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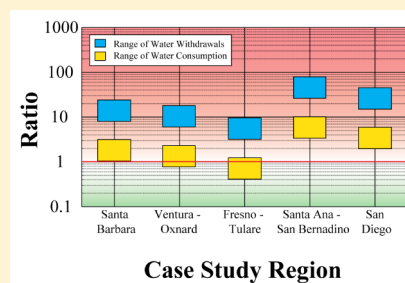
Investigating the Energy-Water Usage Efficiency of the Reuse of Treated Municipal Wastewater for Artificial Groundwater Recharge

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Supporting Information

ABSTRACT: This project investigates the energy-water usage efficiency of large scale civil infrastructure projects involving the artificial recharge of subsurface groundwater aquifers via the reuse of treated municipal wastewater. A modeling framework is introduced which explores the various ways in which spatially heterogeneous variables such as topography, landuse, and subsurface infiltration capacity combine to determine the physical layout of proposed reuse system components and their associated process energy-water demands. This framework is applied to the planning and evaluation of the energy-water usage efficiency of hypothetical reuse systems in five case study regions within the State of California. Findings from these case study analyses suggest that, in certain geographic contexts, the water requirements attributable to the process energy consumption of a reuse system can exceed the volume of water that it is able to recover by as much as an order of magnitude.



INTRODUCTION

In recent years, the experience of persistent severe drought conditions in the Western United States has motivated regional water resource management authorities to seriously pursue a number of alternative sources of freshwater supply.^{1–5} Prominent among these alternative sources is reclaimed or recycled water; synonyms, which refer to the water that can be obtained from a municipal sewage waste stream through the successive application of advanced tertiary treatment processes.^{6,7}

Historically, the majority of projects involving the reuse of treated municipal wastewater have been limited to relatively low quality end use applications such as the irrigation of urban landscape features (e.g., golf courses, cemeteries, etc.) or agricultural crops that are not destined for human consumption (e.g., turf, animal feedstocks, cover crops, etc.).^{8–10} This limitation has not been so much the consequence of any technical inability of wastewater treatment processes to supply highly purified, even potable water, but rather due to the high economic cost or strong social objections to the implementation of projects oriented toward higher quality end uses.^{11–18} Indeed, it is only in the past two decades that the reuse of treated wastewater for relatively higher quality end use applications has become both more socially acceptable and economically viable.^{19–22}

One of the fastest growing of these high quality end use applications for the reuse of treated municipal wastewater is the artificial recharge of subsurface groundwater aquifers.^{23–25} This process involves taking the reclaimed water from its point of production—the wastewater treatment plant (WWTP)—and physically transporting it to another location where it can be returned to the subsurface either through a pump driven direct

injection well or, more commonly, through surface infiltration basins.²⁶ The surface infiltration basins are essentially just small to medium sized (~1–10 ha) engineered ponds whose beds have been lined with highly permeable materials that are meant to facilitate the vertical movement of water downward, under the force of gravity, into the underlying aquifer.²⁷

The use of reclaimed water for the artificial recharge of subsurface aquifers is meant to provide at least two categories of benefits. The first category relates to the various ways in which the activity might improve the health of the aquifer being recharged. These benefits range from the mitigation of overdraft conditions to the prevention of salt-water intrusion in coastal areas.^{28–30} The second category of benefits relates to the choice of reclaimed water as the feedstock for the recharge activity. The main perceived benefit of this choice stems from the commonly held belief that this type of reuse activity provides a net savings of the water that is being constantly produced as treated effluent by wastewater treatment plants; water that would otherwise be “lost” to the environment.^{28–30} It should be noted that this belief implicitly discounts the value of any potential ecosystem services that such effluent discharges might provide.³¹

However, the assertion that the use of treated municipal wastewater for aquifer recharge actually amounts to a net water savings is one which has not yet been rigorously proven by an analysis of the net consumptive water use for an existing reuse system.^{32–35} Furthermore, we hypothesize that the validity of

