Artes
An Integrated Model of Water Supply in L.A. County

California Center for Sustainable Communities at UCLA
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Version 4.0

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Introduction

Los Angeles faces a future with less imported water. Infrastructure and institutions will have to adapt. Understanding emerging policy and investment needs requires analysis across systems, a typically elusive goal within the diverse and disparately managed water systems of L.A. A more comprehensive analysis of water resources in Los Angeles requires an understanding of people, pipes, and plants. It could also be flexible to incorporate the fast-changing landscape of models, data, and analysis that the active agencies of the region continue to develop.

With these goals in mind, we developed a water supply model for the metropolitan L.A. County region (*Artes*) to understand the potential for enhancing local water use across scenarios of demand and supply. The basic approach combines knowledge from engineering, hydrology, ecology, and sociology. The model is intentionally lightweight. Flexible and adaptive modeling can address many questions at multiple geographic scales, while also being able to incorporate new tools, data, and other models that are released. This model was developed to:

- Determine how local groundwater, recycling and stormwater capture supplies could maximally meet water demands across L.A. County, based on current knowledge of hydrology and hydrogeology
- Analyze tradeoffs in per capita water demand and available imported water supplies
- Investigate system-wide effects of increased conservation
- Minimize assumptions regarding data gaps
- Use modeling to highlight to key gaps in scientific understanding, while creatively addressing the shortfalls in a precautionary manner. For instance, we compare modeled and historic groundwater pumping and managed aquifer recharge to assess the potential for groundwater overdraft.
- Evaluate cost-effective options for future water management
- Evaluate energy use for water management by utilities and households
- Evaluate proposed and future recycled water supply opportunities
- Evaluate effects of stormwater capture on urban streamflows

This manual describes important information for understanding model operations, assumptions, inputs, and outputs. The manual version (3.7) was written after development of 7 versions code for different research studies, which are published or under review.

Studies to Date

The model has thus far been used for several studies that include:

A) Analysis of local water supply potential given existing infrastructure and an empirical investigation of aggressive conservation (*Journal of Water Resources Planning and Management, 2017)*.

B) Analysis of the role of groundwater exchange pools in reducing water shortages that occur from system wide mismatches in demands and allocations, as well as reductions of imported water (*Journal of Water Resources Planning and Management, 2018*).
C) Analysis of the potential for Los Angeles to be highly or entirely independent of imported water (*Environmental Management, 2019*).
D) Hydroeconomic analysis and values of local water supplies in comparison to existing sources (*Nature Sustainability, 2018*).
E) Effects of stormwater capture and use on urban streamflows (*Water Resources Management, 2019)*
F) Potential effects of reduced imported water availability on regional governance (*Civil Engineering and Environmental Systems, 2019*).
G) Energy use effects for water management and supply by utilities and in residences (*Under Review, 2019*).

Associated Peer-Reviewed Articles

2019

Porse, Erik and Stephanie Pincetl. (2019). "Effects of Stormwater Capture and Use on Urban Streamflows." *Water Resources Management*. 33.2: 713-723.

Porse, Erik. (2019). "Merging Network Governance and Systems Analysis for Urban Water Management." *Civil Engineering and Environmental Systems*. 2019:1-19.

Pincetl, Stephanie, Thomas W. Gillespie, Diane E. Pataki, Erik Porse, Shenyue Jia, Erika Kidera, Nick Nobles, Janet Rodriguez, and Dong-ah Choi. (2019) "Evaluating the effects of turf-replacement programs in Los Angeles." *Landscape and Urban Planning*. 185: 210-221.

2018

Pincetl, Stephanie, Erik Porse, Kathryn B. Mika, Elizabeth Litvak, Kim Manago, Kartiki Naik, Terri Hogue, Mark Gold, Tom Gillespie, and Diane Pataki. (2018). "Adapting Urban Water Systems to Manage Scarcity in the 21st Century: The Case of Los Angeles." *Environmental Management.* 63.3. pgs 293-308

Porse, Erik, Kathryn B. Mika, Rhianna Williams, Mark Gold, William Blomquist, & Stephanie Pincetl (2018). "Groundwater Exchange Pools and Urban Water Supply Sustainability: Modeling Directed and Undirected Networks." *Journal of Water Resources Planning and Management*, 144(8), 04018040.

Porse, Erik, Kathryn B. Mika, Elizaveta Litvak, Kimberly F. Manago, Terri S. Hogue, Mark Gold, Diane E. Pataki, and Stephanie Pincetl. (2018). "The Economic Value of Local Water Supplies in Los Angeles." Nature Sustainability, May. doi:10.1038/s41893-018-0068-2.

Porse, Erik C. (2018). "Open Data and Stormwater Infrastructure in Los Angeles: Implications for Green Infrastructure and Sustainability". Local Environments. 1-13.

2017

Porse, Erik, Kathryn B. Mika, Elizaveta Litvak, Kimberly F. Manago, Kartiki Naik, Madelyn Glickfeld, Terri S. Hogue, Mark Gold, Diane E. Pataki, and Stephanie Pincetl. (2017). "Systems Analysis and Optimization of Local Water Supplies in Los Angeles." *Journal of Water Resources Planning and Management* 143, no. 9. 2017: 04017049.

2016

Pincetl, Stephanie, Erik C. Porse, and Deborah Cheng. (2016) "Fragmented Flows: Water Supply in Los Angeles County". *Environmental Management*. 58(2). Pg. 208-222.

2015

Porse, Erik C., Madelyn Glickfeld, Keith Mertan, and Stephanie Pincetl. (2015) "Pumping for the Masses: Evolution of Groundwater Management in Metropolitan Los Angeles." *Geojournal*. DOI: 10.1007/s10708-015-9664-0.

Summary of Model Runs to Date

Model Run	**Description**	**Associated Publications**
A	Initial model with max flow formation to maximize the supplies provided by local sources. Uses perfect foresight	Porse, Erik, Kathryn B. Mika, Elizaveta Litvak, Kimberly F. Manago, Kartiki Naik, Madelyn Glickfeld, Terri S. Hogue, Mark Gold, Diane E. Pataki, and Stephanie Pincetl. (2017). "Systems Analysis and Optimization of Local Water Supplies in Los Angeles." *Journal of Water Resources Planning and Management* 143, no. 9. 2017: 04017049.
B	Maximum flow model used to evaluate potential for groundwater exchange pools. Includes an added formulation for directed and undirected network flows. Uses perfect foresight	Porse, Erik, Kathryn B. Mika, Rhianna Williams, Mark Gold, William Blomquist, & Stephanie Pincetl (2018). "Groundwater Exchange Pools and Urban Water Supply Sustainability: Modeling Directed and Undirected Networks." *Journal of Water Resources Planning and Management*, 144(8), 04018040
C	Incorporates new scenarios of conservation, reuse, and groundwater recharge to evaluate potential for cutting imported supplies. Added	Pincetl, Stephanie, Erik Porse, Kathryn B. Mika, Elizabeth Litvak, Kim Manago, Kartiki Naik, Terri Hogue, Mark Gold, Tom Gillespie, and Diane Pataki. (2018). "Adapting Urban Water Systems to Manage Scarcity in the 21st Century: The Case of Los Angeles." *Environmental Management.* 63.3. pgs 293-308

	an annual foresight formulation.	
D	Model runs with a hydroeconomic, least-cost formulation added, including shortages from scarcity.	Porse, Erik, Kathryn B. Mika, Elizaveta Litvak, Kimberly F. Manago, Terri S. Hogue, Mark Gold, Diane E. Pataki, and Stephanie Pincetl. (2018). "The Economic Value of Local Water Supplies in Los Angeles." Nature Sustainability, May. doi:10.1038/s41893-018-0068-2.
E	Model runs with energy use and intensity parameters added. Uses a least-cost formulation with scarcity shortages.	Publication under review.
G	Model runs with new scenarios of proposed and potential water reuse (indirect potable and direct potable)	Presentation given to WateReuse foundation in September 2019, San Diego, CA

Existing Models of L.A. Water

Water in metropolitan Los Angeles region is highly modeled. Multiple agencies have models that simulate or optimize groundwater, water supply, stormwater, wastewater, and flood control operations. We surveyed the existing models and Table 1 below describes models used by agencies throughout Los Angeles to manage water supply, groundwater basins, stormwater systems, and flood control.

Table 1: Relevant models of hydrology, hydrogeology, and water management in Los Angeles County

Study and Model	Developer	Description	Software	Geography
Water Management Modeling System (WMMS)	L.A. County Department of Public Works, U.S. Bureau of Reclamation, developed by Tetra Tech	Hydrologic model rainfall and runoff across L.A. County. Developed to support reoperation of flood control dams for increasing lows to spreading basins along with increased stormwater capture	LSPC, which is a C++ version of HSPF. Displayed in the Map Window GIS interface	L.A. County, including over 2,600 delineated sub-watershed regions
Stormwater Capture Master Plan	City of L.A. Department of Water and Power, developed by Geosyntec	Hydrologic model of rainfall and runoff in the Los Angeles River Basin, including estimates of groundwater recharge. Optimizes locations of distributed stormwater capture sites	LSPC, with estimates of deep groundwater infiltration calibrated using GWAM	Los Angeles River Basin
Los Angeles Sustainable Water Project watershed models	UCLA Grand Challenges and L.A. Bureau of Sanitation	Hydrology models of rainfall, runoff, and shallow zone groundwater infiltration to assess opportunities for increased stormwater capture and local water supply	SUSTAIN	Watersheds in the city of Los Angeles (Ballona Creek, Dominguez Channel, Los Angeles River)
L.A. County irrigation and runoff	USGS and Water Replenishment District of Southern California	Root zone model for estimating varying runoff and recharge in space and time from precipitation and urban irrigation in the Los Angeles basin, California	USGS INFIL model	L.A. County

Water Augmentation Study	U.S. Bureau of Reclamation and Los Angeles & San Gabriel Rivers Watershed Council	The model estimates baseline runoff-recharge conditions across L.A. County watersheds, as well as showing the potential benefit of making changes to how urban runoff is handled by the infrastructure	Ground Water Augmentation Model (GWAM)	Urbanized portions of the Los Angeles River, San Gabriel River, Ballona Creek, and Dominguez Channel watersheds
Water Supply Allocation Model	Metropolitan Water District of Southern California	Water supply management model for allocating annual MWD imports across member agencies	Spreadsheet	MWD service area, covering Southern California
Basin Groundwater Model	USGS	3-D finite difference model of groundwater flows and storage in the L.A. Coastal Plain.	MODFLOW	West Coast and Central Basins

