LONGITUDINAL THERMAL AND SOLUTE DYNAMICS IN REGULATED RIVERS

by

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ABSTRACT
Longitudinal Thermal and Solute Dynamics in Regulated Rivers

by

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Dam releases increase river stage and can reverse the typical groundwater hydraulic gradient towards the river, which is reestablished with the decline of river stage. As the flood, thermal, and solute waves travel downstream in a regulated river, the rate of change in amplitude is anticipated to be affected both by surface water processes and groundwater exchanges due to head reversals. QUAL2Kw was used to simulate these combined influences on dynamics of flood, thermal, and solute waves representative of those observed within the Lower Colorado River (LCR) at Austin, Texas, USA for various hydropoeaking flow scenarios. To do this, four different modules were developed and integrated into QUAL2Kw to approximate the wave properties longitudinally, estimate the volume of exchanges based on an analytical solution for the aquifer head response to periodic stream stage fluctuations, and determine the amount of conservative
solute mass and heat energy exchanged as a function of time and distance downstream. The model was run for various scenarios to quantify the influences of lateral exchanges on instream temperatures and solute concentrations by comparing them with a base case scenario without exchanges. The solute waves were found to be significantly lagged from the flood waves, but lateral exchanges had minimal influence on conservative solute dynamics. Similarly, the flood waves were significantly lagged from the peak thermal responses. This was due in part to traditional heat fluxes at the air-water interface. However, the arrival time of the flood waves and lateral exchanges also had a moderate impact on the longitudinal thermal behavior. These findings provide insight regarding the longitudinal influences of hydropeaking occurring in a large fraction of rivers in the world which has important implications for water quality and the ecology of regulated rivers.

(79 pages)
PUBLIC ABSTRACT

Longitudinal Thermal and Solute Dynamics in Regulated Rivers

Muhammad Rezaul Haider

Dam releases increase river stage and can reverse groundwater movement into and out of the river. As the flood, thermal, and solute waves travel downstream in a regulated river, the size of the waves is anticipated to be affected both by river processes and exchanges with near river groundwater. This study established a modeling framework to quantify the influences of the groundwater exchanges on the temperatures and solute concentration dynamics along regulated rivers. The wave properties, volume of exchanges, conservative solute mass exchanges, and heat energy exchanges were calculated as a function of time and distance downstream. Results show that the temperature and solute concentrations are influenced by the arrival of flood waves. Groundwater exchanges were found to affect temperatures along the river with a minimal effect on solute concentration. These findings provide insight regarding the influences of hydropeaking occurring in a large fraction of rivers in the world which has important implications for water quality and the ecology of regulated rivers.
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# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>PUBLIC ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>METHODS</td>
<td>6</td>
</tr>
<tr>
<td>Water quality model (QUAL2kW) framework</td>
<td>6</td>
</tr>
<tr>
<td>Flow routing through the river and estimation of lateral exchanges</td>
<td>7</td>
</tr>
<tr>
<td>Estimation of mass exchanges</td>
<td>12</td>
</tr>
<tr>
<td>Estimation of heat exchanges</td>
<td>14</td>
</tr>
<tr>
<td>GW Mixing Option</td>
<td>16</td>
</tr>
<tr>
<td>CASE STUDY</td>
<td>17</td>
</tr>
<tr>
<td>Site Description</td>
<td>17</td>
</tr>
<tr>
<td>Model Scenarios</td>
<td>19</td>
</tr>
<tr>
<td>Headwater data / boundary condition</td>
<td>21</td>
</tr>
<tr>
<td>Other site specific information</td>
<td>22</td>
</tr>
<tr>
<td>RESULTS</td>
<td>24</td>
</tr>
<tr>
<td>Flood wave dynamics and influences of lateral exchanges</td>
<td>24</td>
</tr>
<tr>
<td>Aquifer head and lateral exchange response to stream stage variation</td>
<td>29</td>
</tr>
<tr>
<td>Lateral exchange of mass</td>
<td>32</td>
</tr>
<tr>
<td>Lateral exchange of energy</td>
<td>34</td>
</tr>
<tr>
<td>Longitudinal solute and thermal dynamics</td>
<td>35</td>
</tr>
<tr>
<td>Effect of lateral exchanges</td>
<td>35</td>
</tr>
<tr>
<td>Effect of Higher GW Transmissivity</td>
<td>37</td>
</tr>
<tr>
<td>Effect of mixing in aquifer</td>
<td>38</td>
</tr>
<tr>
<td>Cold Water Release</td>
<td>38</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>41</td>
</tr>
<tr>
<td>Wave dynamics</td>
<td>41</td>
</tr>
<tr>
<td>Lateral Exchanges/ Fluxes</td>
<td>44</td>
</tr>
<tr>
<td>Effect of riparian soil properties and dam releases</td>
<td>46</td>
</tr>
<tr>
<td>Influence of simplifying assumptions</td>
<td>47</td>
</tr>
<tr>
<td>CONCLUSION</td>
<td>51</td>
</tr>
</tbody>
</table>
ENGINEERING SIGNIFICANCE ........................................................................................................... 53
REFERENCES ....................................................................................................................................... 55
APPENDICES ....................................................................................................................................... 61
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>(a) is the representation of the river within the water quality model. (b) and (c) present the cross-sections of the river and adjacent aquifer for losing and gaining conditions of the river, respectively.</td>
<td>9</td>
</tr>
<tr>
<td>2.</td>
<td>Location map of study site.</td>
<td>18</td>
</tr>
<tr>
<td>3.</td>
<td>Routed water level at different reaches (values taken at 5 km interval along the study reach) for base case (Base-1.0).</td>
<td>24</td>
</tr>
<tr>
<td>4.</td>
<td>Wave amplitude and arrival time at different reaches for base case (Base-1.0).</td>
<td>25</td>
</tr>
<tr>
<td>5.</td>
<td>Routed water depth at LWP with different wave heights for base case.</td>
<td>26</td>
</tr>
<tr>
<td>6.</td>
<td>Longitudinal variation of (a) wave amplitude and (b) arrival time for different wave heights at base case.</td>
<td>27</td>
</tr>
<tr>
<td>7.</td>
<td>Wave propagation along the LCR for base case (Base-1.0).</td>
<td>28</td>
</tr>
<tr>
<td>8.</td>
<td>GW elevations for 1X (GW-1X) and 10X (GW-10X) scenarios for wave heights of 0.5 m (a and d), 1.0 m (b and e), and 1.5 m (c and f).</td>
<td>30</td>
</tr>
<tr>
<td>9.</td>
<td>Flow exchanges between the river and GW for 1X (GW-1X) and 10X (GW-10X) scenarios for wave heights of 0.5 m (a and d), 1.0 m (b and e) and 1.5 m (c and f).</td>
<td>31</td>
</tr>
<tr>
<td>10.</td>
<td>Mass exchanges between the river and aquifer for different wave amplitudes at Reach 1 for 1X (GW-1X) and 10X (GW-10X) scenarios.</td>
<td>33</td>
</tr>
<tr>
<td>11.</td>
<td>Energy exchanges between the river and aquifer for different wave amplitudes at Reach 1 for 1X (GW-1X) and 10X (GW-10X) scenarios.</td>
<td>34</td>
</tr>
<tr>
<td>12.</td>
<td>Variation of discharge and TDS over time at different locations along the LCR for a wave height of 1.0 m.</td>
<td>35</td>
</tr>
<tr>
<td>13.</td>
<td>Variation of discharge and temperature over time at different locations along the LCR for a wave height of 1.0 m.</td>
<td>36</td>
</tr>
<tr>
<td>No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>14.</td>
<td>Effect of GW transmissivity on (a) TDS and (b) on temperature at Reach 35 for a wave amplitude of 1.0 m</td>
<td>37</td>
</tr>
<tr>
<td>15.</td>
<td>Effect of mixing in aquifer on temperature at Reach 35 for a wave height of 1.0 m</td>
<td>38</td>
</tr>
<tr>
<td>16.</td>
<td>Variation of discharge and temperature at different reaches of the LCR for a wave amplitude of 1.0 m for base case with cold release condition</td>
<td>39</td>
</tr>
<tr>
<td>17.</td>
<td>Effect of GW exchanges on temperature at (a) Reach 14 and (b) Reach 35 for a wave height of 1.0 m</td>
<td>40</td>
</tr>
<tr>
<td>18.</td>
<td>Hydrograph for a hydropeaking flow condition in September, 2016 at model boundaries</td>
<td>62</td>
</tr>
<tr>
<td>19.</td>
<td>Gage height at USGS gaging stations at Hwy 183 and at Bastrop for June, 2014 (a low flow condition)</td>
<td>62</td>
</tr>
<tr>
<td>20.</td>
<td>Observed temperature at Hwy 183 in August, 201</td>
<td>63</td>
</tr>
<tr>
<td>21.</td>
<td>Specific conductivity observed at Hwy 183 in 2016.</td>
<td>63</td>
</tr>
<tr>
<td>22.</td>
<td>GW Temperature recorded at Reach 14 in 2016</td>
<td>64</td>
</tr>
<tr>
<td>23.</td>
<td>Discharge and gage height at USGS gaging stations at Hwy 183 for a hydropeaking event in September, 2016</td>
<td>64</td>
</tr>
<tr>
<td>24.</td>
<td>Discharge at USGS gaging stations at Hwy 183 for a hydropeaking event in October, 2008</td>
<td>65</td>
</tr>
<tr>
<td>25.</td>
<td>Discharge and gage height at USGS gaging stations at Hwy 183 for a hydropeaking event in May, 2017</td>
<td>65</td>
</tr>
<tr>
<td>26.</td>
<td>Head gradient calculated at 0.1 (from GW elevations at $y = 0$ and $y = 0.1$), 0.3 (from GW elevations at $y = 0$ and $y = 0.3$), 0.5 (from GW elevations at $y = 0$ and $y = 0.5$) and so on</td>
<td>66</td>
</tr>
<tr>
<td>27.</td>
<td>Gage height at Reach 1 and Reach 35</td>
<td>67</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Model Scenarios</td>
<td>20</td>
</tr>
<tr>
<td>2.</td>
<td>Wave properties at different reaches (at 5 km interval) for base case (Base-1.0)</td>
<td>25</td>
</tr>
<tr>
<td>3.</td>
<td>Wave amplitude reduction and arrival time at LWP for base case</td>
<td>26</td>
</tr>
<tr>
<td>4.</td>
<td>Rate of lateral exchanges for different flow scenarios</td>
<td>32</td>
</tr>
<tr>
<td>5.</td>
<td>Mass Exchanges at Cell 1 for GW-1.0-1X scenario</td>
<td>68</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

