DEVELOPMENT, CALIBRATION, AND IMPLEMENTATION OF A DISTRIBUTED HYDROLOGIC MODEL FOR USE IN REAL-TIME RIVER FORECASTING

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Abstract

The National Weather Service (NWS) West Gulf River Forecast Center (WGRFC) is currently developing, calibrating, and implementing distributed hydrologic models for use in real-time river forecast operations using the NWS Distributed Hydrologic Modeling System (HL-DHMS). Both the WGRFC and the Arkansas-Red Basin River Forecast Center (ABRFC) are serving as initial test sites for HL-DHMS. The models developed at the WGRFC and the ABRFC are the first distributed models to be implemented into real time river forecast operations within the NWS.

Twenty-five headwater drainage basins across the state of Texas were selected for initial development using HL-DHMS. At the time this paper was submitted for publication, seventeen of these basins have been implemented into WGRFC operations, while eight are still under development. The watershed characteristics for each of these locations vary according to climatology, topography, vegetation type, soil type, land-use, and other hydrologic and hydrometeorologic factors.

Drainage basins are defined on a nominal 4 km by 4 km grid network. Hourly gridded radar-based precipitation is forced into the system. From there, runoff production is computed for each grid cell using the distributed Sacramento Soil Moisture Accounting (SAC-SMA) method and is then routed to the basin outlet using the kinematic wave technique. The model parameters are calibrated utilizing historical precipitation estimates and streamflow data at the basin outlet. Upon successful calibration, each basin is incorporated into WGRFC river forecast operations.

An overview of the issues regarding the development, calibration, and implementation of distributed hydrologic models using HL-DHMS for real time river forecast operations is presented.

INTRODUCTION

Hydrologic distributed modeling holds great potential for revolutionizing the operational forecasting mission of the National Weather Service (NWS) West Gulf River Forecast Center (WGRFC). Distributed modeling is seen as a way to improve the resolution and accuracy of river forecast simulations. Streamflow predictions are also possible at interior locations within a drainage basin where streamflow observations do not exist.

Distributed modeling takes into account the spatial variability of the physiographic characteristics of a watershed drainage area along with meteorological factors such as the forcing of precipitation across the basin. Initial research conducted by the NWS Hydrology Laboratory (HL) has shown that the distributed model developed by HL performs comparably well to the traditional well-calibrated lumped model for several headwater basins. The distributed model has also outperformed the lumped model in basins where the spatial variability of rainfall is significant (Koren et al., 2004).

HL-DHMS MODEL

The Distributed Hydrologic Modeling System (HL-DHMS) was developed by the NWS Hydrology Laboratory (HL). HL-DHMS actually evolved from the Research Modeling System (HL-RMS), also developed at HL. The purpose of HL-RMS was to facilitate research on the use of distributed models to enhance the operational flood forecasting mission of the NWS. Preliminary research indicates that distributed modeling may improve the quality of river forecast operations (NWS, 2004).

HL-DHMS is based on a regular rectangular spatially gridded network, originally derived from the Hydrologic Rainfall Analysis Project (HRAP) grid cells (pixels). For more information on the HRAP coordinate system, see Fulton (1998). Each pixel is dimensioned in an approximate 4 km by 4 km grid cell and consists of a unique rainfall-runoff relationship and unique hillslope and channel routing parameters. In essence, the structure of HL-DHMS is comprised of two parts: (1) a conceptually based soil moisture water balance component, and (2) a physically based hillslope and channel routing component (Koren et al., 2004; NWS, 2004).

Conceptually-Based Component

HL-DHMS uses the Sacramento Soil Moisture Accounting (SAC-SMA) technique, a continuous, and conceptually based soil moisture water balance model, to estimate runoff production for each grid cell. Soil moisture models are designed to relate runoff from an area to the actual processes that occur in nature.

The SAC-SMA model is based on a system of interrelated soil parameters which govern soil-moisture storage, percolation, drainage, and evapotranspiration in a soil profile. The SAC-SMA model consists of two soil layers: (1) a relatively thin surface layer and a somewhat thicker lower layer. Each layer consists of tension water and free water storage components. A percolation equation is used to move water from the upper layer to the lower layer. The fast response components in the system are impervious, surface, and direct runoff. The slow response components include interflow and both supplemental and primary groundwater flow (Koren et al., 2004). A detailed description of these parameters in conjunction with the SAC-SMA model can be found in Burnash, et al. (1973), Armstrong (1978), Anderson (2002), and the National Weather Service River Forecast System (NWSRFS) User's Manual.