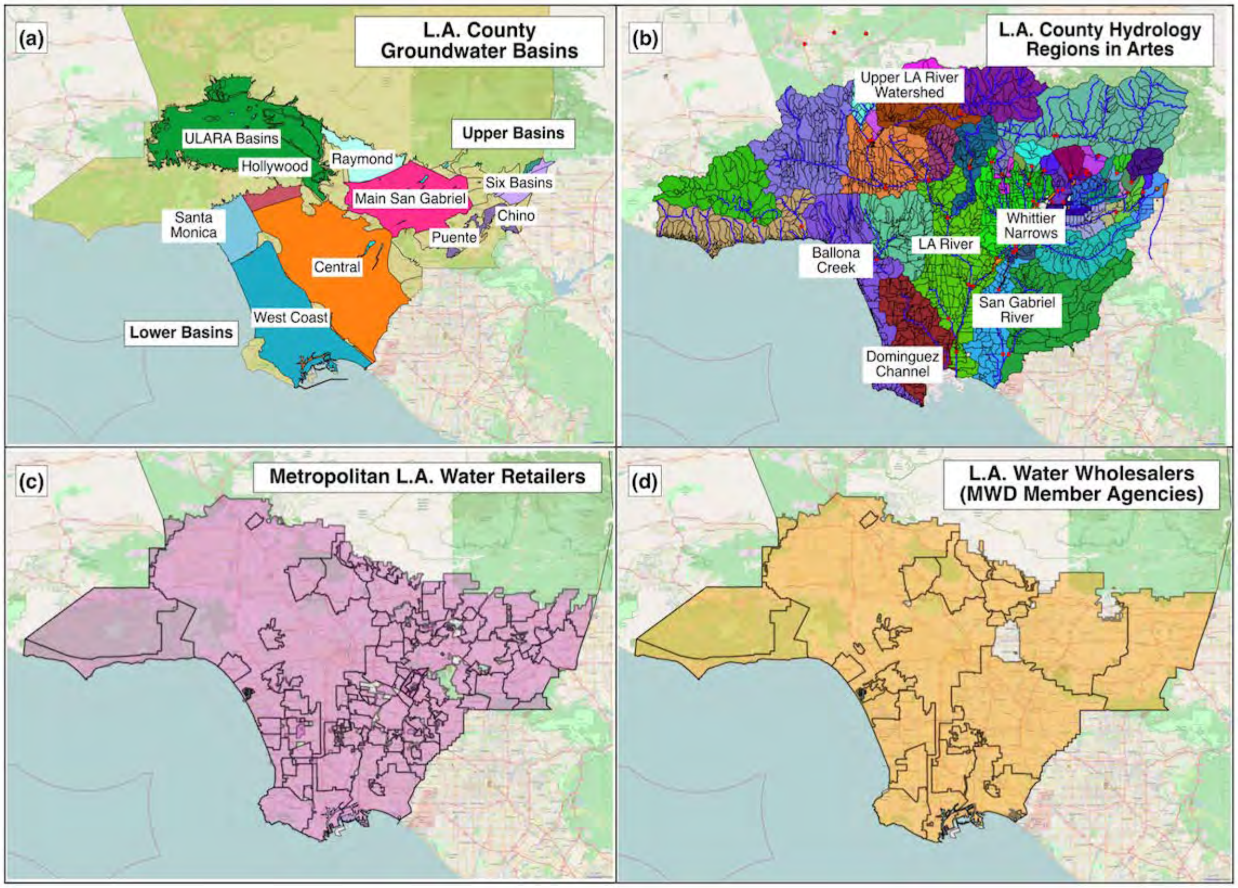
Scope and Geography of *Artes*

Artes is a network flow model of water supply management in Los Angeles. It operates at a monthly time step and runs over as much as 25 years (1996-2010) based on historic flows and imported water supplies. *Artes* currently includes water supply, wastewater, stormwater, and flood control infrastructure. It integrates surface water hydrology based on the *Water Management Modeling System (WMMS)* from LA County and the U.S. Bureau of Reclamation. The model optimizes flows throughout the urban water management system with the specific goal of maximizing flows from local sources of supply, including groundwater basins, water reuse plants, and stormwater capture basins. The model covers the metropolitan LA County region. It includes:

- Over 100 water supply agencies that report operations data based on Urban Water Management Plans (UWMPs)
- Regional wastewater treatment and water reclamation plants from both LA City and LA County.
- Network routing for the 26 stormwater capture facilities, including downstream releases to surface water systems and groundwater infiltration
- Surface water regions, based on watershed areas from *WMMS,* which are aggregated to align with key infrastructure components such as spreading grounds.
- Existing dams and reservoirs for water agencies.

The model also includes nodes and links for vadose zones associated with surface water regions, but these are not connected to groundwater basins due to lack of a couple surface-to-groundwater model that can accurately simulate links in urban hydrology and hydrogeology.

Figure 1: Geographic scope of *Artes* model



Data Sources

Table 2 lists the data sources compiled and used in developing and running the *Artes* model. The table lists the data, source, time frame, and resolution. All data is available in the *Artes* Github repository (https://github.com/erikporse/artes/tree/master/data)

Estimates of precipitation, evapotranspiration, and groundwater infiltration were derived from the WMMS hydrologic model based on aggregating its sub-watershed areas (LACDPW 2013). In addition, monthly records of stream flow were obtained for key stream gauges, which helped in validating results from the WMMS model for use in the optimization.

Monthly volumes of imported water were provided by regional water agencies. MWD provided historic monthly inflows to the region for the State Water Project and the Colorado River Aqueduct for 1986-2014. LADWP provided monthly inflow values for the L.A. Aqueduct that imports water from the Owens Valley and Mono Lake. Finally, inputs from the State Water Project to the San Gabriel Valley Municipal Water District were estimated based on annual allocation rights and available historic data. These sources constitute the primary imported water inputs for L.A. County.

Groundwater pumping rights in the adjudicated basins for public and private entities across L.A. County were extracted from publicly available sources that provide pumping allocations for all rights' holders. Each adjudicated basin in L.A. County publishes an annual report detailing pumping totals and current rights for all rights' holders. For each basin, the total annual extraction rights were recorded, including the sum of adjudicated rights, carryovers from prior year deficits, return rights, and long-term storage, and inserted as pumping rights into the model database. The groundwater adjudications were also used to specify identified safe yield calculations that provided the maximum annual allowed volume of groundwater pumping for each basin. Groundwater basin areas were delineated based on available data sets from L.A. County and the California State Department of Water Resources Bulletin 118 (DWR 2003; LACDPW 2012). Finally, the assessed size of groundwater basins and the smaller extractable volumes were derived from a comprehensive regional assessment (MWD 2007).

Historic flows for wastewater and stormwater were obtained from regional water agencies. LACDPW provided monthly data for flows into stormwater capture basins. LACDPW, LADWP, the City of Burbank, the Sanitation Districts of L.A. County, and the Water Reclamation District of Southern California (WRD) provided monthly data for influent and effluent flows in regional wastewater treatment plants, which ranged from approximately 1994 through 2012 depending upon the treatment plant. Data for sewer service areas and associated wastewater treatment and water reclamation plants were obtained from the Sanitation Districts of L.A. County.

Urban water demands and supply sources for each retailer were extracted from 2010 Urban Water Management Plans (UWMPs). UWMPs are prepared by California's urban water suppliers to support their long-term resource planning and ensure adequate water is available for current and future use. Urban water agencies that supply over 3,000 acre-feet a year or more than 3,000 urban connections must report operations data to DWR using UWMPs to assess water source reliability and report progress towards a 20% reduction in per capita urban water consumption by the year 2020, as required in the Water Conservation Bill of 2009 SBX7-7. The geographic jurisdictions of retailers were compiled by contacting retailers and later validated against a statewide geospatial dataset (CDPH 2014; Pincetl et al. 2016).

The model analyzed local water supply reliance across a range of input parameters for urban water demands (see *Analysis Procedures*). Maximum water demands corresponded with 2010 data extracted from UWMPs. The minimum demand in each retailer was assessed based on estimates of the sum of: 1) basic indoor urban water demands in an industrialized country (~50 gallons/person/day); and 2) needed water volume to maintain existing urban trees and low-water landscapes (Litvak et al. 2017; Litvak and Pataki 2016; Pataki et al. 2011).

Water use by urban vegetation was derived from *in situ* measurements. Tree transpiration was measured using thermal dissipation probes (Granier 1987) that recorded sap flux in urban tree species common in Los Angeles (Pataki et al. 2011) and evapotranspiration of irrigated turfgrass lawns was measured by portable chambers. Trees used in experiments were located in a variety of residential, street, and institutional locations, while turfgrass was exposed to various microclimatic conditions and shading regimes throughout greater L.A. Trees and lawns were well irrigated according to current (but pre-drought) local practices. Our previous studies showed that under the irrigation regimes prevalent in the 2000's, most urban trees in L.A. seldom experienced water stress and commonly had access to non-limiting soil moisture (Litvak et al. 2011, 2012; McCarthy and Pataki 2010; Pataki et al. 2011). Using these measurements, empirical models of tree transpiration and turfgrass evapotranspiration were developed. Tree transpiration was modeled based on tree size and stomatal responses to atmospheric vapor pressure deficit and incident radiation (Litvak et al. 2017). Turfgrass evapotranspiration was modeled based on reference evapotranspiration and empirical landscape coefficients (Litvak and Pataki 2016). Then, using remote-sensing derived estimates of tree and turfgrass cover, ground inventories of urban tree species composition and meteorological parameters from CIMIS, we estimated that total evapotranspiration of Los Angeles landscapes under non-moisture limiting conditions was on average 67±3 gallons/day per capita. In the SP model scenario, we included outdoor demand with an estimate of tree canopy water use (9-25 gpd, depending on seasonal variation) along with an additional 20% of volume to support low-water landscapes.

Historic data for monthly demands of water retailers in California do not exist systematically across the hundreds of agencies. Since 2014, the State Water Resources Control Board has required water agencies to report monthly residential per capita consumption using standardized procedures (SWRCB 2018). Reported monthly data from the SWRCB was compared to monthly demand estimates derived by applying DWR seasonal water use estimates outlined in Bulletin 166 to 2010 UWMP data for each retailer. The comparison showed reasonable seasonal correlations of estimates and actual data (Figure 2).