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this assertion is likely to depend heavily upon the local geographic context of the hydrologic basin in which a reuse project is to be implemented. This hypothesis is rooted in an awareness of the dynamic interrelationship of our energy and water systems, sometimes referred to as the Energy–Water Nexus.^{36–39}

Each different geographic region is characterized by a different portfolio of energy generation technologies that is responsible for the production of the electricity being locally consumed.^{40,41} This portfolio is typically referred to as the local grid mix. It has been observed by others that, depending upon the composition of generation technologies comprising this grid mix, the consumption of electricity within a region can be associated with non trivial withdrawals and or consumption of freshwater due to such processes as the cooling of thermo-electric coal and natural gas fired power plants or the evaporative losses from reservoirs associated with the operation of hydroelectric dams.^{42–44}

We observe that the quantity of process energy consumed by the reuse of treated wastewater for artificial recharge applications is likely to strongly depend upon local geographic context, with characteristics such as the length and the elevation profile of the pipeline corridor connecting the WWTP to the recharge site being intrinsically linked to regional topography, existing landuse, etc.^{45,46} In light of this observation, we further hypothesize the possibility that, in certain settings, the reuse of treated municipal wastewater as a source of new alternative water supply might be associated with process water consumption demands that are in excess of the quantity of water being locally recovered within a given span of time.

If such a situation were found to exist it would mean that these types of reuse activities do not actually save water, in a net sense, but rather amount to little more than a mechanism for the regional importation of virtual water: one wherein water is transported, virtually, in the form of electricity, from the hydrologic basin housing the electricity production facilities to the hydrologic basin housing the water reuse facility.⁴⁷ It is important to recognize that such a situation, in and of itself, would not necessarily nullify the perceived environmental benefits of these types of water reuse projects. Rather, it would only suggest that these assumed benefits be more critically evaluated and in a manner which takes into consideration the spatial relationship between the water scarcity of the watershed in which the reuse project is being implemented relative to the water scarcity within the watershed in which the corresponding energy is being produced.

■ MATERIALS AND METHODS

In order to develop a better quantitative understanding of the expected net energy-water usage efficiency of proposed new water reuse projects involving significant artificial groundwater recharge components we developed a three part numerical modeling framework that consists of both planning and assessment components. The overarching goal of this modeling effort was to provide a generic platform from which the following three challenges could be addressed for any proposed geographic context.

1. Given a discrete bounded geographic domain, rank the aggregate suitability of each site within that domain for the purpose of constructing a surface spreading basin.
2. Given a discrete bounded geographic domain, propose a connected corridor of sites within that domain that

minimally traverses the space between the site of an existing WWTP and a proposed surface spreading basin relative to one or more continuously defined measures of cost/distance.

3. Given a valid corridor specification, evaluate the water withdrawals/consumption required to generate the quantity of electricity that is consumed for the purpose of moving a fixed volume of water between the two end points of the corridor at a rate specified by the permitted maximum flow capacity of the existing WWTP.

Locating Suitable Sites for Artificial Groundwater Recharge Basins. Our approach to *Challenge-1* is based upon a well established cartographic modeling technique known as weighted overlay analysis (WOA).^{48–51} In a WOA, multiple separate raster layers, each corresponding to multiple independent components of aggregate site suitability for a given landuse application, are separately derived from raw spatial data inputs.⁵² In each of these layers, every raster grid cell is encoded with an ordinal ranking corresponding to its component suitability for the landuse activity in question with no weighting applied.⁵² Once these various layers have been appropriately defined, they are then combined, on a cell for cell basis, to generate a uniform representation of aggregate site suitability.⁵²

The implementation of any WOA begins by first defining a discrete area to function as the spatial unit for the analysis. For the purposes of this investigation, this spatial unit was defined as the United States Geologic Survey (USGS) hydrologic unit code system's (HUC) level-8 sub-basin area containing the source WWTP of interest.⁵³ Within California, on average, each of these level-8 sub-basins comprises a closed contiguous area of roughly 1,800 km².⁵³ For our investigation, these spatial units were discretized into raster grids with a cell resolution of 100 by 100 m. This resolution was carried out throughout all of the other spatial modeling activities that will be subsequently discussed.