About 60% of the world’s large river systems are regulated by dams (Nilsson et al. 2005) for a variety of benefits including hydropower generation, flood protection, and water storage for agricultural, industrial, navigation, domestic, and recreational purposes (Nilsson and Berggren 2000). Discharge varies significantly over sub-daily timescales for rivers regulated by dams focused on hydropower generation. Rapid stage changes of more than 1.5 m are not uncommon in these rivers (Arntzen et al. 2006; Gerecht et al. 2011) and the impacts of such regulations extend up to hundreds of kilometers downstream (Gerecht et al. 2011).

The release of water from reservoirs for hydropower production generates flood, thermal, and solute waves that propagate through the receiving water body and have important implications in terms of instream water quality (Casas-Mulet et al. 2015) and ecology (Toffolon et al. 2010). Dam releases increase river stage and reverse groundwater (GW) hydraulic gradients away from the river. The normal hydraulic gradient is reestablished with the decline of river stage, and the water stored in the river banks (bank storage) is discharged back into the river (Squillace 1996). Volumes of exchange water and residence times in the lateral exchange zone (LEZ) are dictated by the amplitude, wavelength, and periodicity of the flood pulses (McCallum and Shanafield 2016). As a flood, thermal, and solute wave travels downstream in a river, the rate of change in amplitude will be affected both by surface water processes and the lateral GW exchanges due to head reversals. Some studies have examined the effects of river
regulation on downstream water quality (Ahearn et al. 2005; Henson et al. 2007); however, the effect of dynamic lateral exchanges induced by hydropoaking flow releases on instream water quality has not been quantified. Given the potential for increased residence times and biochemical transformations associated with lateral exchanges, it is imperative to quantify the longitudinal impacts on instream surface water quality in regulated rivers.

Temperature is a master variable that influences the physical, chemical, and biological condition of a stream. Understanding river temperature dynamics with mathematical models is critical to understanding effective management strategies (Hebert et al. 2011). Early modelling studies dealt with quantifying energy fluxes at the interface of air and water (Marcotte and Duong 1973), whereas more recent studies have included the influence of heat fluxes across the streambed (Hebert et al. 2011; Kim and Chapra 1997; Sinokrot and Stefan 1993; Younus et al. 2000). The relative importance of heat fluxes at the stream bed and bank interface versus those at the air–water interface vary as a function of various waterbody characteristics (e.g., wetted perimeter, top width, and regional GW elevation) (Webb et al. 2008). Additionally, longitudinal trends of instream temperature will be a function of the thermal regimes of tributaries (Null et al. 2009), wastewater treatment plant (WWTP) effluent (Wells et al. 2005), and groundwater inflows (Poole and Berman 2001). The character and extent of groundwater contributions have been identified as controls on stream temperature that are equally important when compared to solar radiation and the transfer of latent and sensible heat between the atmosphere and adjacent sediments (Tague et al. 2007).
Reservoir releases are often characterized by a markedly different temperature from that of the receiving body (Toffolon et al. 2010; Zolezzi et al. 2011) because they are often drawn from surface waters having elevated temperatures or from subsurface outlets that draw cooler water from deep within a reservoir. The volume and thermal signal of a release dictates the thermal regime of the downstream water body; however, the thermal wave moving through the river will be modified by both air-water and sediment-water exchanges (e.g., solar radiation, bed conduction), as well as longitudinal dispersion. Additionally, lateral exchanges associated with variable flow regimes can play an important role in terms of thermal buffering by storing and releasing water of a different temperature. While the nature of stream–groundwater interactions can dictate the stream temperature fluctuations (Stonestrom and Constantz 2004), river reaches that alternate between gaining and losing conditions on a sub-daily basis in response to high frequency stage fluctuations are anticipated to more significantly influence the longitudinal thermal dynamics of regulated rivers.

Short term flow fluctuations in regulated rivers not only influence temperature regimes, they also produce repeated nutrient pulses (Foulger and Petts 1984) and mobilize in-channel sources of suspended solids that can create variations in downstream water quality (Petts et al. 1985). Nutrient pulses moving through the river will again be modified by longitudinal dispersion as well as other nutrient transformations (e.g., nitrification or denitrification). Further, with hydropwaking releases, water and solute mass are exchanged with riparian aquifers and stored there (Boult and Fleming 2009). Enhanced mixing in the LEZ plays a vital role in ecosystem functioning with regard to
biogeochemical processes (Ryan et al. 2010) and nutrient cycling (Brunke and Gonser 1997). Depending on the residence time within the LEZ, which is influenced by the dam release cycle, the exchange water eventually returns back to the river but with an altered quality (Boutt and Fleming 2009; Squillace 1996).

To begin understanding lateral exchanges due to dam releases, Sawyer et al. (2009) estimated the volumetric rate of exchanges and showed that dam-induced river stage fluctuations drive LEZ exchange several meters into the riparian aquifer. They also found that the temperature signal near the channel is affected by the associated thermal advection. However, they did not quantify the influence of these lateral exchanges on downstream temperature and water quality. Boutt and Fleming (2009) simulated mass movement from a surface water body to groundwater under conditions of fluctuating river stage and showed enhanced mixing and significant mass transport. Musial et al. (2016) estimated the tidal bank storage and release exchanges for a river subject to tides fluctuating on average 0.75 m semi-diurnally. They provided a conceptual model for the influence of tidal bank storage on contaminant transport in the tidal freshwater zones. McCallum and Shanafiel (2016) presented results from simulating residence time distributions of surface water-GW interactions under diurnally fluctuating stream stage. They provided estimates of exchanges occurring between the stream and bank GW and concluded that the residence times induced by stream fluctuations are dictated by the timing and magnitude of bank inflows. However, they did not specifically present any results of these lateral exchanges on instream temperature and water quality.
Information on the longitudinal solute dynamics of regulated rivers in relation to dam release patterns can be important to those tasked with addressing water quality limited waterbodies. The thermal regimes of regulated rivers, which are dictated by release patterns and further modified by air-water interface exchanges and lateral exchanges can also affect overall instream water quality. Prior studies (Ahearn et al. 2005; Henson et al. 2007; Lopes et al. 2004; Siergieiev et al. 2014) have yet to determine the combined influence of longitudinal dispersion and lateral exchanges driven by repeated flood pulses on instream temperature and water quality for a regulated river even though the lateral exchanges bear an immense potential to influence the longitudinal pattern of river water quality.

To address these gaps in understanding, this study establishes a modeling framework that quantifies the influences of lateral exchanges on the longitudinal thermal and solute dynamics of a regulated river. Four different surface water-groundwater exchange modules were integrated into an existing 1D surface water quality model to determine the wave properties, and estimate the exchanges of flow volume, conservative solute mass, and energy as a function of time and space as driven by hydropoaking flow releases. This integrated modeling approach was then used to explore the effects of both longitudinal dispersion and lateral exchanges on transport of solute and heat waves through a regulated river. The behavior of conservative solutes and heat provides foundational information to further understand the dynamics of reactive solutes.
CHAPTER 2

METHODS

Water quality model (QUAL2kW) framework

QUAL2Kw is a water quality model intended to capture dominant processes impacting longitudinal chemistry within river and streams including flow dynamics, weather, geometry, and nutrients (major ions) (Pelletier et al. 2006). The newest version (Version 6) of QUAL2Kw adds the capabilities of unsteady and non-uniform flow modeling through the use of kinematic wave flow routing (Chapra 1997) (equations 1 and 2), as well as the impact of transient storage zones.

\[ \frac{\partial Q}{\partial x} + \alpha \beta Q^{\beta-1} \frac{\partial Q}{\partial t} = q \]  

(1)

\[ \alpha = \left(\frac{nB^{2/3}}{\sqrt{S_0}}\right)^{3/5} \]  

(2)

Where \( Q \) = volumetric flow rate \((m^3s^{-1})\), \( x \) = distance downstream \((m)\), \( \beta = 3/5 \), \( t \) = time \((sec)\), \( q \) = lateral inflow rates (treated as point or distributed) per unit length \((m^3s^{-1}m^{-1})\), \( n \) = Manning’s roughness coefficient, \( B \) = channel width \((m)\), and \( S_0 \) = bottom slope of channel.

