and while most commercial fields in these countries are larger than the experimental plots in these studies, they are still much smaller than California rice fields. Tsubo et al. (2007a) reported lateral seepage losses representing 2–75% of total water inputs in Thailand, corresponding to clay contents ranging from 4 to 47%, illustrating the potential for higher contributions of lateral seepage to the rice field water balance in regions with coarse-textured soils.

Table 2
Lateral seepage, water inputs, and field characteristics.

Site	2	3	4
Irrigation[1]	114.0[4]	151.0	122.0
Rainfall[1,2]	1.8	1.3	1.8
Lateral seepage[3]	1.4	1.5	2.3
Lateral seepage (% of inputs)	1.0	1.9	1.2
Field size (ha)	14.4	36.4	43.7
Field perimeter (m)	1496	2572	3571
Growing season length (d)	114	111	124

[1] Irrigation and rainfall were measured during the growing season from first flood (May 7th–11th depending on the site) until soil samples for moisture content were taken just before harvest (September 21st – 28th)

[2] Rainfall data obtained from the nearest California Irrigation Management Information System weather station (https://cimis.water.ca.gov/)

[3] Point measurements were taken on 2–4 dates and extrapolated for the growing season

[4] All units are in cm unless otherwise stated

3.2. Lateral seepage, hydrologic conditions, and soil properties

The substantial relative variability in lateral seepage from rice fields reported here (though small compared to irrigation inputs) and the variability reported elsewhere reflect the fact that many different edaphic and hydrologic factors may affect lateral seepage. Here we measured levee width, percent clay, percent sand, groundwater elevation, field water height, and adjacent water height (Figure S2). It was determined that accurate and representative bulk density and saturated hydraulic conductivity measurements could not be made without destructive sampling of the levee. Saturated hydraulic conductivity can be highly spatially variable even in texturally homogenous soils, due in a large part to variation in bulk density (Morbidelli et al., 2017), and therefore measuring these parameters would have required multiple intact cores to be obtained at depth, which was not possible in the commercial rice fields studied. It is worth reiterating that all of these factors will likely affect lateral seepage under certain conditions, especially at their extreme values. Our objective here was to determine whether non-destructive measurements of local hydrologic conditions and soil properties could reasonably predict lateral seepage in California rice fields, allowing water managers to estimate lateral seepage losses and adapt their management accordingly. The levees studied encompassed a regionally relevant range of values for all measured factors (Figure S2).

Our results show that both adjacent water height and levee width were negatively correlated with lateral seepage across all observations, even after accounting for differences between sites due to unmeasured variables ($p = 0.045$ and $p = 0.025$, respectively; Table 3). The effect sizes for these parameters were small but meaningful, with a 100 cm decrease in adjacent water height or levee width corresponding to a 5.0 and 1.9 cm^2 hr^{-1} increase in lateral seepage, respectively (compared to the range in measured values of 50 cm^2 hr^{-1}; Fig. 4; Table 3). However, percent clay, field water height, and groundwater height were not correlated with lateral seepage (Table 3), and the overall model explained little of the variability in lateral seepage (marginal $r^2 = 0.129$). This variability is not surprising due to the many other factors that may influence lateral seepage rates. Bulk density, saturated hydraulic conductivity, and the prevalence of preferential flow pathways will certainly affect lateral seepage, especially for cases where there is no relationship with adjacent water height, such as for levees bordering fallow fields. Variability between fields was less than in-field variability for levees bordered by drainage ditches or fallow fields, while variability between fields was greater for levees bordering supply canals or higher flooded fields (Fig. 4; Table 4). Despite the apparent hydraulic head gradient for lateral seepage into the field for levees bordering

Table 3
A linear mixed effects model for lateral seepage as a function of soil properties or hydrologic conditions.[1]

	Value	Standard error	p-value	
Intercept	22.44	10.04	0.032	*
Adjacent water height	−0.05	0.02	**0.045**	*
Levee width	−1.93	0.83	**0.025**	*
Field water height	0.13	0.28	0.636	
Percent Clay	−0.09	0.13	0.491	
Groundwater height	0.05	0.04	0.230	

[1] Site is included in the model as a random effect

Table 4
Lateral seepage measurements and hydrologic conditions.