In 2017-18, economic parameters were added to the model and a least-cost optimization was developed to evaluate the economic value of alternative supplies and conservation. For all links connecting nodes in the network, an annualized unit cost for conveying water was added, based on values reported in regional reports and direct communication with local utilities. Additionally, the economic value of demand reductions was estimated based on a willingness-to-pay approach published in previous literature and based on local data for utility specific water rates (prices), population, and income. The procedures are documented in the supplemental data section of the associated study (Porse et al. 2018).

In 2018-19, energy intensity (EI) coefficients for all links throughout the model's network were added to evaluate the energy use effects of various supply and demand scenarios. EI values were compiled from multiple sources, including reports from regional agencies and planning studies, direct communication with utilities, peer-reviewed studies from the region, and other peer-reviewed studies. The procedure and data sources are fully documented in a peer-reviewed publication, which is currently under review.

Figure 2: Comparison of: 1) actual 2015-16 monthly water demand data (solid) and 2) estimated monthly demands derived from applying a monthly usage factor to 2010 annual demand values (dashed) based on monthly estimates from California Bulletin 166. Trend lines correlate by season.

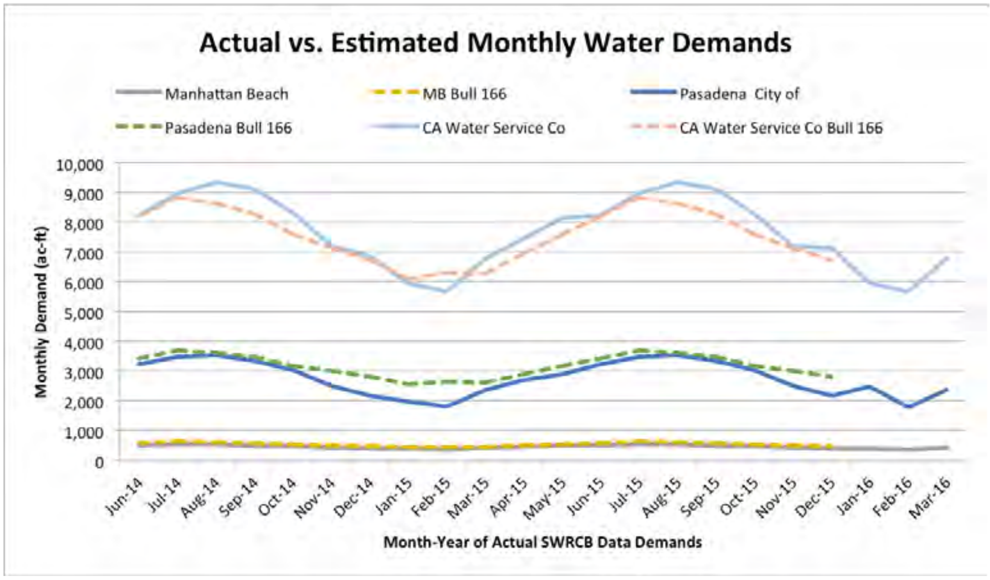


Table 2: Data sources in Artes (Porse et al. 2017)

Parameter	Dataset	Time	Resolution	Source
L.A. County Stream Runoff Data	Gaged runoff data at watershed outlet	WY 1980-2014	Daily, Monthly, Annual	LACDPW
MWD Imported Water	Historical data from MWD on imports and distributions to member agencies	1986-2015	monthly	MWD
WMMS Sub-basin data	Stormwater and watershed modeling parameters for 2600 sub-basins in LA County	varies	daily	LA County, USBR
LA County Stormwater Recharge	Historic monthly recharge for capture basins in LA County	Oct 1987-2014	monthly	LA County
LA County GIS Database	Various shape file data sets of hydrologic, infrastructure, and jurisdictional parameters	varies	varies	LA County GIS
LA County Water Retailers	Shape file polygons of water agencies in L.A. County	n/a	n/a	SWRCB, Pincetl et al 2016
Groundwater Rights	Groundwater pumping rights in adjudicated L.A. County basins	1939-2013	annual	Porse et al (2015), Ground watermaster annual reports
Assessed groundwater basin capacities	MWD assessments of groundwater capacity and available storage	2007	annual	MWD
Supply and Demand	Supplies and demands for agencies throughout the county	2010	annual	Urban Water Management Plans (UWMPs)
Recycled Water Network	Annual allocations of recycled water to treatment plants and among agencies	varies	annual	various
LA County Streamflow Data	Streamflow records for surface flows in L.A. County	1986-2012	monthly	LACDPW
LA County Rainfall Gauge Data	Precipitation records for surface flows in L.A. County, included and aggregated in WMMS	1986-2014	daily, monthly	LACDPW
Wastewater Flows				
LA City Wastewater Treatment Flows	Influent and effluent flows for wastewater treatment plants in the City of L.A.	1994-2015	daily, monthly	LADWP
LA County Wastewater Treatment Flows	Influent and effluent flows for wastewater treatment plants in the County of L.A.	1986-2014	daily, monthly	LACDPW and the Sanitation Districts of L.A. County
Burbank WRP Wastewater Flows	Influent and effluent flows for Burbank water reclamaption plant	1986-2014	daily, monthly	City of Burbank
Edward Little WRP	Influent and effluent flows for the Ed Little water reclamation plant	1986-2014	daily, monthly	WRD

Determining Losses in Water Distribution Systems

For each of the two major wastewater collection systems in the county (the L.A. City Bureau of Sanitation network and the L.A. County Sanitation District network), wastewater treatment inflows were compared to aggregated reported use by retailers (2010) upstream of the treatment plant sewer networks. Without good data to differentiate indoor and outdoor uses, or estimate distributed recharge from irrigation, or determine leakage volumes, losses in the *Artes* model were combined to include both leakage and irrigation. Leakage includes losses from pipe leaks and other infrastructure sources, which can vary widely across retailers. Irrigation losses include soil infiltration and evaporation on irrigated lands, calculated separately from the water balance of WMMS. Results showed variability in the percentage of system losses attributable to irrigation losses (evapotranspiration and groundwater infiltration) and system leaks. Table 3 below shows the calculations for L.A. County's Joint Outfall System and Table 4 shows results for the L.A. Bureau of Sanitation territory including L.A. City, Santa Monica, Burbank, and Glendale. Greater availability of network flow data for sewers would improve the capacity for integrated systems analysis at multiple geographic and temporal scales.

In the County system, upstream water recycling plants can send reclaimed water to spreading basins, route it into purple pipe networks, discharge it to surface drainage, or route partially treated water through the sewer network for downstream blending and treatment. The Joint Water Pollution Control Plant (JWPCP) is the primary treatment plant, while 7 upstream plants treat water to varying degrees based on demands for recycled water.

In L.A. City and its connected cities, most wastewater ultimately flows to the downstream Hyperion Treatment Plant for treatment and discharge. Hyperion does send some treated water upstream for advanced treatment in the Edward Little Water Reclamation Plant managed by the Water Reclamation District (WRD), which uses it to recharge groundwater basins. The Burbank water reclamation plant, too, receives some wastewater from Burbank city to supply non-potable end-uses. The Tillman and Glendale facilities, meanwhile, discharge to the L.A. River.

Table 3: Estimating distribution system losses by comparing reported demands and wastewater plant inflows for treatment plant service areas in the L.A. County Sanitation District territory.

	Monthly Demands (ac-ft)											
	January	February	March	April	May	June	July	August	September	October	November	December
Joint Water Pollution Control Plant												
CITY OF VERNON	715	739	734	813	887	961	1,035	1,010	971	887	838	789
CITY OF LYNWOOD	420	435	432	478	522	565	609	594	571	522	493	464
CITY OF LOMITA	183	189	188	208	227	246	265	258	248	227	214	202
SOUTH MONTEBELLO ID	145	150	149	165	179	194	209	204	196	179	170	160
MONTEBELLO LAND AND WATER COMPANY	242	251	249	276	301	326	351	343	329	301	284	267
CITY OF TORRANCE	1,900	1,965	1,952	2,162	2,358	2,555	2,751	2,686	2,581	2,358	2,227	2,096
CITY OF MANHATTAN BEACH	444	459	456	505	551	597	643	627	603	551	520	490
CITY OF SOUTH GATE	707	731	726	804	878	951	1,024	999	960	878	829	780
BELLFLOWER-SOMERSET MUTUAL WATER COMPANY	370	383	380	421	459	498	536	523	503	459	434	408
CITY OF HUNTINGTON PARK	374	387	385	426	465	503	542	529	508	465	439	413
MAYWOOD MUTUAL WATER CO. #1	48	50	50	55	60	65	70	68	65	60	57	53
CITY OF INGLEWOOD	693	717	712	789	861	932	1,004	980	942	861	813	765
BELLFLOWER HOME GARDEN WATER COMPANY	28	28	28	31	34	37	40	39	37	34	32	30
GOLDEN STATE WATER CO. - METROPOLITAN	6,524	6,749	6,704	7,424	8,099	8,774	9,449	9,224	8,864	8,099	7,649	7,199
CAL WATER SERVICE CO	6,105	6,315	6,273	6,947	7,578	8,210	8,841	8,631	8,294	7,578	7,157	6,736
CAL-AM WATER CO. - BALDWIN HILLS	1,507	1,558	1,548	1,714	1,870	2,026	2,182	2,130	2,047	1,870	1,766	1,662
CITY OF TORRANCE	1,900	1,965	1,952	2,162	2,358	2,555	2,751	2,686	2,581	2,358	2,227	2,096
CITY OF MONTEREY PARK	643	665	661	732	798	865	932	909	874	798	754	710
CITY OF COMPTON	653	676	671	743	811	878	946	923	887	811	766	721
CITY OF LONG BEACH	4,660	4,821	4,788	5,303	5,785	6,267	6,749	6,588	6,331	5,785	5,463	5,142
SATIVA CWD	57	59	59	65	71	77	83	81	77	71	67	63
BELLFLOWER MUNICIPAL WATER SYSTEM	48	49	49	54	59	64	69	67	65	59	56	53
PARK WATER COMPANY	897	928	922	1,021	1,114	1,207	1,300	1,269	1,219	1,114	1,052	990
CITY OF PARAMOUNT	502	519	516	571	623	675	727	709	682	623	588	554
CITY OF SIGNAL HILL	147	152	151	167	182	197	212	207	199	182	172	162
JWPCP or Los Coyotes												
CITY OF PICO RIVERA	397	411	408	452	493	534	575	562	540	493	466	438