As mentioned previously, the WOA approach involves parsing the complex concept of aggregate site suitability into its individual component parts such that is possible to define relative suitability rankings from available spatial data layers. In our WOA implementation, we decomposed the composite suitability for the construction of a surface spreading basin into the following three suitability components: a slope based ranking, an expected hydraulic conductivity based ranking, and an existing landuse based ranking.^{46,54–57}

The raw input geospatial source data that was used to develop the slope based site suitability ranking was the 30 m National Elevation Data set (NED) hosted by the USGS through the National Map Server.⁵⁸ From this raw digital elevation model an output slope layer was computed using a standard eight-neighbor kernel technique. This intermediate slope layer, consisting of percentage slopes ranging from 0 to 100%, was then processed into a layer of ordinal numerical rankings, ranging from 0 to 10, using a histogram equalization procedure. Through this procedure the counts of actual slope percentages in the input layer were transformed such that the frequency of 1's, 2's, 3's, etc. in the output layer conformed to a normal distribution. This procedure has the net effect of producing a nonlinear transformation of slope percentages to slope rankings; penalizing the ranking of steeper slopes more greatly than shallow ones.

The raw input geospatial source data used to develop the hydraulic conductivity based ranking was the STATSGO2/SURGO surface soil characteristics data set hosted by the USDA through the National Geospatial Data Gateway. The raw STATSGO2/SURGO data set exists as a set of vector geometries linked to an underlying database of attribute fields documenting key physical characteristics of various different soil types. The specific attribute used to derive the hydraulic conductivity ranking used in our WOA approach was the hydraulic group categorization. This categorization scheme divides soils into seven groups on the basis of their infiltration rate and overall drainage characteristics. First this input vector layer is converted to a raster output of desired resolution. Then the rasterized version is transformed into the same ordinal ranking scheme, ranging from 0 to 10 as that used for the other suitability criteria using a transformation scheme which preferentially ranks soils with higher degrees of hydraulic conductivity as being more suitable. For more details on both the hydraulic group categorization scheme as well as the exact transformations used please consult the [Supporting Information \(SI\)](#).

The raw input geospatial source data used to develop the landuse base ranking was the National Landuse Landcover Data set hosted by the USGS through the National Map Server. The NLCD encodes each pixel using one of 20 predefined landuse–landcover classifications. First the NLCD raster was clipped and resampled to the desired output spatial resolution, only this time, using a nearest neighbor sampling technique to preserve the integrity of the classification scheme. Next the raster classification scheme used to encode the data was converted into the same ordinal, 1–10 ranking scheme used elsewhere in the analysis using a transformation scheme which designated more highly developed landscapes and those which would present an intrinsic engineering challenge to the implementation of an infiltration basin as being fundamentally less suitable than undeveloped open land. Here again, for more details on the exact transformations used please consult the [SI](#).

It is conceivable that there might be other additional dimensions of suitability that might be relevant to the evaluation of aggregate site suitability for this particular landuse. And indeed, various other data sources, in various different combinations, have been proposed in previous studies with similar goals.^{49–51,59,60} However, it was only by limiting the scope of the required spatial data inputs to these three components that we were able to collect and process raw data inputs covering the breadth desired geographic domain (the entire state of California) at the desired spatial resolution (100 × 100 m).

The additive combination of these three component measures of overall site suitability results in the output of a single aggregate suitability layer. In order to select a single site as the choice of the surface spreading basin from within this layer, the following additional processing steps are taken. First the aggregate suitability ranking layer is converted to a binary format by applying a minimum aggregate suitability ranking threshold. Once this thresholded layer is produced, the closed connected regions of contiguously high aggregate site suitability are ranked relative to one another on the basis of their size, with larger areas being considered most favorable since they can store more water. Finally, the single largest area within this set is chosen and its corresponding centroid cell computed as the final destination site for the location of the surface spreading basin. The size of the final selected suitable regions used in the

five case studies were: Santa Barbara: 0.75 km², Oxnard: 3.63 km², Fresno and Tulare: 19.07 km², Santa Ana and San Bernadino: 15.90 km², San Diego 3.95 km².