HL has developed gridded soil based (a priori) SAC-SMA parameters for the entire WGRFC area. Additional information on the derivation of SAC-SMA parameters from soil properties can be found in Koren et al. (2000). By using this gridded parameter concept, spatially variable soil moisture parameters are defined across the watershed resulting in unique rainfall-runoff relations for each pixel. A priori estimates are available for 11 of the 16 SAC-SMA parameters for each individual pixel. At this time, five of the SAC-SMA parameters can only be estimated using a single lumped value for the entire basin. A priori methods are very helpful in establishing the initial baseline estimates for each individual parameter; however, calibration of these parameters is required to achieve optimal model simulations (NWS, 2004).

The 16 SAC-SMA parameters are calibrated in conjunction with each other to simulate the rainfall-runoff relations for the drainage basin. For the 11 SAC-SMA parameters where a gridded network is available, a multiplicative factor is applied uniformly across the basin to each pixel in order to keep the distributed nature of the soil parameters intact. Evapotranspiration (ET) is represented by the average monthly potential evaporation (PE) mapped to the HRAP grid. Like most of the SAC-SMA parameters, a multiplicative factor can be applied to each average monthly PE value as part of the calibration. The HL-DHMS model is calibrated by comparing simulated flows with observed flows at the basin outlet (NWS, 2004).

Physically-Based Component

HL-DHMS uses the kinematic wave technique for both the hillslope and channel routing components of the system. HL-DHMS defines a number of conceptual hillslopes to develop overland flow planes for each grid cell. Each grid cell is relatively large in size consisting of approximate 4 km by 4 km (i.e. ~16 km^2) rectangular sections. Each cell is subdivided into equally sized overland flow planes using a drainage density parameter. Runoff from each conceptual hillslope flows into a conceptual channel within the same grid cell. From there, water moves from upstream to downstream pixels to the basin outlet using a topographically defined cell-to-cell connectivity sequence (Koren et al., 2004).

HL-DHMS assumes that all of the hillslopes have the same properties within each grid cell; however, these hillslope properties may differ between grid cells. The length of the main channel within each cell is assumed to equal the diagonal distance across the grid. The main channel in a selected pixel usually represents the highest order stream. Channel routing between cells is accomplished using a flow direction grid (Koren et al., 2004).

HL-DHMS Simulations

Procedures have been developed to integrate the water balance component with the hillslope and routing component to simulate the distributed hydrologic model. Precipitation is forced into the system using hourly multi-sensor data, which incorporates radar-based precipitation. These data sets are generated at the WGRFC using the Multisensor Precipitation Estimator (MPE) (Seo and Breidenbach, 2002).

Runoff computed by the SAC-SMA method is applied to the kinematic wave model for each individual grid cell. Fast response runoff is routed over conceptual hillslopes to a conceptual channel. Slow response runoff, however, bypasses the hillslope routing process and enters the channel directly from the soil. From there, the fast response component, the slow response component, and outflow from upstream grid cells are routed through the conceptual channel (NWS, 2004; Koren et al., 2004).

HL-DHMS assumes that there is no physical connection between soil moisture states in adjacent grid cells. Thus, the only source for water exchange between neighboring grid cells is by the conceptual channel. The kinematic wave model is accurate for steep slopes; however, accuracy begins to decline for hydraulically mild slopes (Koren et al., 2004).

WGRFC DISTRIBUTED MODELING PROGRAM

The WGRFC has embarked on a hydrologic distributed modeling program, since the WGRFC is located in one of the most hydrologically active regions in the United States. Approximately 20% of WGRFC forecast basins have hydrologic response time of 6 hours or less; 50% of 12 hours or less; 65% of 18 hours or less; and 75% of 24 hours or less. Given the close proximity to the Gulf of Mexico, abundant atmospheric moisture is frequently drawn into storm systems moving over the region, resulting in the production of significant rainfall. The most hydrologically sensitive area in the state is the Texas Hill Country, a region where intense short duration rainfall events are quite common. This rainfall, in conjunction with the steep terrain and thin soil structure, can produce excessive runoff in a very short period of time resulting in a fast hydrologic response on area streams and rivers.

The WGRFC currently uses a six hour lumped model within the NWSRFS to produce river forecasts. This six hour model is often inadequate to forecast rivers with very fast response times. Because of this fact, the WGRFC is viewing with keen interest the HL-DHMS distributed model with one hour multi-sensor precipitation inputs as a way to improve the accuracy and overall quality of river forecasts during fast-response flood events.