The channel is assumed to be well-mixed vertically and laterally. As is the case for a one-dimensional model, the output consists of concentrations of different constituents for specified distances (reaches) downstream from the headwater location. Energy balances and temperature dynamics are simulated as a function of meteorology on continuously varying or repeating diel time scales. All water quality state variables are
also simulated on continuously varying or repeating diel time scales and account for
dominant biogeochemical processes. Point and non-point loads and abstractions are also
accounted for as point or distributed inflows. For each source, the volumetric flow rate,
temperature, and concentrations of each constituent of interest must be specified for the
simulation period. This version can perform continuous simulation with time-varying
boundary conditions for periods of up to one year.

**Flow routing through the river and estimation of lateral exchanges**

To account for the influences of dynamic lateral exchanges between the river and
riparian GW within QUAL2Kw for repeated flood waves, an analytical solution to the
partial differential equation describing the stream aquifer interaction (Singh 2004) with
an assumed sinusoidal boundary condition (Eqns. 3-7) was incorporated into the
QUAL2Kw code.

\[
\frac{\partial^2 h}{\partial y^2} - \frac{1}{\beta \frac{\partial h}{\partial t}} = 0
\]  

(3)

Where \( h \) = GW elevation at a distance \( y \) from the stream aquifer interface at time \( t \) [L]

\( \beta = \frac{T}{S} = \) hydraulic diffusivity of aquifer [L^2T^{-1}]

\( T= \) transmissivity of aquifer [L^2T^{-1}] = \( Kb \)

\( K = \) hydraulic conductivity of the aquifer [LT^{-1}]

\( b = \) Saturated thickness of the aquifer [L]

\( S = \) Storage coefficient of the aquifer [dimensionless]
The initial condition of GW elevation is given by:

\[ h(y, t = 0) = H(0) \]  \hspace{1cm} (4)

Where \( H(0) \) is the initial stream stage with respect to the river bed, which is known.

At the river bank \( (y = 0) \), GW elevation equals the river stage:

\[ h(y = 0, t) = H(t) \]  \hspace{1cm} (5)

At large distance from the river, lateral flow in the aquifer approaches zero:

\[ \frac{\partial h}{\partial y} = 0 \quad \text{at} \; y \to \infty, 0 \leq t \leq \infty \]  \hspace{1cm} (6)

\( H(t) \) is the stream stage and is assumed to be a sinusoidal wave, which is given by:

\[ H(t) = A \sin(\omega t + \phi) \]  \hspace{1cm} (7)

Where \( A \) is the amplitude of the sinusoidal stream stage (L), and \( \omega \) is the angular frequency (T\(^{-1}\)), and \( \phi \) is the phase (dimensionless). These equations assume a homogeneous, unconfined aquifer adjacent to a river with periodic stream stage fluctuations.

Four different modules were developed to calculate the wave properties, estimate the volume of exchanges, conservative solute mass exchanges, and heat energy exchanges as a function of distance downstream over time.

For the first module, the appropriate wave amplitude \( (A) \) and period \( (\omega t) \) for each QUAL2Kw model cell had to be determined. To do this, sinusoidal waves representative of hydropeaking flow events were hydraulically routed through the QUAL2Kw model.
domain without considering lateral exchanges. These routed wave amplitudes provided surface water stage \((H(t))\) at each location (or model cell) over time (Figure 1). Combining these and time variable riparian GW elevation \((h(t))\) at different locations laterally \((y)\), lateral exchanges could be estimated for different model scenarios.

![Diagram of river and groundwater](image)

Figure 1 (a) is the representation of the river within the water quality model. (b) and (c) present the cross-sections of the river and adjacent aquifer for losing and gaining conditions of the river, respectively. \(H(t)\) is the instream water level that varies over time and space. \(H(0)\) is the initial stream stage (represented by dash line) with respect to river bed. And \(h(t)\) is the GW elevation response to dynamic stream stage.
To estimate \( h(y,t) \), Singh (2004) presented the associated analytical solution for the head response in a semi-infinite aquifer:

\[
h(y,t) = A \exp \left( -y \frac{\omega}{2\beta} \right) \times \sin \left( -y \frac{\omega}{2\beta} + \omega t + \phi \right)
\]  

(8)

Equation 8 is valid for a homogeneous and isotropic aquifer that is significantly thicker than the amplitude of water-table fluctuations. This solution assumes that both the river and aquifer are in equilibrium prior to the river stage variation and that riverbed resistance is negligible. \( h(y,t) \) is evaluated with respect to the river bed \((H(t) = 0)\) by adding the initial river water depth at each model cell.

For the second module, Equation 8, which is valid for consistent periodic conditions and after a sufficiently long time from the initiation of observations, was incorporated into QUAL2Kw. Routed flood waves no longer remained sinusoidal and symmetrical at each respective model cell, however, the wave period remained the same. Regardless of the asymmetry, a sinusoidal wave with the amplitude and period of the routed wave at each model cell was imposed at river bank \((y = 0)\) as the boundary condition. To estimate the exchange of water between the aquifer and river, Equation 8 was solved to calculate the GW elevation at \((y = 0)\) and close proximity of the river bank \((y = 0.1)\) from the bank. Here \( b \) was set to 5 m taken as an average of the range (1 to 10 m) (Sawyer et al. 2009) to represent an average depth of the aquifer. However, because of the temporally varying stream stage, the saturated thickness \((b)\) of the aquifer that interfaces directly with the river will vary as a function of time which led to an estimate
of the volumetric flow rate (Sawyer et al., 2009) across the bank per unit length of the river by:

\[ q(t) = -K b(t) \frac{\Delta h(y = 0, t)}{\Delta y} \]  

(9)

Where, \( q(t) \) = rate of water flow as a function of time (m\(^3\) s\(^{-1}\) per meter of bankline), \( K \) is the horizontal hydraulic conductivity, \( b(t) \) is the saturated thickness at the river/aquifer interface over time, and \( \Delta H(y = 0, t)/\Delta y \) = dynamic hydraulic gradient which is determined as:

\[ \frac{\Delta h(y = 0, t)}{\Delta y} = \frac{h(y = 0, t) - h(y = 0.1, t)}{0.1} \]  

(10)

For these calculations \( K \) was kept equal to the minimum of the range obtained from Sawyer et al. (2009) (1.4E-4 ~ 1.4E-3 in m/s) and \( b(t) \) was set equal to the GW elevations at the river bank (\( h(y = 0, t) \)) obtained from Equation 8.

Using Equations 9 and 10 in the second module, the time series of exchange volumes (\( q(t) \)) for various scenarios were generated for each model cell. These exchange volumes were then doubled to account for the total exchanges occurring across both banks of the river. Positive values indicate flow from the aquifer into the river and negative values indicate flow to the aquifer from the river. Because the lateral exchanges will influence the flood wave propagation, an iterative approach to capture the feedbacks of the lateral exchanges and in-channel routing was completed by:

1. Hydraulically routing a sinusoidal wave of a given amplitude through the study reach.
2. Storing amplitudes of the wave for each model cell and estimating the times series of exchange volumes via equations 8 through 10.

3. Routing the same sinusoidal wave through the study reach, but account for the influence of the lateral exchanges estimated in step 2.

4. Store new wave amplitudes and update time series of estimated exchange volumes.

5. Repeat steps 3–4 until a steady state solution of the wave amplitude is obtained for the downstream most cell of the model.

In short, we found that the lateral exchanges tend to reduce the wave amplitudes in the model cells progressively in the downstream direction. Once a steady state solution (step 5 above) was obtained, the time series of total exchange volumes were averaged to yield hourly values and automatically incorporated as hourly exchange volumes in the Abstraction or Inflow Columns within QUAL2Kw (depending upon losing or gaining phase of the river) of the “Continuous Sources” sheet.

**Estimation of mass exchanges**

With each flood wave, a series of conservative solute boundary conditions were also released and routed through the study reach. With each release condition, river water, together with a time variable concentration at each location along the study reach, is pushed into the aquifer and the resulting final concentration in the aquifer (total mass over total volume) is released back to the river as the stage recedes.