CITY OF NORWALK	168	174	173	191	209	226	244	238	229	209	197	186
PICO CWD	240	249	247	274	298	323	348	340	327	298	282	265
CITY OF DOWNEY	1,199	1,241	1,233	1,365	1,489	1,613	1,737	1,696	1,630	1,489	1,406	1,324
SAN GABRIEL VALLEY WATER COMPANY	2,794	2,890	2,871	3,179	3,468	3,757	4,046	3,950	3,796	3,468	3,275	3,083
Los Coyotes WRP												
CITY OF WHITTIER	596	617	613	679	740	802	864	843	810	740	699	658
CITY OF SANTA FE SPRINGS	458	474	470	521	568	616	663	647	622	568	537	505
ORCHARD DALE WATER DISTRICT	165	170	169	187	204	221	238	233	224	204	193	182
Los Coyotes or Whittier Narrows WRPs												
CITY OF SOUTH PASADENA	346	358	355	393	429	465	501	489	470	429	405	382
SAN GABRIEL CWD	513	531	528	584	637	690	744	726	698	637	602	567
CITY OF ALHAMBRA	1,104	944	937	1,038	1,132	1,227	1,321	1,289	1,239	1,132	1,069	1,006
AMARILLO MUTUAL WATER COMPANY	28	28	28	31	34	37	40	39	37	34	32	30
VALLEY WATER COMPANY	167	173	172	190	207	225	242	236	227	207	196	184
CITY OF EL MONTE	192	199	198	219	239	259	279	272	261	239	225	212
LA CANADA Irrigation District	159	165	164	181	198	214	230	225	216	198	187	176
San Jose (SJC) WRP												
SUBURBAN WATER SYSTEMS	3,625	3,750	3,725	4,125	4,500	4,875	5,250	5,125	4,925	4,500	4,250	4,000
LA PUENTE VALLEY CWD	191	197	196	217	236	256	276	269	259	236	223	210
VALLEY VIEW MWC	41	43	42	47	51	56	60	58	56	51	48	46
CITY OF AZUSA	1,661	1,718	1,707	1,890	2,062	2,234	2,406	2,348	2,257	2,062	1,947	1,833
FRANK BONELLI PARK	0	0	0	0	0	0	0	0	0	0	0	0
CITY OF COVINA	463	479	476	527	575	623	671	655	629	575	543	511
VALENCIA HEIGHTS WATER COMPANY	62	64	64	71	77	83	90	88	84	77	73	68
WALNUT VALLEY WATER DISTRICT	1,626	1,682	1,670	1,850	2,018	2,186	2,354	2,298	2,209	2,018	1,906	1,794
VALLEY CWD	642	664	660	731	797	864	930	908	872	797	753	709
CITY OF GLENDORA	924	955	949	1,051	1,146	1,242	1,338	1,306	1,255	1,146	1,083	1,019
VALLEY CWD	642	664	660	731	797	864	930	908	872	797	753	709
ROWLAND CWD	876	906	900	997	1,087	1,178	1,268	1,238	1,190	1,087	1,027	966
SJC or Whittier Narrows WRPs												
RUBIO CANON LAND AND WATER ASSOCIATION	141	146	145	161	176	190	205	200	192	176	166	156
KINNELOA IRRIGATION DISTRICT	49	51	50	56	61	66	71	69	67	61	58	54
EAST PASADENA WATER COMPANY	0	0	0	0	0	0	0	0	0	0	0	0

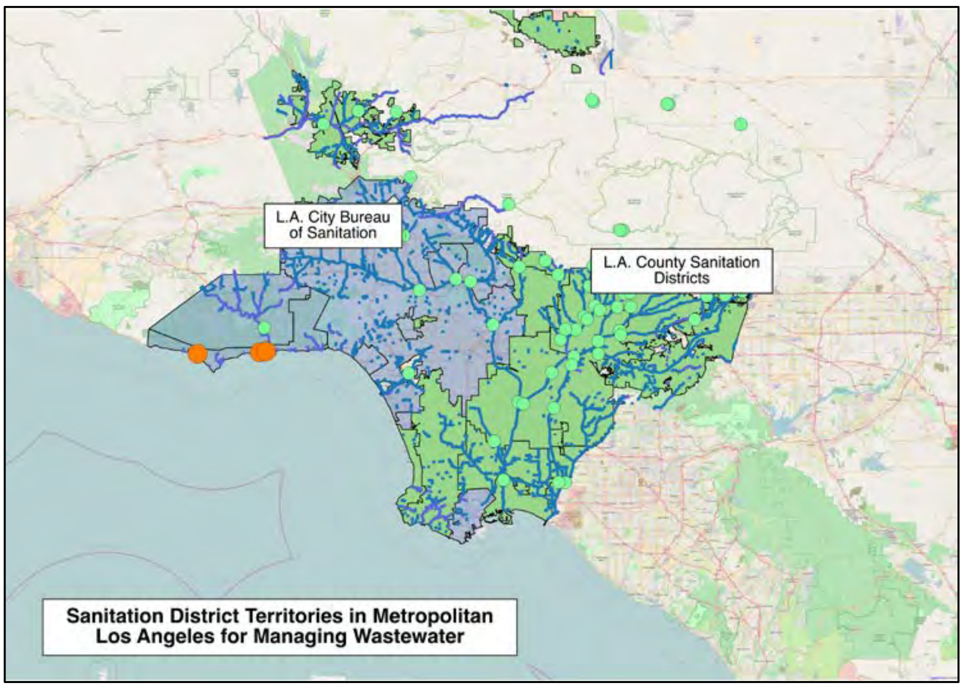
SUNNY SLOPE MUTUAL WATER COMPANY	179	185	184	203	222	240	259	253	243	222	209	197
CITY OF SIERRA MADRE	218	225	224	248	270	293	315	308	296	270	255	240
CITY OF MONROVIA	574	593	589	653	712	771	831	811	779	712	672	633
CAL-AM WATER CO. - BALDWIN HILLS	1,507	1,558	1,548	1,714	1,870	2,026	2,182	2,130	2,047	1,870	1,766	1,662
LINCOLN AVENUE WATER COMPANY	162	168	167	185	201	218	235	229	220	201	190	179
CITY OF PASADENA	2,558	2,646	2,629	2,911	3,175	3,440	3,705	3,616	3,475	3,175	2,999	2,823
CITY OF ARCADIA	1,172	1,212	1,204	1,333	1,454	1,576	1,697	1,656	1,592	1,454	1,374	1,293
LAS FLORES WATER COMPANY	36	37	37	41	44	48	52	51	49	44	42	40
JWPCP or Long Beach WRP												
CITY OF LAKEWOOD	646	669	664	735	802	869	936	914	878	802	758	713
Long Beach WRP												
CITY OF CERRITOS	1,150	1,190	1,182	1,309	1,428	1,547	1,666	1,626	1,563	1,428	1,349	1,269
Ponoma WRP												
CITY OF POMONA	1,721	1,781	1,769	1,959	2,137	2,315	2,493	2,434	2,339	2,137	2,018	1,900
CITY OF LA VERNE	603	624	620	686	749	811	874	853	820	749	707	666
Total	59,905	61,772	61,360	67,949	74,127	80,304	86,481	84,422	81,127	74,127	70,008	65,890
% to Sewage Treatment												
JWPCP Inflows	27,035	24,986	26,503	25,667	26,436	25,606	26,356	26,325	25,081	26,073	24,724	28,517
Long Beach WRP Inflows	1,751	1,605	1,787	1,485	1,723	1,875	1,873	1,884	1,858	1,855	1,719	1,882
San Jose Creek WRP Inflows	7,426	6,728	7,182	7,029	7,266	6,995	7,127	7,071	7,057	7,251	6,985	7,948
Whittier Narrows WRP Inflows	712	627	656	582	551	614	668	600	653	675	735	788
Los Coyotes WRP Inflows	2,581	2,262	2,127	1,992	1,928	1,776	2,027	1,702	1,793	1,821	1,786	2,272
Ponoma WRP Inflows	836	780	796	802	832	816	837	827	774	849	877	996
WWTP Total Inflows	40,341	36,988	39,051	37,558	38,737	37,683	38,889	38,409	37,215	38,524	36,827	42,402
% Losses	33%	40%	36%	45%	48%	53%	55%	55%	54%	48%	47%	36%

Table 4: Estimating distribution system losses by comparing reported demands and wastewater plant inflows for treatment plant service areas in the L.A. City territory, also including the connected systems of Burbank, Glendale, and Santa Monica.

	Monthly Demands (ac-ft)											
	January	February	March	April	May	June	July	August	September	October	November	December
LA City: Hyperion												
CITY OF BURBANK	1,573	1,628	1,617	1,790	1,953	2,116	2,279	2,224	2,138	1,953	1,845	1,736
CITY OF GLENDALE	2,227	2,303	2,288	2,534	2,764	2,994	3,225	3,148	3,025	2,764	2,611	2,457
L A COUNTY WATERWORKS DIST #29	623	644	640	709	773	837	902	880	846	773	730	687
L A COUNTY WATERWORKS DIST #21	4	4	4	5	5	6	6	6	6	5	5	5
CITY OF SAN FERNANDO	252	261	259	287	313	340	366	357	343	313	296	279
CITY OF BEVERLY HILLS	919	951	945	1,046	1,141	1,236	1,331	1,300	1,249	1,141	1,078	1,014
CITY OF GLENDALE	2,227	2,303	2,288	2,534	2,764	2,994	3,225	3,148	3,025	2,764	2,611	2,457
L A COUNTY WATERWORKS DIST #80	0	0	0	0	0	0	0	0	0	0	0	0
CITY OF LOS ANGELES	44,296	45,823	45,518	50,406	54,988	59,570	64,153	62,625	60,181	54,988	51,933	48,878
CITY OF EL SEGUNDO	1,225	1,267	1,259	1,394	1,520	1,647	1,774	1,732	1,664	1,520	1,436	1,351
LAS VIRGENES MWD												
CITY OF SANTA MONICA	1,014	1,049	1,042	1,154	1,259	1,364	1,469	1,434	1,378	1,259	1,189	1,119
CRESCENTA VALLEY CWD	323	335	332	368	402	435	468	457	439	402	379	357
Total	54,683	56,569	56,192	62,226	67,883	73,540	79,197	77,311	74,294	67,883	64,112	60,340
WWTP Inflows	54,895	50,769	54,565	52,215	53,011	51,445	52,084	53,236	49,835	53,204	50,985	58,107
% Difference	0%	10%	3%	16%	22%	30%	34%	31%	33%	22%	20%	4%

Network Routing for Wastewater and Stormwater Outflows
Creating the network in *Artes* required determining flows of both water supply and wastewater to the greatest extent possible. Each retailer in L.A. County is associated with one or more water reclamation plants (WRPs) that are connected through pipe networks. Retailers were aggregated based on the WRP or groups of WRPs that can receive sewage. The heavily shaded (green) region to the east is the L.A. County Sanitation District territory, while the lighter shaded (blue) region to the northwest includes service areas of the L.A. City Bureau of Sanitation, Santa Monica, Burbank, Glendale, and Las Virgenes. The two major service territories are shown below in Figure 3.