Drainage Basins

Twenty-five headwater drainage basins were selected for initial development of distributed models across Texas. At the time this paper was submitted for publication, seventeen of these basins have been implemented into WGRFC operations with eight more under development. The location of these basins is shown in Figure 1. Watershed characteristics for each basin vary according to climatology, topography, vegetation type, soil type, land-use, and other hydrologic factors. Climatic regimes vary across the state from very humid in East Texas to semi-arid in West Texas. Each of these basins are NWS river forecast points, each basin has real-time United States Geological Survey (USGS) gauge data available at the outlet, and a continuous record of historical flow data available for calibrating the distributed model parameters. Twenty-three of these basins have also been examined extensively in other hydrologic studies (Seo et al., 2003).

HL-DHMS Distributed Model Calibration and Validation

Calibration of the HL-DHMS model was primarily a manual iterative process. Both the kinematic wave routing parameters and the SAC-SMA parameters were adjusted to achieve the best continuous simulation over the period of record at the basin outlet. The kinematic wave parameters were adjusted so the rising limb, falling limb, and peak ordinate of the simulated hydrograph agreed with the hydrologic timing of the observed basin hydrograph. The SAC-SMA parameters were calibrated so the overall simulated hydrograph compared as well as could be achieved to the observed hydrograph at the basin outlet given various hydrologic constraints for each drainage basin.

XDMS, a data visualization tool delivered with the HL-DHMS software allows the user to view traces of historical and simulated flow time series at a drainage basin outlet. Two example graphical representations of XDMS for the East Fork Trinity River at McKinney location are shown in Figures 2 and 3. XDMS also allows the modeler to view various distributed hydrologic characteristics for a basin such as flow directions, and SAC-SMA distributed parameters and states. A good indication of the varying hydrologic response within a drainage basin can be gained from the spatial representation of these parameter grids.

Another utility, STAT-Q, was used to measure the statistical "goodness of fit" for each of the basin calibrations. STAT-Q is a flexible statistical package that computes a number of statistical measures for time series including percent bias, root mean square (rms) error, and correlation coefficient. Each of these measures can be computed as a composite for the entire simulation period, or categorized by individual years, by individual months, or by separate flow ranges. Stratifying the calibration statistics by time and by flow range provides the modeler valuable insight into the performance of the model with relation to physical processes that occur within a basin. The overall composite statistical results for the entire period of record for these basins are shown below in Table 1. The percent bias ranged between -30.03 to 61.74; the rms error ranged between 7.77 to 32.39; and the correlation coefficient ranged from 0.51 to 0.88.

In several cases, natural flow was impacted by "man induced" influences. Processes such as wastewater effluent discharges, diversions, detention basins, etc. can have a major impact on the observed hydrologic response of a basin. These processes may not be accounted for in model simulations. Another factor that can adversely impact calibration is the bias in the multi-sensor precipitation forcing data. Algorithms which produce the precipitation data have evolved over time creating a potential bias in the forcing data over some of the WGRFC area. Since more recent precipitation data is considered more accurate, primary emphasis was given to calibrating over the most recent time periods. This precipitation bias was evident at the Aransas River at Skidmore location. For the eight year time period from July 1997 until May 2005, the percent bias is 67.74; the rms error is 15.09; and the correlation coefficient is 0.59. When the time period is reduced to a more recent two year time period from January 2003 to May 2005, the percent bias reduces markedly to 4.36; the rms error is 22.01; and the correlation coefficient significantly improves to 0.83

During calibration, SAC-SMA parameters were selected with an emphasis on peak flow since the mission of the WGRFC is to provide river forecasts, primarily during flood events. Because each SAC-SMA parameter is interrelated, appropriate baseflow parameters were selected since they have a direct impact on the SAC-SMA percolation process and resulting surface runoff. When hydrologic situations occurred which were outside the normal hydrologic process for the watershed, adjustments were made to the SAC-SMA parameters with an emphasis towards matching peak flow.

The modeler must often look beyond pure statistical metrics to arrive at the optimal calibration for forecast operations. Visual comparison of simulated verses observed flows in XDMS provides invaluable insight into how well the model is simulating peak flows, recessions, and base flow over the entire calibration period. Using this approach, the HL-DHMS model was calibrated for the eight year time period from 1997 through 2005. Reliable hourly multi-sensor radar based precipitation data was not available prior to this time for the WGRFC area. Due to the relatively short time period for which suitable historical data was available, the model was calibrated over the entire time period. The model is being validated on a real-time basis as storm events occur.