To account for the mass exchange at each model cell as a function of time, Equations 11 through 14 were incorporated into the third module. First, it was assumed
that the volume of mass accumulated in the aquifer does not mix with GW. During losing conditions from the river, the incremental volume of water transferred to the aquifer at each time-step was calculated and added to yield an accumulated volume \( V_R \). Where

\[
V_R = \sum_{i=1}^{n} V_i
\]  

(11)

Based on the predicted values of river solute concentration \( C_i \) and flow volume \( V_i \) at each time step, the incremental mass within the aquifer at each time-step was also calculated and added to yield the accumulated mass \( M_{max} \) within the aquifer (Equation 12).

\[
M_{max} = \sum_{i=1}^{n} C_i V_i
\]  

(12)

Where \( M_{max} \) = maximum accumulated mass (g) within the aquifer over the losing condition of the river, \( C_i \) = concentration of solute (mg L\(^{-1}\)) in river at i-th time step during losing conditions, \( V_i \) = incremental volume of water (m\(^3\)) in aquifer at i-th time step during the losing condition of the river, \( n \) = the time step indicating the start of the receding stage.

Based on the above assumption, the resulting final concentration of solute in the aquifer before the receding stage \( C_{max} \) was also calculated (Equation 13).

\[
C_{max} = \frac{M_{max}}{V_R}
\]  

(13)
Solute mass leaving the groundwater at each time-step of the receding stage was calculated (Equation 14).

\[ M_{out}(j) = \sum_{j=1}^{m} C_{max}V_j \]  (14)

Where \( M_{out}(j) \) = total mass (g) released back from the aquifer at the receding stage, \( V_j \) = the volume of water (m\(^3\)) that returned back from the aquifer at j-th time step to the river, \( m \) = the time step at which river stage starts to rise at the next cycle.

The resulting concentration (Equation 13) of the bank storage water entering the river during receding conditions was constant for each time step during the receding stage for each model cell.

**Estimation of heat exchanges**

Similar to the conservative solute waves, various temperature boundary conditions were released together with the flood wave at the upstream boundary. To account for the energy exchange at each model cell as a function of time, equations 15 through 18 were incorporated into the fourth module. With each release condition, river water together with a time variable temperature at each location along the study reach is pushed into the aquifer. Similar to mass, we first assumed that the volume accumulated in the aquifer does not mix with GW. We also assumed there is no heat transfer to or from the aquifer sediments. The resulting final temperature in the bank storage water is released back to the river as the stage recedes.
From known values of temperature ($T_i$) and flow volume ($V_i$) at each time step, the incremental heat within the aquifer at each time-step was calculated (Equation 15) and added to yield the accumulated heat ($H_{\text{max}}$) for the losing condition of the river.

$$H_{\text{max}} = \rho C_p \sum_{i=1}^{n} T_i V_i$$  \hspace{1cm} (15)

Where, $H_{\text{max}} =$ accumulated heat (Cal) within the aquifer over the losing condition of the river, $T_i =$ temperature of water ($^\circ$C) in river at i-th time step during losing conditions, $V_i =$ incremental volume of water ($m^3$) in aquifer at i-th time step during losing conditions of the river, $n =$ the time-step indicating the start of the receding stage, $\rho =$ density of water (g.m$^{-3}$) at river temperature, and $C_p =$ specific heat of water (Cal. g$^{-1}$.°C$^{-1}$).

The resulting temperature in the aquifer before the start of receding stage ($T_{\text{max}}$) was also calculated (Equation 16).

$$T_{\text{max}} = \frac{H_{\text{max}}}{V_R \rho C_p}$$  \hspace{1cm} (16)

The outgoing heat at each time step of the receding stage was also calculated (Equation 17).

$$H_{\text{out}}(j) = \rho C_p \sum_{j=1}^{m} T_{\text{max}} V_j$$  \hspace{1cm} (17)

Where, $H_{\text{out}}(j) =$ total heat (Cal) released back from the aquifer at the receding stage, $V_j =$ the volume of water ($m^3$) that returned back from the aquifer at j-th time-step at the gaining condition of the river.
The resulting temperature (Equation 16) of the bank storage water entering the river during receding conditions was constant for each time step during the receding stage for each model cell.

**GW Mixing Option**
To test the influence of various heat transfer mechanisms (e.g., conduction, dispersion) on water temporarily stored within the aquifer, we allowed a simple “mixing” with groundwater of a different temperature. We assumed that the volume of water accumulated in the aquifer from the river mixes with an equal volume of GW with a temperature of 20 °C (an average temperature of regional GW obtained from measurement at Reach 14) (Figure 22 in Appendix). The resulting final temperature in the bank storage water is calculated as

\[
T_{\text{max}} = \frac{H_{\text{max}} + T_{\text{GW}} V_{\text{GW}} \rho C_p}{V_{\text{Total}} \rho C_p}
\]

(18)

Where, \( T_{\text{GW}} \) = temperature (°C) of GW which is set at 20 °C, \( V_{\text{Total}} = V_{\text{GW}} + V_{\text{R}} \). This resulting final temperature in the bank storage water is released back to the river as the stage recedes.
CHAPTER 3

CASE STUDY

Site Description
In order to test the applicability of this modeling approach, a case study was completed for the Lower Colorado River (LCR) in and around Austin, Texas. The study reach (Figure 2) is bounded upstream by the USGS gage # 08158000 below Hwy 183 (Hwy 183) and downstream by the LCRA gage at Little Webberville Park (LWP). Upstream of the USGS gage below Hwy 183, the Tom Miller dam releases water to generate hydroelectric power for the city of Austin (Sawyer et al. 2009). Longhorn dam lies in between the Tom Miller dam and the USGS gage below Hwy 183. The Longhorn dam forms a recreational lake (Lady Bird Lake) as well as a cooling reservoir for an adjacent power plant (Sawyer et al. 2009). This lake operates as epilimnetic release. At Bastrop, 90 km downstream from Hwy 183, another USGS gage (# 08159200) consistently shows the influences of hydropeaking at this distance (Figure 18 in Appendix A).

The land use distribution within the LCR catchment area consists mainly of agricultural, residential, and urban areas (Briody et al. 2016). The Walnut Creek Wastewater Treatment Plant is located at a distance of nearly 5 km upstream from the Hornsby Bend (HBU in Figure 2). This treatment plant discharges 0.43 million m$^3$ of treated effluent into the LCR each day (LCRA 2014). At 14.58 km downstream of HBU, the LCR receives effluent from SAR WWTP (Figure 2). Under low-flow conditions in the LCR, a relatively high percentage of total discharge is derived from treated
wastewater, which results in an excessive supply of nutrients (nitrogen and phosphorus) and thereby causes dramatic increases of aquatic algae and vegetation (LCRA 2014). Additionally, the study reach of the LCR is a strongly gaining reach and is influenced by tributaries and WWTPs making the LWP flows 1.6 times greater than that at Hwy 183. Thus the LCR is subject to significant influence of regional groundwater inflow especially at low flow periods and minimal tributary contributions.

![Figure 2 Location map of study site. Numbers in parentheses indicates distance (km) upstream along the channel measured from Bastrop (0.0 km).](image-url)
The LCR undergoes various degrees of hydropumping (Briody et al. 2016) where the magnitude of releases is related to demand for hydropower, demand for irrigation water, and water levels within reservoirs. During drought conditions water levels have still been observed to fluctuate ~25 cm daily at Hwy 183, whereas they remain almost constant at Bastrop (Figure 19 in Appendix). However, during hydropumping conditions in September 2016, water level fluctuations were 1.25 m at Hwy 183 which is damped to nearly 0.2 m at Bastrop (Figure 18 in Appendix).

**Model Scenarios**

A number of scenarios were developed to determine the influences of lateral exchanges on the propagation of different waves through the river. A base case scenario was developed for three wave heights (0.5, 1.0, and 1.5 m) that represent the range of releases commonly observed (Table 1, Scenario #1a-1c). Each simulation accounted for 6 days of consistent releases of the flood, thermal, and solute waves from the upstream boundary. The base case did not consider the influence of groundwater contributions, lateral exchanges, or surface inflows (tributary / WWTP). The results from these base case scenarios are used as the baseline condition to compare to all other model scenarios that incorporated the influences of lateral exchanges.

Three wave heights (0.5, 1.0, and 1.5 m) were considered for each scenario and compared to the corresponding wave heights from the base case scenario (#1). The scenarios investigate the influences of ranges of soil properties or transmissivities, treatment of heat transfer in the aquifer, and cold vs. warm water releases at the upstream boundary condition.
To begin, GW-1X (#2) represents 3 different wave heights that account for GW exchanges with an aquifer of a relatively low value of hydraulic conductivity \((k)\). In this case, the river water is not allowed to “mix” with GW. GW-10X (#3) is a repeat of Scenario #2 except a higher value of \(K\) was considered. GW-Mix-1X (#4) is the same as GW-1X (#2), but the water from the river is allowed to mix thermally with the GW. GW-Mix-10X (#5) is the same as GW-Mix-1X (#4), except a higher \(k\) value was considered again. Base-Cold (#6a) and GW-Cold-10X (#6b) includes exchange with the higher \(k\), no mixing, but investigates the influence of a cold release boundary condition.