Site	Border type	N	Seepage ($cm^2 hr^{-1}$)	Adjacent water height (cm)	Levee width (m)	Field water height (cm)
1	Drainage ditch	4	4.16 (0.96)[1]	−124.5 (2.3)	6.9 (0.2)	8.3 (1.0)
	Fallow field	2	2.21 (1.77)	−117.5 (11.1)	4.3 (0.0)	8.5 (2.2)
	Higher flooded field	2	0.77 (0.59)	3.5 (0.3)	7.2 (0.1)	6.5 (2.0)
	No road	3	19.87 (8.05)	–33.5 (2.1)	3.1 (0.0)	8.6 (2.4)
2	Fallow field	4	8.71 (4.66)	−97.3 (12.3)	6.8 (0.3)	5.0 (1.6)
	Higher flooded field	1	5.51	11.0	5.2	16.7
	Lower flooded field	2	4.71 (2.21)	−11.9 (1.0)	5.2 (0.0)	18.3 (0.2)
	No road	2	1.78 (0.10)	−83.8 (1.3)	5.5 (0.6)	15.3 (1.6)
	Supply canal	2	0.41 (0.36)	10.9 (18.0)	6.7 (0.8)	14.7 (1.2)
3	Drainage ditch	10	7.17 (1.03)	−98.2 (5.4)	7.9 (0.2)	7.3 (1.1)
	Supply canal	2	10.51 (1.43)	10.9 (0.6)	7.7 (0.4)	6.5 (0.4)
4	Drainage ditch	4	14.73 (6.22)	−80.5 (9.8)	8.7 (1.1)	16.2 (1.6)
	Supply canal	4	3.74 (1.83)	28.5 (4.0)	7.8 (0.3)	11.7 (2.3)
5	Drainage ditch	2	1.05 (0.54)	−12.9 (1.1)	6.7 (0.0)	9.9 (1.3)
	Higher flooded field	2	−15.65 (1.44)	7.9 (1.9)	8.0 (0.3)	12.1 (1.8)
6	Drainage ditch	2	1.57 (0.49)	−60.1 (11.2)	5.5 (0.0)	10.1 (0.6)
	Supply canal	2	−4.68 (1.86)	74.1 (1.3)	8.9 (0.4)	11.4 (1.9)

[1] Values are the mean and standard error (in parentheses)

supply canals or higher flooded fields, positive lateral seepage rates (or seepage out of the field) were observed at most sites (Fig. 4). In these cases, the upper extent of the saturated zone in the levee was below the surface water elevation on either side of the levee, and the unsaturated zone served as a sink for lateral seepage from both sides of the levee. This is an important consideration for efforts to model or predict lateral seepage, especially for those that rely on the Dupuit equation (Agrawal et al., 2004; Tsubo et al., 2007b), which assumes no flow in the vertical direction (Fetter, 2001). The presence of downward flow within levees, as opposed to lateral flow across levees, has also been inferred from soil moisture data and numerical modeling (Huang et al., 2003).

No significant relationship between lateral seepage and percent clay or field water height was observed in our study. While soil texture undoubtedly affects lateral seepage, the high clay content typical of California rice fields limits the responsiveness of lateral seepage to further changes in this property, and factors like the prevalence of preferential flow pathways may become more important. As discussed above, correlations between lateral seepage and percent clay are much stronger in regions with less clay-rich soils and more variability in soil texture (Tsubo et al., 2007a). In addition to soil texture, bulk density affects the soil pore size distribution, and higher bulk density is typically associated with lower lateral seepage rates (Janssen and Lennartz, 2009; Patil et al., 2011). Although bulk density could not be measured in our study, it is likely that most levees had a high bulk density, given that they have been compacted by heavy machinery for many years. Similar to Janssen and Lennartz (2009), field water height had no relationship with lateral seepage rates in this study, likely due to the relatively small contribution of field water height to the total hydraulic head gradient. To the best of our knowledge, no studies have directly evaluated the effect of adjacent water height on lateral seepage in rice fields. However, Gallucci (2006) found that higher adjacent water height in drainage ditches lowered the export of dissolved organic carbon and nitrate, which indirectly showed that higher adjacent water height reduced lateral seepage.