Figure 3: Map of sanitation district areas used to route sanitary sewer flows to treatment plants.

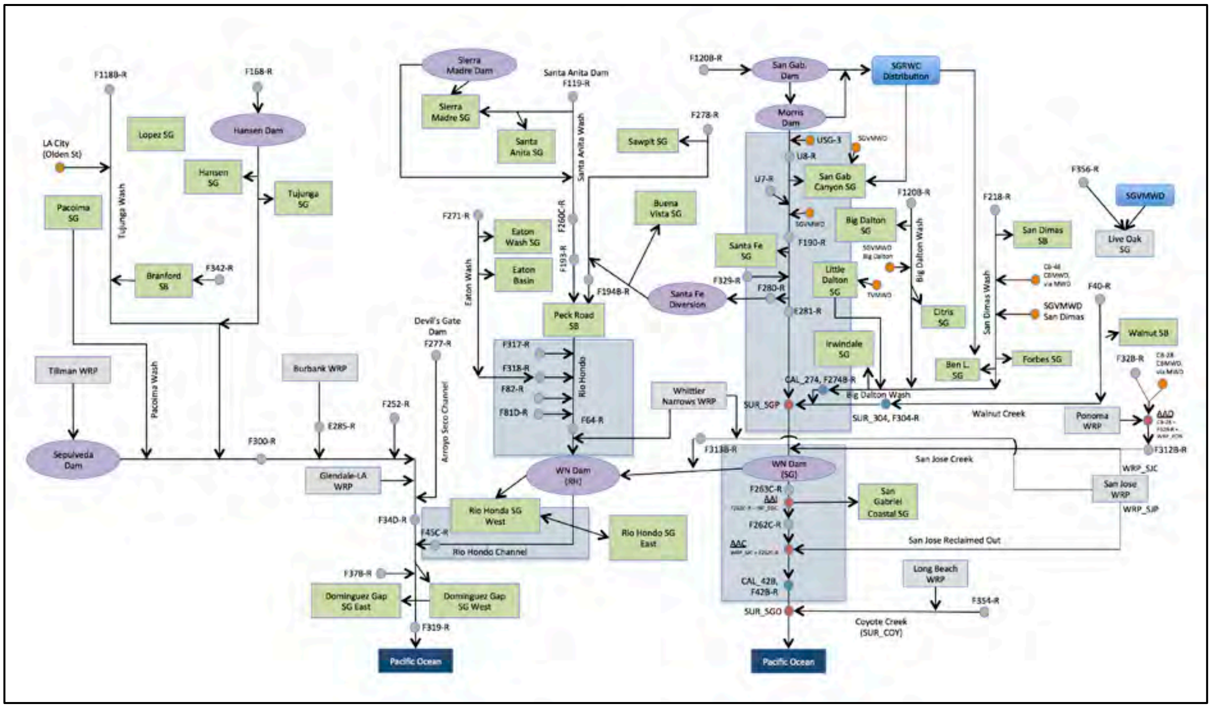


While actual flow data in sewer networks was not collected, the service territories for each of the sanitation districts in the metropolitan area, especially the two largest (L.A. County Sanitation District that runs the Joint Outfall System with numerous plants and the L.A. City Bureau of Sanitation that runs Hyperion Treatment Plant and others) were linked with the sanitary sewer networks for each of the retailers. Other smaller networks, such as in Las Virgenes, Glendale, and Burbank, treat more limited geographic areas and may discharge to main sewer trunks or local water bodes such as the L.A. River.

Wastewater outflows are discharged into the ocean or spill into the extensive network of engineered drainage, flood control dams, and spreading basins managed by the L.A. County Flood Control District and the L.A. County Department of Public Works. Based on diagrams of the L.A. County flood control system, the engineered drainage network of large-scale features (not including detailed sewer pipes) was translated into a link-node network for use in *Artes*

(Figure S3). Runoff and inflows were then tied to the 46 watershed areas in *Artes* based on the geographic locations of upstream runoff areas for each feature in the drainage network.

Figure 4: Engineering schematic of the flood control and sanitation outflow network, adapted from the Los Angeles County Department of Public Works.



Validating the Rainfall-Runoff Model (WMMS)

Hydrologic and hydraulic routing data in WMMS was tested to understand its accuracy in simulating flows. The L.A. County Department of Public Works contracted with *TetraTech* to develop WMMS, based on LSPC and its underlying routing model, Hydrology Programming Software-Fortran. HSPF, which is based on the Stanford Watershed Model, has been tested in a variety of geographic areas and is a widely used watershed model for continuous simulation of rainfall, runoff, and water quality in larger geographic regions, including urban and rural areas (Borah and Bera 2004; Lee et al. 2010). It calculates overland flow using Manning's equation with input parameters for land cover and topography. Hydraulic routing calculations use the kinematic wave equation. It tracks groundwater infiltration in multiple shallow and deep groundwater zones through a non-linear reservoir procedure. It also has robust sediment transport modules for estimating water quality (Bicknell et al. 1996; LACDPW and Tetra Tech 2009). HSPF has been subsequently incorporated into the EPA *SUSTAIN* model for its sediment transport features. In WMMS, LSPC primarily calculates surface runoff and water quality, and though it does keep track of shallow and deep water infiltration, it is not calibrated for these uses and as such, groundwater balances were not calculated in the reported version of *Artes*.

WMMS includes engineering infrastructure with spreading basins and flood control dams, but it does not include sewer system drainage networks. The urban water systems analysis required additional representation of treatment plant outflows, which connects to the drainage network run by the county. As shown in Figure 5, historic monthly flows from stream gauge data for the major watersheds was compared to modeled data that summed: 1) WMMS model outputs for engineered drainage network, and 2) Collected monthly outflow data for treatment plants based on their discharge locations within the system.

WMMS model results were compared using two methods: 1) using only outflows from the L.A. County WMMS model (total upstream accumulated flows for each river); and 2) summing total accumulated flows and wastewater reclamation plant discharges from city and county plants. Adding wastewater treatment plant outflows increases accuracy of model, especially during summer months. Adding treatment plant outflows increased the accuracy of model outputs in many cases, especially during summer months. Table 5 below shows the comparison of actual (gauge) and modeled (with vs. without treatment plant outflows) for the L.A. River and San Gabriel River watersheds.

Figure 5: Comparing modeled vs. actual data for major L.A. County stream systems: 1) L.A. River (upper left); 2) San Gabriel River (Upper Right); 3) Ballona Creek(Bottom). Modeled data (solid line, green) includes the sum of WMMS outflows and treatment plant releases. Stream gauge data (dashed, red) was derived from the network of L.A. County stream gauges.

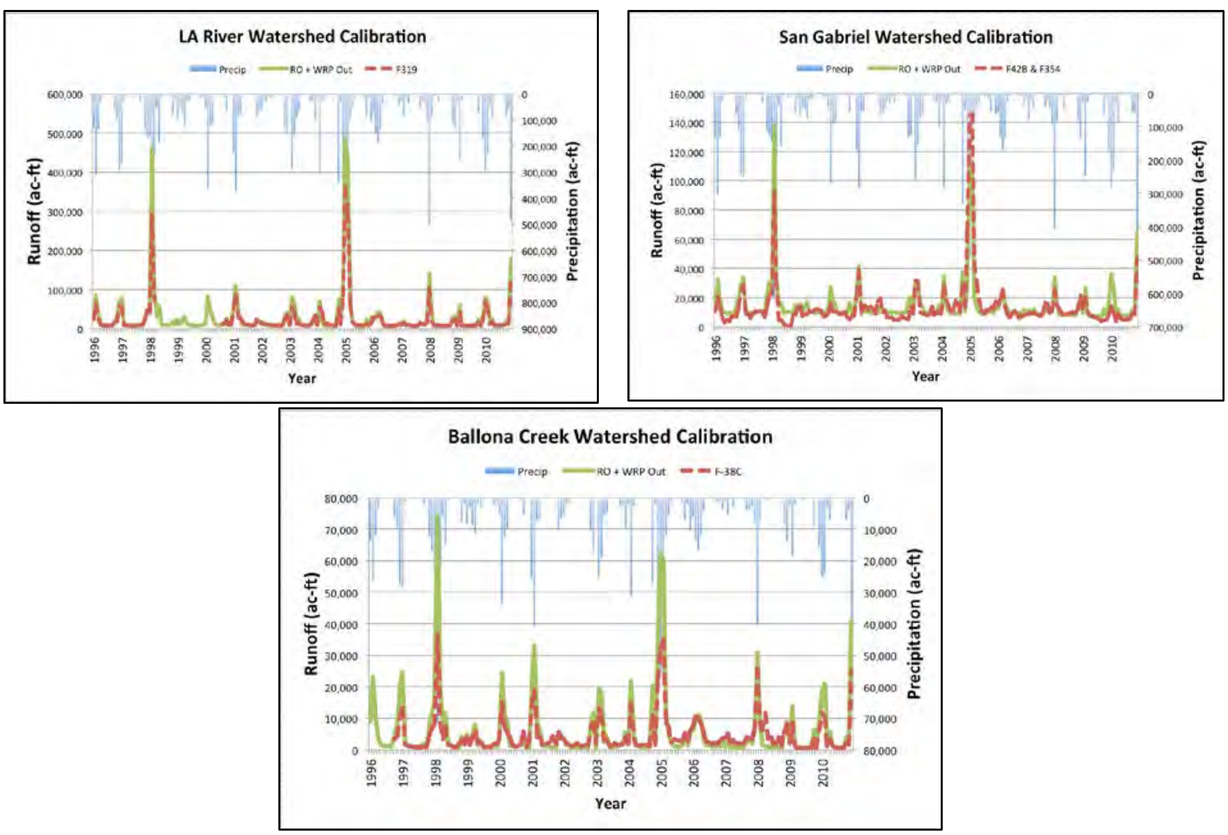


Table 5: Mean and standard deviation of the difference in modeled and actual stream gauge data for outflows to the ocean from the Los Angeles and San Gabriel Rivers.