WGRFC Operations

The one hour HL-DHMS distributed model is now being run in conjunction with the current WGRFC six hour lumped operational river forecast model. HL-DHMS is run in the background every hour. Time series results are generated and are plotted in the WGRFC operational model alongside the lumped model. The river forecaster has the option of selecting either simulation when generating operational river forecasts for each individual basin.

CONCLUSIONS

The NWS West Gulf River Forecast Center has a vested interest in the development of distributed hydrologic models. These models hold the potential to capture the spatial variability of precipitation, as well as the spatial variability of physiographic characteristics over a watershed which can be masked by lumped parameter models.

Currently the HL-DHMS is a prototype operational model. The NWS Hydrology Laboratory has done a tremendous job in developing this model and providing it to the field for evaluation and testing. In its current state HL-DHMS is suitable for modeling headwater basins where natural streamflow remains unaltered by "man-induced" processes such as reservoirs, diversions, and effluent discharges. Soil based SAC-SMA parameters provide a sound starting point for model calibration, but finer simulations can be obtained through manual calibration of the original parameters. Manual calibration is an arduous and time consuming task, but is an essential step in model development. Furthermore, it is imperative that the modeler have a sound understanding of the SAC-SMA model and the interrelationships of its parameters in order to arrive at an optimal calibration.

HL-DHMS is still in its infancy. The HL is working diligently to integrate the model into mainstream operations at all NWS field offices. Though HL-DHMS is a prototype model, WGRFC is able to import the results into the operational forecast model, giving hydrologic forecasters the ability to evaluate and use the resulting forecasts.

This project has provided the WGRFC with invaluable experience in distributed modeling, although we still have much to learn in order to utilize this technology to its fullest. While early indications are that distributed modeling may greatly enhance the river forecast capability of the WGRFC, additional research and development is needed to fully integrate distributed modeling into real time river forecast operations.

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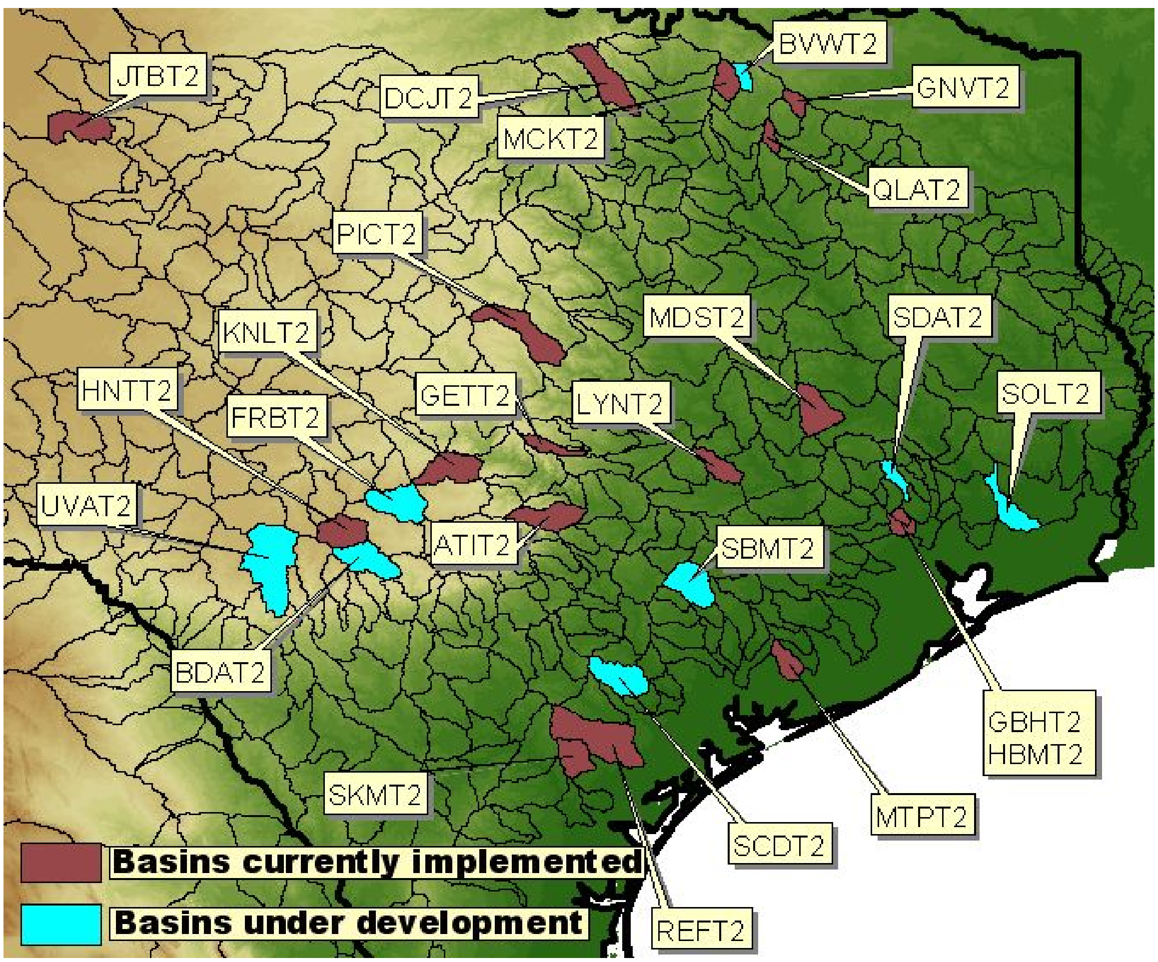