As previously mentioned, the mean lateral seepage rates reported here were comparable to many other studies, but small compared to the total water balance for commercial California rice fields. The slow lateral seepage rates may suggest a dominant role for matrix flow through the levees at the measured locations, but variable seepage rates were observed at two sites (Sites 2 and 4) for levees with similar hydrologic conditions and soil properties. Preferential flow pathways could play a role in the observed variability in lateral seepage rates under similar conditions. The soils at both of these sites contained shrink-swell smectitic clays (Table 1), which would not be expected to have preferential flow pathways due to soil structure when saturated (Favre et al., 1997); nevertheless, preferential flow pathways due to macrofaunal activity, especially rodents and crayfish, are common in rice fields and are supported by anecdotal observations. If these pathways play a role in lateral seepage losses in California rice fields, this would have important implications for nutrient and pesticide transport. However, determining the relative contributions of matrix flow and preferential flow to lateral seepage would require detailed tracer experiments (e.g. Flury et al., 1994), which were beyond the scope of our study.

3.3. Lateral seepage measurement methodology: Benefits and limitations

In this study, we directly measured lateral seepage rates using a methodology that operates on principles analogous to a double-ring infiltrometer (Janssen and Lennartz, 2009). Several other methodologies have been used to estimate or directly measure lateral seepage in rice fields, with the study objectives and the scale of the study influencing the choice of methodologies. Perhaps the most common methodology is measuring all of the other components of the field water balance (irrigation, rainfall, evapotranspiration, runoff or drainage, percolation, and the change in soil moisture) and estimating lateral seepage as the missing term (Agrawal et al., 2004; Kukal and Aggarwal, 2002; Tsubo et al., 2007a; Wopereis et al., 1994). Advantages of the water balance approach are that it accounts for in-field spatial variability and that irrigation, rainfall, evapotranspiration, runoff or drainage, and even percolation are typically easier to measure or independently estimate than seepage. The notable shortcomings of the water balance approach include: 1) the lateral seepage estimate will include errors in the measurement of all the other water balance terms, the error for some of which (e.g. irrigation) may be comparable in magnitude to the lateral seepage term, and 2) the relationship between lateral seepage and local edaphic or hydrologic properties cannot be explored in detail, as lateral seepage can only be determined at the field or plot level. Direct measurements of lateral seepage in rice fields are less common but have included collecting lateral seepage water in containers dug into the far side of each levee (Liang et al., 2008; Liang et al., 2013) and the three-sided double frame methodology used in this study (Janssen and Lennartz, 2008; Janssen and Lennartz, 2009). While these methods allow for a more detailed study of lateral seepage and avoid incorporating the errors associated with all the terms of the water balance, they are frequently more labor-intensive than the water balance approach and sufficient replication is required to account for in-field variability. Given the constraints associated with measurements in commercial rice fields and the sub-field scale of our objectives, we decided that the three-sided double frame methodology was most appropriate for this study, yet we recognize the potential sources of error inherent in scaling up point measurements (Racz et al., 2012).

3.4. Conclusions and future research

The relatively low lateral seepage rates measured in this study indicate that lateral seepage generally has a small contribution to water loss at the field-level in California rice fields. Nevertheless, the role of lateral seepage and particularly of lateral preferential flow pathways in agrochemical movement should not be discounted, especially since the point measurements used in this study will not capture all of the preferential flow pathways within a given rice field. Significant preferential flow pathways were anecdotally observed in some fields, especially around outlet pipes for tailwater drainage. Grower attention to these leaks could help reduce field-level water losses and thus applied water to rice fields. Lateral seepage rates were negatively correlated with levee width and the relative water height in the adjacent drainage ditch, field, or supply canal, but not with percent clay, field water height, or groundwater height. It is important to note that these latter properties certainly influence lateral seepage in many situations and that their lack of a relationship with lateral seepage in this study is likely due to their limited range of variation and the low lateral seepage rates observed in California rice fields. Future research should examine the prevalence of preferential flow pathways in rice field levees due to macrofaunal activity and the potential for transport of nutrients or agrochemicals through these flow pathways.

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Declaration of interests

None

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.04.030.

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