Table 1 Model Scenarios.

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Scenario Name</th>
<th>Scenario Name abbreviated as</th>
<th>Wave height (m)</th>
<th>Temperature boundary condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Base Case</td>
<td>Base-0.5</td>
<td>0.5</td>
<td>Sinusoidal, (A = 2.5^\circ C)</td>
</tr>
<tr>
<td>1b</td>
<td></td>
<td>Base-1.0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1c</td>
<td></td>
<td>Base-1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>Base Plus GW with low GW transmissivity and no mixing allowed in aquifer</td>
<td>GW-0.5-1X</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td></td>
<td>GW-1.0-1X</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2c</td>
<td></td>
<td>GW-1.5-1X</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Base Plus GW with high GW transmissivity and no mixing allowed in aquifer</td>
<td>GW-0.5-10X</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td></td>
<td>GW-1.0-10X</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3c</td>
<td></td>
<td>GW-1.5-10X</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Base Plus GW with low GW transmissivity and thermal mixing allowed in aquifer</td>
<td>GW-1.0-Mix-1X</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Base Plus GW with high GW transmissivity and thermal mixing allowed in aquifer</td>
<td>GW-1.0-Mix-10X</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6a</td>
<td>Base case with Cold release</td>
<td>Cold-Base-1.0</td>
<td>1</td>
<td>9°C</td>
</tr>
<tr>
<td>6b</td>
<td>Base Plus GW with Cold release and high GW transmissivity and no mixing allowed in aquifer</td>
<td>Cold-GW-1.0-10X</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
**Headwater data / boundary condition**

To account for the influences of riparian groundwater exchanges and instream responses to hydropoaking, appropriate upstream boundary conditions are needed for flow, temperature, and solute concentration. Rapid stage changes of up to 1.5 m are common (e.g., September, 2016 or January, 2017) for the LCR. To cover the range of releases, idealized sinusoidal flood waves with three wave amplitudes (0.5, 1.0, and 1.5 m) that represent the range of common conditions observed (on 09/22/2016, 05/03/2017, and 05/22/2017, respectively) at Hwy 183 were used as flow boundary conditions. In order the apply the analytical solution (Equation 8) for calculating GW elevations, which requires amplitude and period of a sinusoidal wave at the respective model cells, the flow conditions were assumed to be sinusoidal with different wave amplitudes. The base flow occurring during these hydropoaking events was taken as the constant minimum flow on top of which flood waves of respective release magnitudes were imposed.

To keep track of the propagation of the thermal and solute waves through the model cells, the thermal and solute boundaries were also assumed to be sinusoidal while capturing the peaks (maximum and minimum) observed within the LCR. The daily river temperature in the LCR varied from 28.2° to 32.5°C as observed at Hwy 183 in August, 2016 (Figure 20 in Appendix). A thermal sinusoidal wave ranging from a low at 28.5°C to as high as 32.5°C, corresponding to dam storage and release cycles, was applied as the thermal boundary condition that would capture the range of observed conditions. In order to show how the conservative solutes travel downstream as influenced by hydropoaking flow events observed specific conductance (SC) data were used as a solute boundary condition. The SC in the LCR varied from 572 to 600 µS/cm as observed at Hwy 183.
over a month (observation for one day in August, 2016 is shown in Figure 21 in Appendix). The SC values were then converted into total dissolved solids (TDS) by using Equation 19 (Crittenden et al. 2012):

\[
TDS = 0.5SC
\]  

(19)

Where SC is in µS/cm, TDS is in mg L\(^{-1}\).

This resulted in TDS values with a range of 286 to 300 mg L\(^{-1}\). A slightly broader range (250 to 325 mg L\(^{-1}\)) of TDS with sinusoidal variation was chosen as the boundary condition to determine how solute waves disperse as they travel through a 35 km reach of the LCR.

**Other site specific information**

Additional site specific information that were necessary to characterize the stream and its surroundings include geometric, hydraulic, shade, and meteorological data. The study reach of the LCR was segmented into 35 model cells each 1.0 km in length. The latitude, longitude, and elevation data of each reach were assigned in the reach information sheet. The banklines during a hydropeaking event (06/04/2014) were digitized from Google Earth imagery and processed in ArcGIS software to obtain the average width for each model cell. An overall average channel width (80 m) for the whole reach was calculated from these average widths. The channel was assumed to be rectangular in cross-section, and the longitudinal slope was set to 0.0003, which was extracted from a DEM of the study reach. Hourly meteorological data (air temperature, wind speed, relative humidity) were collected from a weather station installed at an intermediate site that is 14 km downstream from Hwy 183. The percent of solar radiation that is blocked because of
shade from topography and vegetation was assumed as 10% based on field visits and Google Earth images of the LCR.
CHAPTER 4

RESULTS

Flood wave dynamics and influences of lateral exchanges

Sinusoidal flood waves of different amplitudes applied at the upstream boundary deviate from the sinusoidal shape and no longer remain symmetrical as they travel downstream (Figure 3). The peak water levels are attenuated and wave amplitudes are diminished progressively in the downstream direction (Figure 3 and Table 2) for the base case scenario (base-1.0). The time required for the wave to travel 35 km and arrive at LWP (arrival time) is 15.66 hours (Table 2 and Figure 4) for the same scenario.

![Figure 3 Routed water level at different reaches (values taken at 5 km interval along the study reach) for base case (Base-1.0).]
Table 2 Wave properties at different reaches (at 5 km interval) for base case (Base-1.0).

<table>
<thead>
<tr>
<th>Reach ID</th>
<th>Distance (km) from Hwy 183</th>
<th>Max WL (m)</th>
<th>Min WL (m)</th>
<th>Amplitude (m)</th>
<th>Arrival time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.34</td>
<td>0.27</td>
<td>0.53</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1.33</td>
<td>0.33</td>
<td>0.50</td>
<td>2.06</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.32</td>
<td>0.37</td>
<td>0.48</td>
<td>4.50</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>1.32</td>
<td>0.41</td>
<td>0.45</td>
<td>6.84</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>1.31</td>
<td>0.44</td>
<td>0.43</td>
<td>9.09</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>1.30</td>
<td>0.47</td>
<td>0.42</td>
<td>11.34</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>1.30</td>
<td>0.50</td>
<td>0.40</td>
<td>13.50</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
<td>1.29</td>
<td>0.52</td>
<td>0.38</td>
<td>15.66</td>
</tr>
</tbody>
</table>

Figure 4 Wave amplitude and arrival time at different reaches for base case (Base-1.0).

For base case scenarios, flood waves with 1.0 and 1.5 m wave heights arrive at LWP 4 and 6 hours earlier, respectively, when compared to the 0.5 m wave height (Figure 5). Reduction of the wave amplitude is maximized for a wave height of 1.5 m (Figure 6a and Table 3). The change in arrival time is minimized for a wave height of 1.5 m (Figure 6b) because the waves with greater magnitudes travel faster than those with
lower magnitudes. The arrival time reduces from 18.75 hours to 13.31 hours for an increase of wave heights from 0.5 m to 1.5 m (Table 3).

Figure 5 Routed water depth at LWP with different wave heights for base case.

<table>
<thead>
<tr>
<th>Wave amplitude (m)</th>
<th>Amplitude reduction from Hwy 183 to LWP (m)</th>
<th>Arrival time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.09</td>
<td>18.75</td>
</tr>
<tr>
<td>1</td>
<td>0.15</td>
<td>15.66</td>
</tr>
<tr>
<td>1.5</td>
<td>0.19</td>
<td>13.31</td>
</tr>
</tbody>
</table>

Table 3 Wave amplitude reduction and arrival time at LWP for base case.
Figure 6 Longitudinal variation of (a) wave amplitude and (b) arrival time for different wave heights at base case.

Flood, thermal, and solute waves at the upstream boundary were set to peak at the same time for the base case scenario (Base-1.0) (Figure 7a). Water temperature steadily decreases from 12 am to 4 am at Reach 14 (Figure 7b) which still continues to decrease and reaches its minimum at 6 am. Water temperature then starts to rise and reaches its
maximum at 5 pm followed by decreasing until 6 am of the following day. The thermal peak appears to be lagged by 6 hours at Reach 14 when compared to the peak flood level (Figure 7b).

Figure 7 Wave propagation along the LCR for base case (Base-1.0). Discharge, temperature, and TDS values have been non-dimensionalized by dividing the respective maximum values at the three reaches (Reach 1, Reach 14, and Reach 35) for comparison among the waves.
On the other hand, at Reach 35, water temperature steadily decreases from 12 am to 9 am (Figure 7c) which then increases and reaches its maximum at 2 pm. With the arrival of the flood wave at Reach 35 (Figure 7c) when water level starts to increase at 2:30 pm, water temperature starts to decrease in part because of increased water column depths and volumes. In general, the peak temperatures are overwhelmed by the arrival of the flood wave. However, the arrival time of the thermal wave is difficult to distinguish because thermal regimes also show the influence of solar radiation and other atmospheric exchanges. The solute waves are lagged by 3.5 and 10 hours, respectively, at Reach 14 (Figure 7b) and Reach 35 (Figure 7c), when compared to the flood waves due to the influences of dispersion on solute wave propagation.