		L.A. River (model only)	L.A. River (model + WWTP outflows)	S.G. River (model only)	S.G. River (model + WWTP outflows)
Jan	*Mean*	-20%	19%	-48%	20%
	StDev	39%	20%	52%	43%
Feb	*Mean*	12%	37%	-26%	32%
	StDev	42%	36%	52%	47%
Mar	*Mean*	-23%	22%	-65%	21%
	StDev	47%	33%	28%	58%
Apr	*Mean*	-41%	11%	-66%	23%
	StDev	46%	33%	34%	42%
May	*Mean*	-64%	-4%	-86%	26%
	StDev	43%	26%	28%	67%
Jun	*Mean*	-79%	-12%	-93%	19%
	StDev	41%	18%	26%	41%
Jul	*Mean*	-80%	-9%	-93%	21%
	StDev	41%	12%	26%	50%
Aug	*Mean*	-87%	-4%	-93%	3%
	StDev	35%	12%	26%	29%
Sep	*Mean*	-78%	3%	-90%	10%
	StDev	36%	13%	26%	33%
Oct	*Mean*	-43%	22%	-68%	46%
	StDev	48%	26%	45%	74%
Nov	*Mean*	-39%	16%	-60%	42%
	StDev	41%	24%	49%	71%
Dec	*Mean*	-8%	24%	-48%	26%
	StDev	40%	37%	39%	40%

Incorporating Economic Parameters

For the hydroeconomic model, all costs were annualized based on historic inflation (2%) and rate increases (3-7%). Table 1 reports ranges for unit costs associated with supply sources and conveyance in LA County from reports and peer-reviewed sources. The estimates are based on reported prices, not summed costs for production, operations, and maintenance. Specific values and sources are noted in the data and model input spreadsheets located in the Github repository.

Economic effects of residential water shortages were estimated using a linear demand function method with retailer-specific domestic water rates, which is a procedure outlined previously in literature. This yielded estimates of perceived monetary loss to residents from reduced residential deliveries that specifically supply outdoor irrigation (Buck et al. 2016; Jenkins et al. 2003). The unit value of economic losses varied by retailer, with estimates ranging from \$0.41-\$3.46/m^3 (\$500-\$4,270/ac-ft) based on standard methods using available data for median incomes, utility water rates, and published estimates of demand elasticity (Buck et al. 2016; DeShazo et al. 2015). These were also annualized for a 20-year period based on assumed price increases.

Table 1: Current and annualized unit costs of water supply sources in LA County. Sources for each are provided in the *Methods*. (m^3 = cubic meter, ac-ft = acre-foot). Originally published in Porse et al (2018).

Cost of Supply/Shortage Source	Annual Cost Increase Rate	Cost per m^3 (per ac-ft)		Benefits per m^3 (per ac-ft)
		Current	*Annualized*[**]	
MWD Imported Water (Tier 1 treated)	0.06	\$0.76 (\$942)	\$1.20 (\$1,476)	n/a
MWD Imported Water Following "Delta Tunnel" Upgrades (estimated for Tier 1 treated)	0.06	\$0.93 (\$1,142)	\$1.45 (\$1,790)	n/a
Groundwater Pumping	0.07	\$0.28 (\$340)	\$0.47 (\$582)	n/a
Existing Large Stormwater Capture	0.04	\$0.16 (\$200)	\$0.21 (\$256)	\$0.03 (\$40)
Proposed Large Stormwater Capture Upgrades	n/a	n/a	\$0.30-\$1.61 (\$371-\$1,988)	\$0.03 (\$40)
Existing Recycled Water	0.06	\$0.29-\$0.85 (\$355-\$1,050)	\$0.45-\$1.33 (\$556-\$1,646)	n/a
Proposed Recycled Water Upgrades	n/a	n/a	\$0.83-\$1.65 (\$1,023-\$2,043)	n/a
Conveyance and Transfers	0.06	\$0.08 (\$100)	\$0.13 (\$157)	n/a
Cost of Residential Water Shortages	n/a[#]	\$0.41-\$3.46 (\$500-\$4,270)	\$1.05-\$7.64 (\$1,300-\$9,437)	n/a

[+]Benefits values based on existing large stormwater capture basins.
[#] Rate of increase in shortage estimate related to assumptions of water rate increases
[##] Annualized costs were calculated over a 20-year period, except for unit costs extracted from the LA Basin Study for stormwater capture, which calculated unit costs based on a projected 50-year lifetime.

The analysis did not include revenue losses to utilities or expenses incurred by residents in replacing landscapes as part of the objective function, though some portion of the costs to residents could be considered as part of the economic loss calculation.

Calibration Procedures for Optimization

A significant challenge for modeling tools using is achieving realistic outcomes that reflect actual system conditions. Typically, optimization procedures include sufficient constraints. To this end, in addition to the system constraints by the equations in the optimization, flows was constrained to match runoff routing to historic values in WMMS with adjustable boundary tolerances.

Each node in the *Artes* model has losses associated with a particular time step that are at greater than or equal to a pre-determined loss rate, derived from WMMS or through analysis (as described for the urban water agencies) under conditions of feasibility. For urban water supply agency nodes, inputs include water supply from various sources and losses represent system leakage along with outdoor irrigation (soil infiltration and evapotranspiration).

For each of the 46 watershed zones in *Artes*, losses similarly represent evapotranspiration and groundwater infiltration, while inflows come from rainfall and upstream runoff. *Artes* performs a water balance equation but does not run an underlying hydrologic model to simulate rainfall and runoff. Instead, it receives inputs from a model run of WMMS, including inflows and outflows for each of the 46 watersheds.

Table 6: Watershed zones in *Artes*, the corresponding number of sub-watersheds in WMMS, and the sub-watershed for the farthest downstream watershed in WMMS

Artes Watershed Area	*Artes* Watershed Key	# of WMMS Sub-watersheds	WMMS Code for Farthest Downstream Sub-Watershed
Arroyo Seco	SUR_ASE	69	6402
Ballona Creek above gauge	SUR_BAL	77	1007
Ballona Creek below gauge	SUR_BAC	188	1001
Ben Lomond SG	SUR_SDL	7	5459
Big Dalton Dam	SUR_BDU	5	5490
Big Dalton SG	SUR_BDS	1	5489
Big Tujunga Dam	SUR_BTD	37	6791
Branford SG	SUR_BRF	2	6685
Buena Vista SG	SUR_BVS	20	5245
Citris SG	SUR_BDM	16	5471
Coyote Creek Watershed	SUR_COY	94	5002
Dominguez Watershed	SUR_DOM	130	2001
Eaton Basin	SUR_EAB	13	6240
Eaton SG	SUR_EAT	12	6253
Forbes SG	SUR_SDM	3	5466
Hansen SG	SUR_HAN	66	6726
Irwindale SG	SUR_BDL	27	5433
Little Dalton SG	SUR_LIT	3	5487

Live Oak SG	SUR_LOS	2	5408
Lopez Basin	SUR_PCU	6	6714
Lower LA River	SUR_LAL	209	6001
Lower San Gabriel River	SUR_SGL	75	5001
Malibu Coastal	SUR_MAL	178	3001
Malibu Creek	SUR_MAC	56	3002
Morris Dam	SUR_MOR	3	5270
Pacoima Dam	SUR_PCD	6	6720
Pacoima SG	SUR_PCL	25	6689
Peck Road SG	SUR_SAL	33	6301
Puddingstone Dam	SUR_PUD	12	5399
Rio Hondo SG	SUR_RHU	168	5153
San Dimas Dam	SUR_SND	9	5413
San Dimas SG	SUR_SDU	1	5412
San Gabriel Canyon Dam	SUR_SGD	87	5273
San Gabriel Canyon SG	SUR_SGU	7	5263
San Gabriel Coastal SG	SUR_SGC	11	5142
San Gabriel River Reach 3	SUR_SGP	35	5226
San Jose Creek	SUR_SJC	58	5158
Santa Anita Canyon	SUR_SAC	7	6343
Santa Anita SG	SUR_SAU	2	6341
Sawpit SG	SUR_SAW	3	6309
Sierra Madre SG	SUR_SMD	5	6334
Thompson Creek	SUR_THM	11	5157
Upper LA River	SUR_LAU	209	6575
Verdugo Wash	SUR_VER	64	6513
Walnut Creek	SUR_WLL	25	5369
Walnut SG	SUR_WLU	5	5394

As noted, WMMS incorporates LSPC and HSPF to do routing, so it calculates runoff, evapotranspiration, and groundwater infiltration in several shallow and deep groundwater areas for each of its 2,600 sub-watersheds. These WMMS sub-watersheds were aggregated to the 46 watershed zones that represented the upstream contributing runoff zones for key network features, primarily including spreading basins, flood control dams, stream junctions, or key stream gauges. Table S6 lists the major features associated with each of the watersheds in *Artes*, along with the number of WMMS sub-watersheds aggregated into that area and the WMMS code for the farthest downstream sub-watershed.

WMMS tracks the hydrologic and hydraulic inputs and outputs for each sub-watershed, as well as the total runoff from all contributing upstream watersheds for a given time. We developed custom *Python* scripts to calculate the sum of values of WMMS sub-watershed inputs and outputs, including: precipitation, groundwater inflows, active groundwater inflows, infiltration, evapotranspiration, groundwater outflows, surface water outflows, groundwater storage, surface water storage, and total runoff from contributing upstream watersheds. The sub-watersheds were aggregated to the 46 *Artes* zones.

WMMS is best calibrated for simulating surface water runoff and water quality. The multi-reservoir configuration used to track groundwater infiltration and storage is simplistic, but a detailed and available groundwater model does not exist for the entire L.A. County region. Thus, WMMS is not best configured to simulate groundwater movement and storage. Additionally, WMMS derives estimates of evapotranspiration across its historical hydrology based on data from the California Irrigation Management Information System (CIMIS). Multiple CIMIS stations exist in Los Angeles, but their accuracy is degraded in urban areas due to significant differences in surface temperature based on, for example, shade of lawns from trees, as noted previously.