Figure 1. Headwater Drainage Basin Locations

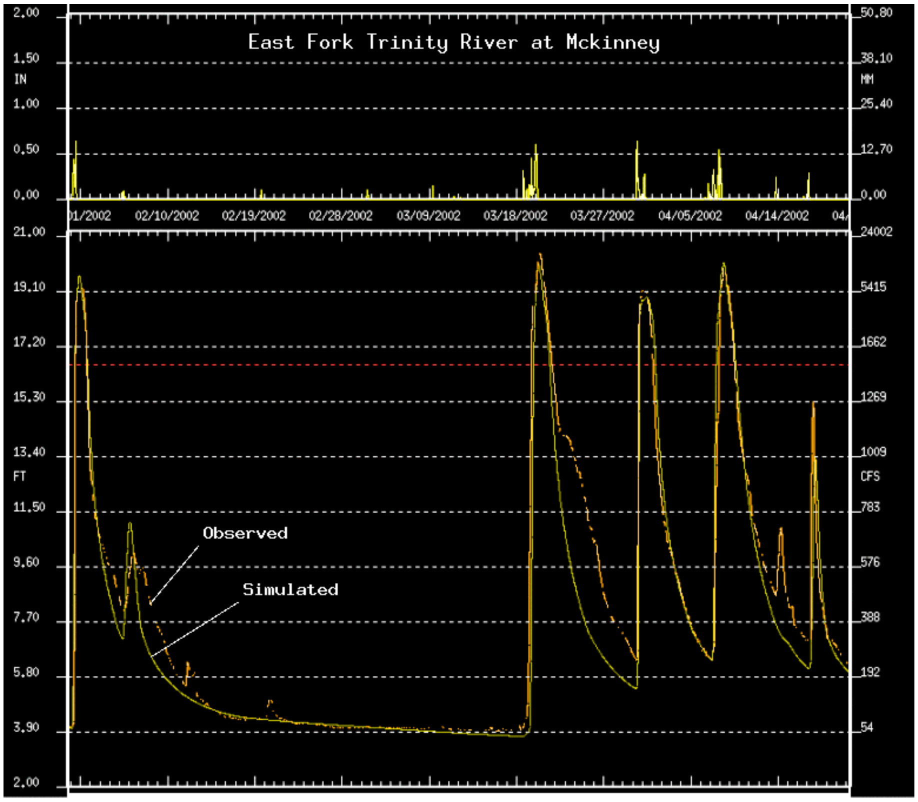

Figure 2. East Fork Trinity River at McKinney

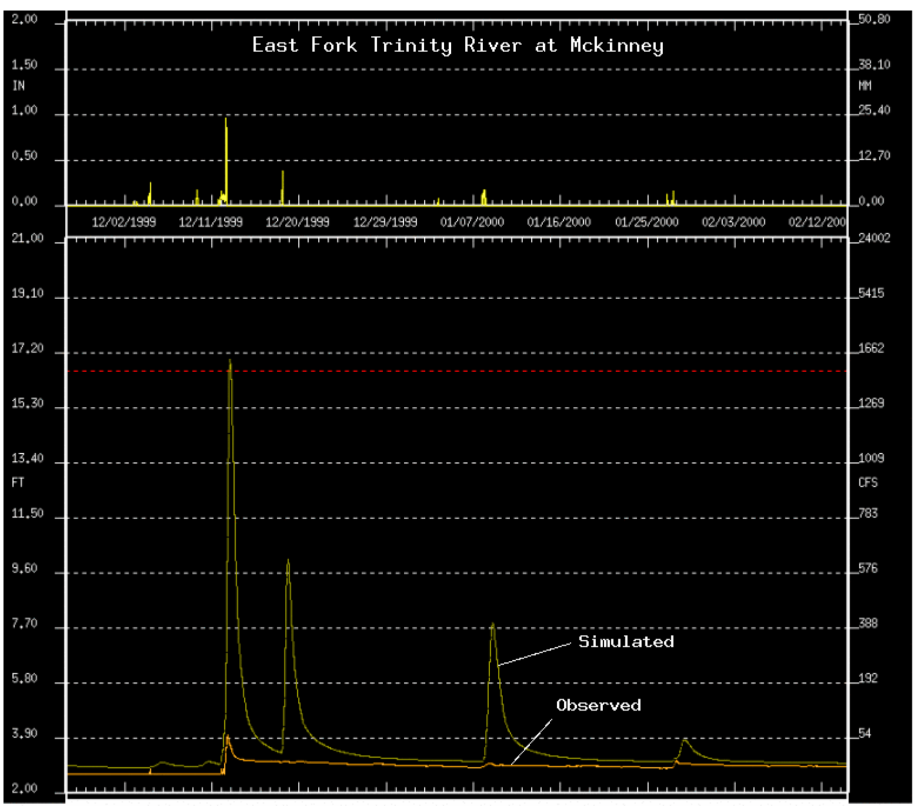

Figure 3. East Fork Trinity River at McKinney

Table 1. Statistical Summary of Calibrations for 25 WGRFC Headwater Distributed Model Basins

Location	River Basin	Drainage Area (sq mi)	Time to Peak (hrs)	Percent Bias	Residual Mean Square (rms) Error	Correlation Coefficient
NORTH TEXAS						
Greenville (GNVT2)	Cowleech Fork Sabine River	77.7	16	-5.57	11.69	0.68
Quinlan (QLAT2)	South Fork Sabine River	78.7	12	-24.76	13.59	0.64
Justin (DCJT2)	Denton Creek	400.0	6	50.89	12.81	0.58
McKinney (MCKT2)	East Fork Trinity River	164.0	14	-17.71	8.79	0.81
Blue Ridge (BVWT2)	Sister Grove Creek	83.1	Under Development			
Justiceburg (JTBT2)	Double Mountain Fork Brazos River	1466.0	9	27.54	10.04	0.71
CENTRAL TEXAS						
Pidcoke (PICT2)	Cowhouse Creek	455.0	6	14.28	16.91	0.59
Lyons (LYNT2)	Davidson Creek	195.0	18	23.44	7.77	0.79