**Aquifer head and lateral exchange response to stream stage variation**

When accounting for the influences of surface water being exchanged with the local aquifer during hydropeaking, the aquifer heads are progressively attenuated and lagged as you move away from bankline (Figure 8). The aquifer head fluctuations increase with increasing headwater amplitudes (e.g., Figures 8a, 8b, and 8c, respectively for 0.5, 1.0, and 1.5 m wave heights). Further, the lateral exchange rates are amplified with increasing headwater amplitudes (Figure 9, and Table 4). For a given wave height (for example 1.0 m), the lateral exchanges are much higher when considering a higher transmissivity (Figures 9b versus 9e).
Figure 8 GW elevations for 1X (GW-1X) and 10X (GW-10X) scenarios for wave heights of 0.5 m (a and d), 1.0 m (b and e), and 1.5 m (c and f). GW-0 indicates the GW elevation at the river bank. GW-0.1, and GW-1 are the GW elevations at 0.1, and 1 m away from the river bank and so on.
Figure 9 Flow exchanges between the river and GW for 1X (GW-1X) and 10X (GW-10X) scenarios for wave heights of 0.5 m (a and d), 1.0 m (b and e) and 1.5 m (c and f). Negative values indicate flow from the channel into the aquifer. Rchs 1 to 35 are the model cells.
Table 4 Rate of lateral exchanges for different flow scenarios.

<table>
<thead>
<tr>
<th>Flow scenario</th>
<th>Wave amplitude (m)</th>
<th>Maximum value of lateral exchange rate (m$^3$/s) per km of bankline</th>
<th>Average value of lateral exchange rate (m$^3$/s) per km of bankline</th>
<th>Observed value of lateral exchange rate (m$^3$/s) per km of bankline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Losing phase at (cell 1 to cell 35)</td>
<td>Gaining phase at (cell 1 to cell 35)</td>
<td>Losing phase at (cell 1 to cell 35)</td>
</tr>
<tr>
<td>GW-1X</td>
<td>0.5</td>
<td>-0.010 to -0.007*</td>
<td>0.006 to 0.004</td>
<td>-0.006 to -0.004</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-0.029 to -0.020</td>
<td>0.014 to 0.012</td>
<td>-0.017 to -0.012</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-0.059 to -0.044</td>
<td>0.027 to 0.024</td>
<td>-0.033 to -0.026</td>
</tr>
<tr>
<td>GW-10X</td>
<td>0.5</td>
<td>-0.033 to -0.021</td>
<td>0.018 to 0.014</td>
<td>-0.019 to -0.013</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-0.093 to -0.065</td>
<td>0.044 to 0.038</td>
<td>-0.053 to -0.039</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-0.186 to -0.141</td>
<td>0.084 to 0.077</td>
<td>-0.105 to -0.082</td>
</tr>
</tbody>
</table>

* Negative value of exchange rate indicates flow from river towards aquifer.

** Sawyer et al (2009).

** Lateral exchange of mass **

Mass exchanges increase with an increase in headwater wave amplitude (Figure 10a, or 10b). At a site (e.g., Reach 1), the mass exchanges with higher transmissivity is much higher than those with a lower transmissivity (Figure 10b versus 10a).
Figure 10 Mass exchanges between the river and aquifer for different wave amplitudes at Reach 1 for 1X (GW-1X) and 10X (GW-10X) scenarios. Negative values indicate loss of mass from the channel into the aquifer and positive values indicate the mass that returns back from the aquifer into the channel.
**Lateral exchange of energy**

Energy exchanges increase with an increase in headwater wave amplitude (Figure 11a or 11b). Similar to mass, the energy exchanges are higher with an increase in transmissivity (Figure 11b versus 11a).

Figure 11 Energy exchanges between the river and aquifer for different wave amplitudes at Reach 1 for 1X (GW-1X) and 10X (GW-10X) scenarios. Negative values indicate loss of heat from the channel into the aquifer and positive values indicate the heat that returns back from the aquifer into the channel.
Longitudinal solute and thermal dynamics

Effect of lateral exchanges

The solute waves are lagged by 5 and 10 hours when they arrive at Reach 14 and Reach 35, respectively, when compared to the flood waves (Figure 12b and 12c) for GW-1.0-1X or Base-1.0 scenarios. During the receding stage of the river, the TDS of river water increases (Figures 12c). Lateral exchanges tend to negligibly increase the TDS (up to 0.33 mg/L at LWP (Figures 12c)) for GW-1.0-1X scenario when compared to that for Base-1.0 scenario.

Figure 12 Variations of discharge and TDS over time at different locations along the LCR for a wave height of 1.0 m.
The thermal waves are lagged by 7 hours as they reach at Reach 14 (Figure 13b) when compared to the flood peak. However, as illustrated at Reach 35 (Figure 13c), it is difficult to distinguish the lag or lead between the flood and thermal waves because air-water heat exchanges can significantly alter thermal wave dynamics.

Figure 13 Variation of discharge and temperature over time at different locations along the LCR for a wave height of 1.0 m.
Regardless, lateral exchanges tend to decrease river water temperature up to 0.10 °C at Reach 35 (Figure 13c) for GW-1.0-1X scenario when compared to that for Base-1.0 scenario. At Reach 35, river water temperature increases form 9 am to 2:30 pm due in part to solar radiation influences, which then start to decrease (Figure 13c). There is a slight increase in temperature at 7 pm because of the arrival of a slightly warmer flood wave. Such behavior of river water temperature is something unique to regulated rivers. At the receding stage, river water temperature decreases when there is no solar radiation. This cooling steadily continues until 9 am of the following day when the solar forcing drives a rise in water temperature.

Effect of Higher GW Transmissivity

TDS values slightly increased (up to 0.71 mg/L, Figure 14a) during the losing phase and decreased (up to 0.28 mg/L) during gaining conditions of the river for the higher GW transmissivity scenario (GW-1.0-10X) when compared to GW-1.0-1X scenario with lower GW transmissivity. During losing conditions, the river water temperature increases (up to 0.21 °C) for GW-1.0-10X scenario when compared to that for GW-1.0-1X scenario (Figure 14b).

Figure 14 Effect of GW transmissivity on (a) TDS and (b) on temperature at Reach 35 for a wave amplitude of 1.0 m. Variation of discharges are also shown.
Effect of mixing in aquifer

During gaining conditions to the river, the water temperature decreases (up to 0.15 °C) for the GW-1.0-Mix-10X scenario when compared to those for GW-1.0-10X scenario (Figure 15) for a wave height of 1.0 m. This is because the water pushed from the river into the aquifer gets thermally mixed with GW of a lower temperature. This cooler water returns back to the river during the receding stage and exerts a cooling effect on the river water.

![Figure 15 Effect of mixing in aquifer on temperature at Reach 35 for a wave height of 1.0 m. Variation of discharges are also shown.](image)

Cold Water Release

When hypolimnetic or cold constant temperature water (9 °C) is released at Hwy 183 (Figure 16a), the temperature response is greatly modified as it travels downstream (Figures 16b and 16c). Temperature starts to decrease with the arrival of the flood wave at the downstream stations (Figures 16b and 16c). As the flow rate (and hence flow volume) starts to increase at 2 pm at Reach 35 (Figure 16c), this greater volume of cool water translates into decreasing temperatures until it reaches a minimum at 12 am. After 12 am, there is still a steady rise of water temperature (Figure 16c) because of smaller
volumes at the receding stage and continues up to 9 am at which the next cycle starts. The
temperatures ranged from 11 °C to 16 °C (Figure 16b) and 16 °C to 23 °C (Figure 16c) at
Reaches 14 and 35, respectively.

Figure 16 Variation of discharge and temperature at different reaches of the LCR for a
wave amplitude of 1.0 m for base case with cold release condition.
At Reach 35, for the Cold-GW-1.0-10X scenario, the lateral exchanges increase river water temperature by 0.55 °C (Figure 17b) when compared to the base case for cold water scenario (Cold-Base-1.0) for a wave height of 1.0 m.

![Figure 17 Effect of GW exchanges on temperature at (a) Reach 14 and (b) Reach 35 for a wave height of 1.0 m.](image-url)
CHAPTER 5

DISCUSSION

This idealized modeling study for the LCR shows that lateral exchanges cause considerable influence on the thermal regime although the influences on conservative solute concentrations are not as significant. The influences of lateral exchanges on water temperature and solute concentrations are subject to release patterns (Boulton et al., 2000), however, a simple sinusoidal release is only investigated here. The arrival time for the flood wave, variable with respect to the hydropeaking release magnitude, poses significant influence on the longitudinal thermal behavior of the LCR. Additionally, the results have been found to be sensitive to several parameters (e.g., riparian soil properties, cold vs. warm dam releases).