Given these data limitations and the noted desire to minimize assumptions in the optimization, *Artes* lumps together losses from evapotranspiration and infiltration for each time step for each of the 46 watershed zones. Losses from the WMMS hydrologic model were calculated and used to determine a loss rate for each of the 46 sub-watershed zones. The *Artes* model was then run and model results (based on constraining watershed outflows using loss rates) were compared to WMMS outputs. Analysis ultimately determined that the formulation based on loss rates yielded unsatisfactory results, with widely divergent outflows as compared to historical results. Thus, for the 46 watershed zones, a second set of constraints was added that, under conditions of feasibility, calculated losses (L_{jt}) that were greater than or equal to the rate for that time step and additionally within a range as compared to the WMMS value (W_{jt}):

$$0.75 * W_{jt} \leq L_{jt} \leq 1.25 * W_{jt} \quad (10)$$

The range of values accounts for the divergence of flows that may occur under a decision set that better matches the goal than the historical data, but does not allow complete free reign in determining outputs of the optimization.

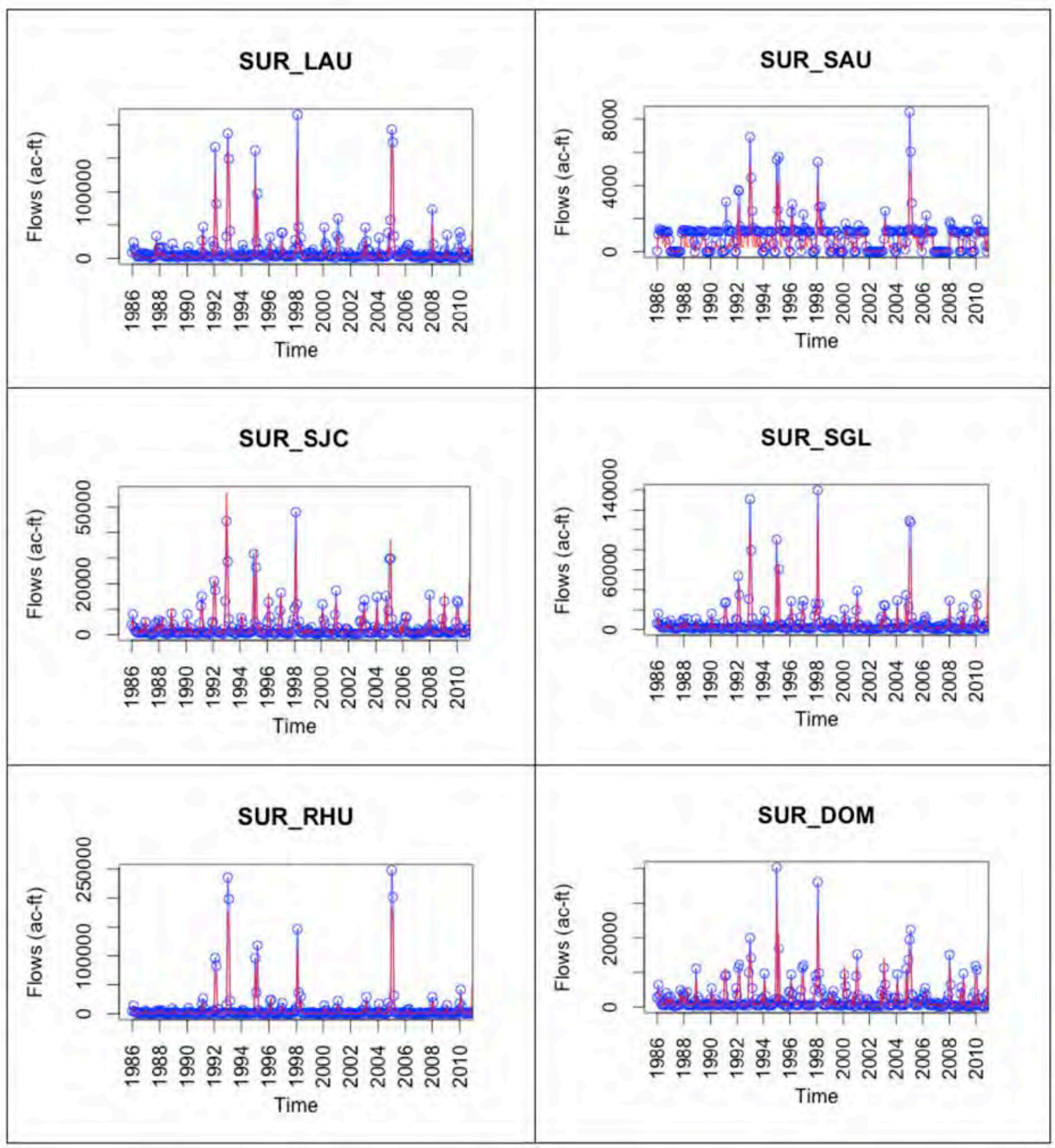
Models for each watershed zone in *Artes* were plotted to compare hydrologic and optimization. For the baseline scenario of 100% demands and supplies, Figure 6 below displays plots for 6 of the 46 watershed zones, including: The Upper Los Angeles River watershed, Santa Anita Spreading Grounds watershed, San Jose Creek watershed, Lower San Gabriel River watershed, the Upper Rio Hondo watershed, and the Dominguez Channel watershed.

Wastewater Treatment Plant Outflows

Historic monthly flow data exists for most wastewater treatment and reclamation plants (Table 7) in L.A. County since approximately 1996. In *Artes*, wastewater were constrained to historic flow data similar to watershed zones, but using a wider range to compensate for the potential of greatly reduced or increased flows from management decisions:

$$0.15 * Q_{WWTP\ Hist_{jt}} \leq Q_{WWTP\ Opt_{jt}} \leq 1.5 * Q_{WWTP\ Hist_{jt}} \quad (11)$$

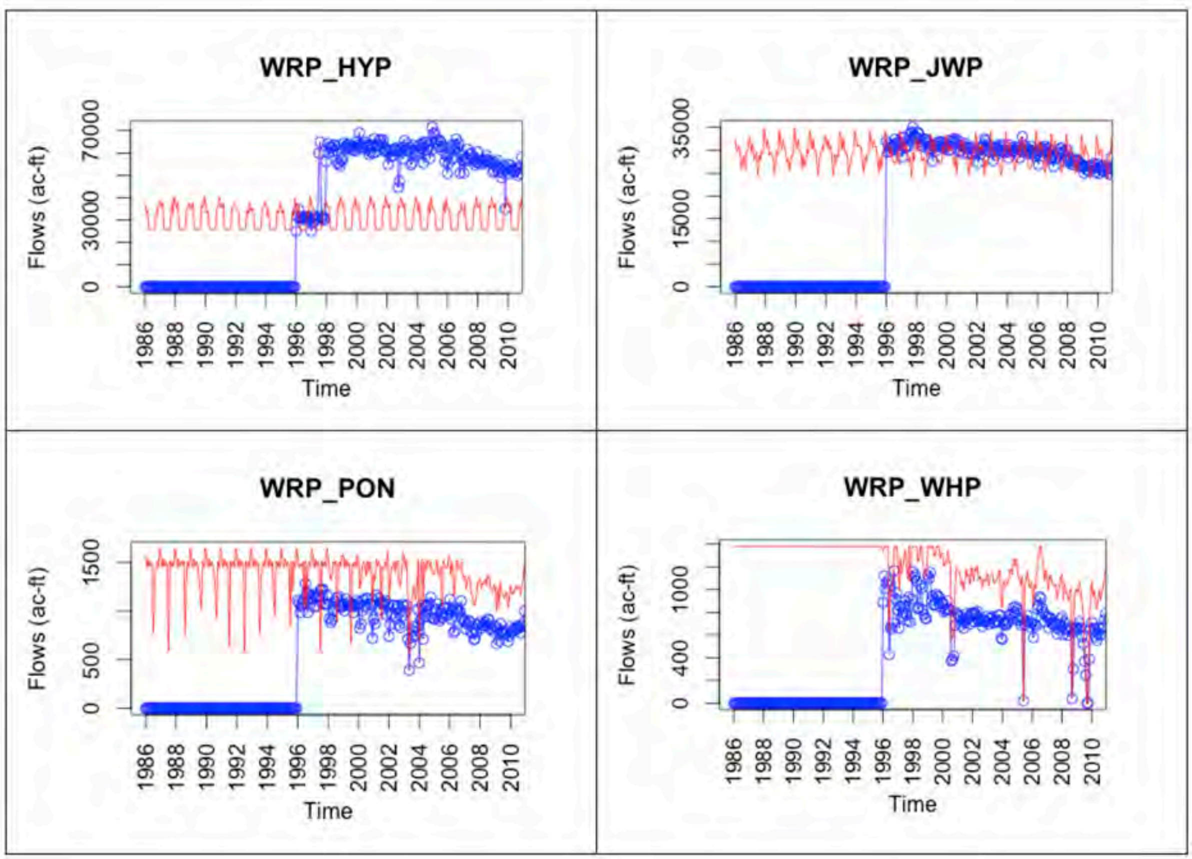
Figure 6: Calibrating surface runoff values for *Artes* and WMMS for selected watersheds in the base case (100% supplies and demands). Plots correspond with watersheds in Table 6.



WWTP and WRP outflows could not be constrained during the period of 1986-1996 due to a predominant lack of data. Thus, if desired model runs in *Artes* sought to achieve a completely constrained system to mirror historic flows, the model would run over a 15-year time 1996-2010.

Plots were generated for each of the facilities to compare modeled and historic data for calibration and understanding system function under optimized scenarios (Figure 7).

Figure 7: Comparing historic and modeled wastewater treatment and water reclamation plant discharges in the baseline model run. Titles correspond with facilities listed in Table 7. Modeled data are unmarked lines (red) while historic data lines are marked with circles (blue).



Of the two primary wastewater treatment plants, Hyperion (Figure 7-top left), primarily discharges less water compared to historic levels in the baseline scenario (100% supplies and demands), which JWPCP is approximately equal. An additional downstream water reclamation plant, Terminal Island, also sees much less influent flow. This relates to the goal of recycling water in the upstream reclamation plants for groundwater recharge in spreading basins and indirect potable reuses. The period of constrained (1996-2010) and unconstrained due to lack of data (1986-1996) are shown.

Table 7: Wastewater treatment and water reclamation facilities represented in *Artes*

Wastewater Treatment / Water Reclamation Plant	*Artes* Key
Burbank WRP	WRP_BUR
Glendale WRP	WRP_GDL
Hyperion WTP	WRP_HYP
Joint Water Pollution Control WTP (JWPCP)	WRP_JWP
La Canada WRP	WRP_LAC
Long Beach WRP	WRP_LBP
Los Coyotes WRP	WRP_LCP
Ed Little WRP	WRP_LIT
Malibu Mesa WRP	WRP_MMS
Ponoma WRP	WRP_PON
San Jose Creek WRP	WRP_SJC
Santa Monica Water Reclamation Facility (SMURF)	WRP_SMR
Tapia WRP	WRP_TAP
Terminal Island WRP	WRP_TER

Variables Included in Artes

Table 8 below lists model variables, with key decision variables indicated in bold type.