Georgetown (GETT2)	South Fork San Gabriel River	133.0	10	-23.38	10.68	0.68
EAST TEXAS						
Madisonville (MDST2)	Bedias Creek	321.0	21	-2.83	23.79	0.71
Splendora (SDAT2)	Caney Creek	105.0	Under Development			
Sour Lake (SOLT2)	Pine Island Bayou	336.0	Under Development			
HILL COUNTRY						
Hunt (HNTT2)	Guadalupe River	288.0	3	15.62	15.56	0.66
Kingsland (KNLT2)	Sandy Creek	346.0	7	8.06	14.61	0.71
Laguna (UVAT2)	Nueces River	737.0	Under Development			
Bandera (BDAT2)	Medina River	427.0	Under Development			
Fredericksburg (FRBT2)	Pedernales River	369.0	Under Development			
GULF COAST						
Midfield (MTPT2)	Tres Palacios River	145.0	17	9.49	8.46	0.87
Refugio (REFT2)	Mission River	690.0	39	61.74	15.90	0.79
Skidmore (SKMT2)	Aransas River	247.0	12	4.36	22.01	0.83
Schroeder (SCDT2)	Coleto Creek	357.0	Under Development			
Sublime (SBMT2)	Navidad River	331.0	Under Development			
URBAN AREAS						
Austin (ATIT2)	Onion Creek	321.0	9	14.47	32.39	0.51
Houston (HBMT2)	Brays Bayou	94.9	3	-30.03	13.32	0.88
Houston (GBHT2)	Greens Bayou	68.7	5	13.48	19.21	0.67