Wave dynamics

The simulated wave amplitudes are reduced by 15 cm (0.53 m at Reach 1 vs 0.38 m at Reach 35) when the waves reach at Reach 35 for the base case scenario (Base-1.0) (Table 2). This reduction of wave amplitude is much less than the 25 cm reduction (Figure 23 Appendix) observed at the LCRA gaging station for a similar size hydropeaking event in September, 2016. This is due in part to the actual hydropeaking release patterns primarily resembling a square wave (Figure 24 in Appendix). However, in this study repeated sinusoidal waves were released at the upstream boundary and the LCR is exposed to peak discharge for a smaller duration in this analysis. Again, in reality, the minimum water level persists for a longer duration (Figure 24 in Appendix) than that with assumed sinusoidal waves. Additionally, a number of tributaries and WWTPs join
the LCR within the study area (Figure 2). These point sources can be significant with respect to the main channel flow, especially during low flow conditions, as they impact the wave amplitudes and propagation substantially.

Another important parameter is the channel width, which is variable along the study area and acts differently to modify the wave amplitudes along the study reach. In order to minimize the confounding influences of hydraulic variables on the wave propagation, this modeling effort considers a uniform width throughout the study area which alters longitudinal dispersion and arrival times. Further, as the exchanges at each model cell are driven by the wave amplitudes, the influences of the point sources and variable channel widths that are not captured in the modeling can be important controls for a regulated river that were not considered here.

Finally, because of repeated release of the sinusoidal waves, there is an overlap among the flood waves such that the minimum water levels are elevated compared to that for a single release wave. Longitudinal dispersion results in a decrease in wave amplitude as the flood waves travel downstream, but increases the duration of the flood wave and therefore overlap. The wave amplitudes dictate the lateral exchanges, which feedback to the longitudinal transport of the waves through the channel. In short, the cumulative effects of these exchanges and feedback on solute (Figure 12b versus 12c, and Figure 14a) and thermal (Figure 13b versus 13c, and Figure 14b) dynamics are more pronounced at Reach 35 than at Reach 14 due to continued dispersion and lateral exchanges as the waves travel downstream.
The arrival time of flood waves are significantly reduced with increasing amplitudes (Figures 5, 6b, and Table 3). The atmospheric forcing functions influence the temperature regime of the channel. However, due to differential arrival times of flood, thermal, and solute waves the longitudinal patterns of temperature and TDS are different than if there were no hydropeaked flow releases. For example, the thermal peaks were overwhelmed by the arrival of flood wave (Figures 7c and 13c) which could reach much higher peak temperatures and have ecological consequences. Thus the release pattern and timing is an important control for regulated rivers. Moreover, the delayed arrival of the flood waves for lower magnitude releases (0.5 m) when compared to that for higher magnitude release (1.0 and 1.5 m) alters the longitudinal thermal pattern.

The flood, thermal, and solute waves boundary conditions were set to peak at the same time (Figure 7a). They eventually separate from each other and the solute waves are significantly lagged as they travel downstream when compared to the flood waves (Figure 7b and 7c) because of continued longitudinal dispersion. On the other hand, the lag or lead between the flood and thermal waves are difficult to determine because of influences of other processes (e.g., dispersion, solar forcing functions and other heat transfer mechanisms). At locations further downstream, the repeating releases on a daily to sub-daily basis results in overlapping of waves (flow, temperature and solute) and impart significant influences on each other. In turn, this alters the longitudinal patterns (wave amplitude, travel time).

Toffolon et al. (2010) identified two characteristic phases of the thermal wave dynamics where there is an initial overlap (the thermal wave is strongly affected by the
hydrodynamic wave) and a subsequent separation (where the hydrodynamic wave separates from the thermal wave). In order to distinguish between the celerity at which the hydrodynamic and thermal waves propagate downstream they ignored the heat exchanges and concluded that the hydrodynamic wave travelled downstream at a speed faster than that of the thermal wave. They also showed that the amplitudes of the thermal response remain unaltered both spatially and temporally although the thermal wave deviates from the square shape because of initial overlap and subsequent separation by the hydrodynamic wave (Figures 4 through 7 in Toffolon et al. (2010)). Then to illustrate influence of external heat exchanges on the dynamics of thermopeaking wave propagation, they included radiative and convective heat fluxes in their model to show the reduction of temperature oscillations between the head and the tail of the thermal waves which influences the amplitudes of the thermal response over time and space (Figure 10 in Toffolon et al. (2010)). In the current study on the LCR, the temperature dynamics were created by a complex interplay between the thermal wave propagation itself and the relevant external heat fluxes. This hindered the ability to determine the relative celerity of the hydrodynamic and thermal waves as they travel downstream. Moreover, in the current study, the typical thermal responses were consistently overwhelmed with the arrival of the flood wave.

**Lateral Exchanges/ Fluxes**

For the GW-1.0-1X scenario with a wave height of 1 m, at Reach 1, the estimated rate of lateral exchanges varied from -0.029 and +0.014 m$^3$/s per km of bankline. The measured exchange rate by Sawyer et al. (2009) for the same study reach was reported to be -0.06 to +0.13 m$^3$/s per km of bankline. Thus the measured exchange rates reported by
Sawyer et al. (2009) for the same study reach are about two and nine times to those estimated by the current study during the losing and gaining conditions, respectively. The current study assumes a flat GW table which results in much smaller gains than those reported by Sawyer et al (2009) that used observed piezometric heads at the bank for the same study area where regional groundwater gains are significant.

McCallum and Shanafield (2016) reported a higher exchange rate during losing conditions than that during gaining conditions of the river (-0.049 m$^3$/s per km of bankline for losing versus +0.045 m$^3$/s per km of bankline for gaining) for a sinusoidal stream stage fluctuation of 2 m on a diurnal basis. The higher exchange rate during the losing conditions were attributed to the filling of the variably saturated portion of the aquifer with the rise of stream stage. They also noticed that the peaks associated with the losing phase are narrower than those for gaining condition. But the timing of losses versus gains were different so that the same volume of water was returned back to the stream during the receding stage and a dynamic steady state was achieved. Results from the current study on the LCR shows that the exchanges are higher during losing conditions than those during gaining conditions (Table 4). A higher transmissivity value in the current study on the LCR resulted in the lateral exchanges which are three times those using the reference value of transmissivity (exchange values under GW-10X versus those under GW-1X scenarios in Table 4). Thus, our results show that the exchange rates and patterns can vary significantly depending upon the riparian soil properties.

For GW-1X scenario with a 1 m wave height, the volume of water exchanged through the banks varied temporally from 0.0002% to 0.10% at model cell 1 (exchange
volumes and river discharges for a few time steps are shown in Table B1 in Appendix) which was further reduced (0.0002% to 0.07%) at model cell 35 due to a high mean river discharge of 29.20 m$^3$/s (and therefore high river stage) that was maintained due to the overlapping flood waves. Musial et al. (2016) reported a flux rate of 0.14 m$^3$/s across 17 km of banks and 0.34 m$^3$/s across 17 km of bed which accounted for a 3% of river water that is being exchanged laterally through the banks when a mean discharge of 4.33 m$^3$/s is maintained for a tidal river with an average amplitude of 0.75 m. For the LCR, the lateral exchanges increased as a function of increased wave amplitudes at the upstream boundary. Thus the magnitude of releases is an important factor for longitudinal thermal and solute dynamics. Additionally, sinusoidal waves were imposed as the upstream boundary for this study and hydropeaking releases of the LCR can be more similar to a square wave (Figure 24 in Appendix) or a step function (Figure 25 in Appendix) rather than a sinusoidal wave. If the river banks are exposed to a peak (maximum or minimum) water level for a longer duration, as with a square wave, then it would induce substantially higher lateral exchanges and likely have an appreciably greater impact on instream conditions than those observed with a sinusoidal upstream boundary. Thus the duration of wave releases is also an important factor to consider in regulated rivers.

**Effect of riparian soil properties and dam releases**

For the higher transmissivity (GW-1.0-10X) scenario, lateral exchanges increase temperature up to 0.21 °C when compared to the GW-1.0-1X scenario (Figure 14b). With this higher transmissivity scenario, TDS of the river water slightly increased (up to 0.71 mg/L) during the losing phase and decreased (up to 0.28 mg/L) during the gaining condition due to lateral exchanges (Figure 14a). As already stated, a single transmissivity
value (obtained for Reach 14) was applied for the whole model domain, however, the variability of these characteristics will be significant over such a large study reach. Regardless, these results highlight that the site specific soil properties are also an important factor in determining the magnitude and influence of lateral exchanges.

The results from the cold water release scenario shows that the lateral exchanges for a Cold-GW-1.0-10X scenario can increase the river water temperature by up to 0.55 °C (Figure 17b) at Reach 35. Lateral exchanges were found to decrease water temperature by up to 0.10 °C (Figure 13c) at Reach 35 with warmer release condition. Thus depending upon the bottom / top release of dam proves to be an important control for regulated rivers.