Table 8: Variables in *Artes*

Variable	Definition	Unit
$\boldsymbol{Q_{ijk}}$	Water flows between node *i* and *j* over link *k*	Acre-feet
$\boldsymbol{Q_a}$	Sum of water flows between when the source node *i* is a source of local water supply.	Acre-feet
S	Total shortages	Acre-feet
D_j	Water demands at node *j*	Acre-feet
I_j	Inflows from external sources to node j	Acre-feet
R_j	Storage capacity of node *j*	Acre-feet
L_j	Losses for node *j*	Acre-feet
C_{ijk}	Capacity of link between nodes *i* and *j*	Acre-feet

Software

Artes uses custom-developed software set that includes an optimization engine and open-source code for managing inputs, outputs, and model parameters. Custom-developed software using *Python* manage inputs from spreadsheets, writes output to text files for post-processing, and constructs the model objective function and constraints (JetBrains 2015; Python Software Foundation 2001). Optimization using linear programming is performed by the *Gurobi* optimization engine (Gurobi Optimization, Inc. 2015). Model constraints for each time step are written in *Python* and the entire model is sent to *Gurobi* based on the *Python* interface integrated into the optimization engine. The *Gurobi* software requires a license to run on a local machine.

Additional scripts from *Python* and *R* included in the Github repository (below) were used to aggregate watershed zones, perform pre-processing of data, or analyze some results. Post processing from output text files was primarily performed using spreadsheet software, but can be custom developed for visualization, analysis, aggregation, or linked to additional models.

Using the Model

The model is lightweight and can be run on a local machine. The model is not fancy and does not yet have a Graphical User Interface (GUI), so an adventurous spirit or some prior coding experience are helpful. Or you can just email Erik Porse at UCLA with questions.

Software

Source code and data is available in a *Github* repository for download:

https://github.com/erikporse/artes

The model uses several packages in *Python*, some of which may not be stable if using a version of *Python* newer than 2.7.6. Installed *Python* packages that are called by the software include:

xlrd, xlwt, xlutils.copy (not currently used)
tablib (only used for outputting shadow values)
sys, os
math, numpy
matplotlib.pyplot, matplotlib.dates
gurobipy

The last package in particular, is critical for allowing the *Python* software to interpret the *Gurobi* interface. If using another solver, another installation package would similarly handle interface in processing software and the optimization.

Data Inputs and Formats

Inputs are stored in a spreadsheet database with multiple tabs. The location of the spreadsheet on the local machine should be changed manually in the *Python* software. The database includes multiple tabs (tables) with information for each node and associated attributes. Attributes associated with nodes or links are listed in Table 9 below.

Table 9: Attributes for nodes and links

Node Attributes	**Link Attributes**
Node Code	Origin Node
Node Name	Terminal Node
Annual Demands	Capacity
Monthly Demands	Cost
Upper Storage Bounds	Energy Intensity, broken down as treatment, conveyance, distribution, and acquisition
Lower Storage Bounds	
Inflows for each time step	
Demands (by month)	
Loss Rates (by month)	
Some nodes have monthly capacities for inflows, outflows, change in storage, or reuse	

Nodes have attributes that relate to either monthly or annual totals. Annual allocation volumes, such as nodes with groundwater pumping, are represented as annual maximum capacities, while monthly capacities are associated with flows such as wastewater treatment plant influent and stormwater capture basin inflows. As a monthly model, upper limits for flow capacities to such facilities are estimates that would be more accurate if using a time step with higher resolution.

The database includes multiple tables (sheets) as shown in Table 10.

Table 10: Tables in *Artes* Database. Tables are individual sheets for database versions in Excel.

Table (Sheet) Name	**Description**
Nodes	List of nodes and associated attributes
Demands	Demands by month for nodes
Losses	Loss rates by month for nodes
Links	List of links with origin node, terminal node, flow capacity, cost, and energy intensity
GW Pool Links In	Table of links (origin and terminal nodes) for inflows to groundwater exchange pools, in runs using this formulation
GW Pool Links Out	Table of links (origin and terminal nodes) for outflows from groundwater exchange pools, in runs using this formulation
Storage Pumpers	Groundwater pumpers with storage rights, for model runs with exchange pools
Monthly Capacities	Monthly flow capacities for nodes with monthly capacity limitations, including spreading grounds and wastewater treatment and reuse plants. Reuse

	plants have separate flow capacities for dry and wet months.
Storage Nodes	Nodes with storage capacity and maximum change per time step for those nodes
Groundwater	Groundwater nodes and annual safe yield, which is the total of annual pumping for all pumpers in a basin
Demand Nodes	List of demand nodes with seasonal loss rates
Month Nodes	List of nodes with monthly constraints, used for post-processing
Calibration Nodes OLD	Old sheet with calibration nodes that include both surface water zones and wastewater treatment plants
Calibration Nodes	Sheet with data being used for monthly calibration that includes only wastewater treatment plants. Surface water calibration is handled in the *Surface* sheet below for each time step
Local Sources	List of nodes that are local sources, used in optimization
Recycled	List of recycled water nodes and monthly reuse production capacity
Purple	List of purple pipe water recipients, used for aggregating results
Spreading	List of spreading grounds, used for aggregating results
Surface	Monthly WMMS outputs for each sub-watershed zone in *Artes*, for each month and year, used to constrain flows in optimized results.
Years	Editable list of years for running optimization. If changing, inputs must be manually changed in the *Nodes* sheet if wanting initial conditions for storage.
Calib Years	Editable list of years for calibration
Months	List of months for use in model. Runs in calendar year (not water year).

The three main sources of imported water- the Colorado River Aqueduct, the State Water Project through the Sacramento-San Joaquin Delta, and the Los Angeles Valley to the Owens Valley- have associated monthly historic values of monthly inflows. These values, found in the Nodes sheet (rows 84, 105, and 257) can be changed to test assumptions of imported water losses. In analysis from the initial study, these were changed based on percentage decreases in 10% increments from historic values (Pincetl et al. 2019).

Additional water enters the region as rainfall, driven by the WMMS hydrologic model outputs that were aggregated to the *Artes* watershed zones.

Running the Model

Running the model is straightforward. Once the location of the database is specified in the Python code and packages are installed, execute the script.

If using a GUI interface for Python, such as PyCharm, this can be done as a right-click on the code tab or a hotkey. This would change depending on favorite method for running Python scripts.

Two current formulations are available for the model. First, a global optimization procedure, sometimes called *perfect foresight*, allows for optimizing flows across the entire model period (maximum 25 years). This has the effect of hedging to the extent that solutions are improved by increasing shortages in one year in favor of more water in later years. The global optimization procedure can take anywhere from 10 minutes to 2 hours to run, depending on speed of machine, formulation, time frame of simulation, and other factors that affect the number of decision variables. As noted in Porse et al (Under Review), the model does not yield feasible solutions. *Gurobi* iterates through procedures to identify feasible primal or dual problem solutions. This could be address by assuming water additions to account for data gaps or infeasible capacities on surface flows. Current commercial solvers incorporate tools to iterate through solutions or allow for particular infeasible constraints to appear while still producing optimized (but potentially not optimal) results. If the network were fixed to address the infeasibility issues, the linear program would be quite fast.

Second, a formulation with annual (12-month) optimization was developed to test the effects of limited foresight and hedging. This formulation completes a model run in 3-6 minutes, depending on the number of years included in the optimization. The difference is primarily due to limiting the number of decision variables in a given problem set, but running that over multiple iterations (years).

Output
Once completed, the model writes output to text files that are saved in the desired location, which can be changed in the Python code. Output files are listed in Table 11. For most files, an output value is written for each node and each time step (year and month). Two output files specifically summarize values (supplies_annual and supplies_monthly) that are useful in analysis.

Table 11: Output files from *Artes*.

Output Text Files	Description
curr_storage	Storage of current time step. Outputs for all nodes but only groundwater basins, reservoirs, and spreading grounds have storage capacity
prev_storage	Storage of previous time step.
demands	Demands for each node. Copied from input file
exports	Outflows from a node (decision variable)
gw_storage_pool	Output of groundwater storage pool flows, if included in model run

inflows	Inflows for each node. Copied from input file.
losses	Volumetric losses for each node and time step, based on loss rates.
shortages	Volume of shortages in each time step.
summary_annual	Summary of annual operations, for each year. Includes summary columns for: supplies of imported, recycled, surface, and groundwater; stormwater capture; groundwater recharge; imported water for recharge; recycled water from Hyperion (to Ed C. Little); ocean inflows; shortages; barrier injection wells; and State Water Project flows to LA City
summary_monthly	Summary of monthly operations for each year, with many of the same parameters
supplies	Flows in to a node (decision variable). Different than the inflows sheet. This represents supplies to a node for meeting demands.
supplies	Flows in to a node (decision variable). Different than the inflows sheet. This represents supplies to a node for meeting demands.
supplies_gw_ann supplies_gw_month	Flows to a node (decision variable) only from groundwater for either monthly or annual values. The output file was added in 2018 for improved post-processing and GIS analysis
supplies_imports_ann supplies_ imports _month	Flows to a node (decision variable) only from imported sources for either monthly or annual values. The output file was added in 2018 for improved post-processing and GIS analysis
supplies_recycled_ann supplies_recycled _month	Flows to a node (decision variable) only from recycled water sources for either monthly or annual values. The output file was added in 2018 for improved post-processing and GIS analysis
supplies_surface_ann supplies_surface_month	Flows to a node (decision variable) only from surface water sources for either monthly or annual values. The output file was added in 2018 for improved post-processing and GIS analysis
energy_conveyance energy_gw_source energy_import_source energy_ww_treatment energy_intensity energy_total	For each node, these values estimate the total energy use required to get water to that node, or the energy intensity of total water supply to that node. These output files were developed in 2018. to improve post-processing and GIS analysis.

An additional Excel spreadsheet output is available that can write parameters for links included in the Irreducible Infeasible Set used to address infeasibility, or shadow values for each link that represent the marginal unit value of an additional unit of water over that connection.

Post-processing was primarily completed in Excel, but could get as fancy as one likes based on the output text files.

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