**Influence of simplifying assumptions**

The flood waves were found to deviate considerably from the sinusoidal shape as they travel downstream (Figure 3). Still a sinusoidal wave with amplitude and period recorded at each model cell was imposed at river bank to calculate the GW elevations as a function of time and space. This represents an idealized solution as if the flood waves were of perfect sinusoidal shape at all the model cells. Thus the boundary conditions for calculating GW elevations using the analytical solution (Equation 8) do not represent the actual conditions experienced throughout the study reach.

The saturated thickness of the aquifer at the bank varies following the temporally varying stream stage. The calculation of GW elevation at the river bank involves a hydraulic diffusivity of the aquifer (\(\beta\) in Equation 8) that was determined based on saturated thickness (\(b\)). In equation 8, this value was held constant at 5 m which is the
assumed depth of the aquifer. The underlying assumption of a confined aquifer (constant $b$) within this solution does require that the variability in the saturated thickness associated with the flood wave is minimal. Given that some locations within the aquifer experience significant variability in the saturated thickness, there is some uncertainty in the accuracy of the $h(y,t)$ estimates. However, in an effort to account for the variability of $b$ for the portion of the aquifer interfacing with the river, the lateral exchange estimated used a time variable $b$ that was set to the temporally varying water depths at the respective model cells. In an effort to understand the influence of the $h(t)$ estimates at different $y$ locations, the head gradients calculated from GW elevations at the bank ($y = 0$) and $y = 0.1$ m were compared with those calculated from $y = 0$ and $y = 0.3$, $0.5$, or even up to $1.0$ m away from the bank. The differences were found to be minimal (Figure 26 in Appendix).

Based on observations, discharge at Reach 35 is consistently 60% higher than that at Reach 1 (Figure 27 in Appendix). This reach of the LCR is a gaining reach subject to significant influence of regional groundwater inflow and the influence of tributaries and WWTPs. The current study estimates that for the GW-1.0-IX scenario (which assumes no regional groundwater influences) and a $1$ m wave height at Reach 1, on an average, the river exchanges vary from -0.017 to 0.008 m$^3$/s of water per km due to dam operations (Table 4). This does not include the regional GW inflows. Sawyer et al. (2009) estimated 0.052 m$^3$/s per km of lateral exchanges based on the piezometer records at Reach 14 where 0.041 m$^3$/s per km are contributed by regional groundwater inflow and the remaining 0.012 m$^3$/s per km by dam operations. Thus dam operated exchange
volumes we estimated are slightly over- and under-estimated, respectively at losing and
gaining conditions when compared to that reported by Sawyer et al. (2009) for Reach 14.
This highlights how dependent exchanges can be on the local GW elevations. GW
elevations (whether the river is gaining or losing and the slope of GW elevation) can also
vary over larger reaches which will further influence the system.

Another important assumption made within this modeling deals with groundwater
mixing. For GW-1.0-Mix-1X and GW-1.0-Mix-10X scenarios, the water pushed into the
aquifer during losing conditions is mixed with an equal volume of GW in the bank. This
bank storage water is returned back to the river during the receding stage. These
exchanges and limited mixing (only thermal) are continued over 24 hour cycles. Because
of this simplified assumption of mixing, the residence time of the bank storage water is
not accounted for in the current analysis. McCallum and Shanafield (2016) reported that
75% of the water is returned during the bank outflow immediately following the bank
inflow event. They also demonstrated that the water from a single bank inflow event
remains persistent in the bank for a long period of time, with 9% of the water remaining
in the bank after 20 days. Measurements by Watson (2016) similarly showed that the
influence of lateral exchanges on GW temperature can last up to 7 days. Although the
dam influenced lateral exchanges over 24 hour cycles were captured in the current study,
the residence times, realistic mixing effects, and heat transfer with the aquifer sediments
were not accounted for. While the estimated lateral exchanges have been found to
minimally influence TDS concentrations and moderately influence temperature, there
could still be significant influences on reactive solutes given the complex mixing patterns
and influences on transformations illustrated within Shuai et al. (2017). Depending upon the residence times in aquifer, which are dictated by the release timing and magnitude and aquifer properties, reactive solutes have been shown to undergo biogeochemical transformations (Bardini et al. 2012; Boano et al. 2010; Boano et al. 2014) in the LEZ and eventually released back to the stream with an altered condition.
CHAPTER 6

CONCLUSION

This study presents a modeling framework that integrates four modules into QUAL2Kw that estimates lateral exchanges, mass, and heat fluxes for quantifying the influences of lateral exchanges on the longitudinal thermal and solute dynamics of a regulated river. The arrival time of flood waves at the downstream reaches is significantly reduced with increasing wave amplitudes. Atmospheric forcing functions and heat fluxes influence the temperature regime of the channel as does the propagation of flood waves. Therefore, due to differential arrival times of flood, thermal, and solute waves, the longitudinal patterns of temperature and TDS differ under hydropeaking releases. The peak temperatures can be reduced depending upon the release pattern (timing and magnitude), which can have ecological consequences. Thus the release pattern and timing is an important control for regulated rivers. This highlights the need for accurate predictions of temperatures and solute concentration as a function of time and space in order to manage regulated rivers.

Lateral exchanges were found to have considerable influence on longitudinal thermal behavior although the influences on TDS concentrations were not significant. The lateral exchanges were enhanced as a function of increasing wave amplitudes at each model cell. Again highlighting that the release magnitude is an important factor for longitudinal thermal and solute dynamics. Additionally, the exchange magnitudes have been found to vary significantly with the GW elevation condition (neutral versus gaining river reaches). Thus the GW elevation proves to be a driver for determining the exchange
magnitudes and associated impacts on instream conditions for regulated river. With higher transmissivity (GW-1.0-10X scenario), lateral exchanges increase river water temperature (by up to 0.21 °C) when compared to those for the GW-1.0-1X scenario. Thus site specific groundwater properties are additionally an important factor for river water quality managers. Lateral exchanges were found to decrease water temperature by up to 0.10 °C at Reach 35 with warmer release condition whereas it increased temperature by 0.55 °C at the same site for a cold release boundary condition. Thus a bottom or top release from a dam proves to be an additional consideration in regulated rivers.
CHAPTER 7

ENGINEERING SIGNIFICANCE

This work contributes to the disciplines of river water quality and stream ecology by expanding our understanding of (i) the longitudinal transport of the flood, thermal, and solute waves through regulated rivers, and (ii) the added effects of lateral exchanges on instream temperature and TDS.

There is a knowledge gap on the dynamics of the flood, thermal, and solute waves in regulated rivers and the influence of the dynamic lateral exchanges on the transport of these waves downstream. This research attempts to fill this gap via a modeling study. The flood, thermal and solute waves are lagged significantly as they travel downstream. During propagation the waves overlap with each other. In addition to major heat exchanges typically accounted for in temperature / water quality modeling, the arrival of the different waves at downstream reaches and lateral exchanges induced by hydropoeaking impart considerable impact on the longitudinal thermal dynamics with little influence on the solute transport.

The peak temperature at downstream sites are dictated by the release magnitude and frequency. River temperature is a key attribute known to have significant influence on the physical, chemical, and biological processes of the river. This modeling approach can be used to evaluate existing release schedules and design new release schedules, if needed, that consider ecological influences downstream. Given that exchanges can vary according to GW elevation and riparian soil properties, water quality managers need to
determine these to quantify site specific responses downstream of regulated rivers.

Finally, enhanced knowledge on the wave dynamics and lateral exchanges in regulated rivers will help us to manage river water quality and maintain an ecological balance.
REFERENCES


APPENDICES
Appendix A: Figures.

Figure 18 Hydrograph for a hydropoaking flow condition in September, 2016 at model boundaries.

Figure 19 Gage height at USGS gaging stations at Hwy 183 and at Bastrop for June, 2014 (a low flow condition).
Figure 20 Observed temperature at Hwy 183 in August, 2016.

Figure 21 Specific conductivity observed at Hwy 183 in 2016.
Figure 22 GW Temperature recorded at Reach 14 in 2016.

Figure 23 Discharge and gage height at USGS gaging stations at Hwy 183 for a hydropoaking event in September, 2016.
Figure 24 Discharge at USGS gaging stations at Hwy 183 for a hydropeaking event in October, 2008.

Figure 25 Discharge and gage height at USGS gaging stations at Hwy 183 for a hydropeaking event in May, 2017.
Figure 26 Head gradient calculated at 0.1 (from GW elevations at y = 0 and y = 0.1), 0.3 (from GW elevations at y = 0 and y = 0.3), 0.5 (from GW elevations at y = 0 and y = 0.5) and so on. The differences are minimum up to 1.0 m after which the head gradients differ significantly.
Figure 27 Gage height at Reach 1 and Reach 35.
## Appendix B: Tables.

Table 5 Mass Exchanges at Cell 1 for GW-1.0-1X scenario.

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