Figure 1 provides a graphical illustration of our WOA analysis based site suitability modeling framework for a sample

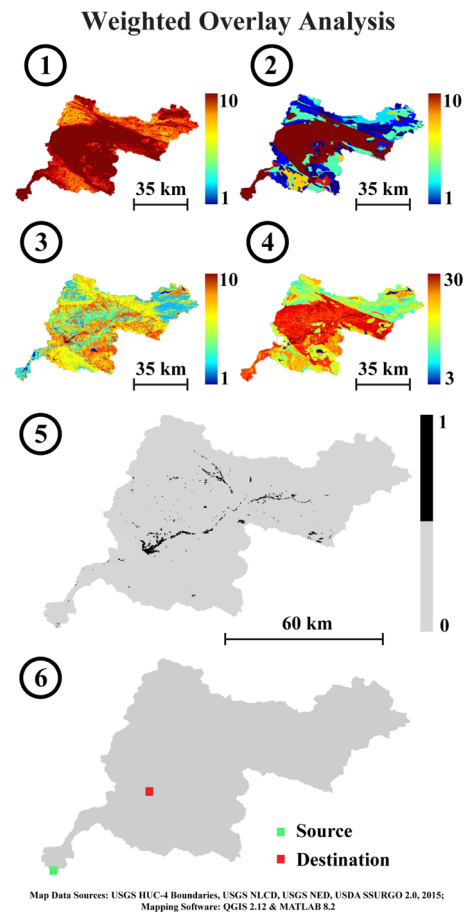


Figure 1. Graphical illustration of the weighted overlay analysis based site suitability modeling framework implemented for a case study region encompassing the Southern California cities of San Bernadino and Santa Ana. Figure elements include: slope score (1), hydraulic conductivity score (2), existing landuse score (3), composite suitability score (4), binary mask (5), reference source with selected destination (6).

case study region encompassing the Southern Californian cities of San Bernadino and Santa Ana. Figure 1 elements ① - ② - ③ depict the ordinal rankings for the slope, permeability, and existing landuse suitability components, respectively. Element ④ depicts the intermediate output aggregate suitability layer. Element ⑤ depicts the binary encoded layer mask depicting connected areas of high aggregate suitability. And finally, element ⑥ shows the final selected destination site for the surface spreading basin, relative to that of the source WWTP (magnified for visual clarity). The sources of the raw data inputs used for the WOA site suitability model are provided in the [SI](#).

Locating Optimal Corridors for Water Distribution Infrastructure. Once a single site has been proposed as the location for the destination surface spreading basin, the process of addressing *Challenge-2*, involving the search for an optimal corridor for the water distribution pipeline that will connect it to the site of the source WWTP, can begin. The naive solution

to this problem would be to simply select the raster grid cells which fall along the Euclidean shortest path linking the source and the destination. Such an approach, however, would ignore the possibility there might be many different types of cost/distance relationships associated with the location of a pipeline corridor within the spatial domain and the likelihood that these costs each be continuously nonuniformly distributed within the domain.^{56,61,62}

The canonical name for this problem is the multiobjective corridor location (MOCL) problem.⁶³ It exists as a subset of the generic category of graph theoretical shortest path (SP) problems and has been shown to be NP-hard in its construction; meaning that there are no known deterministic algorithms capable of generating optimal solutions in a runtime that is some polynomial function of problem size.⁶⁴ As such, the development of effective heuristic approaches to its solution is an important and practically useful topic of research within the areas of combinatoric optimization and operations research.

The combination of the broad extent and the high resolution of the raster grids being used for this analysis translated into the proposition of MOCL problem statements whose search domains comprised on the order of $n = 10^6$ – 10^7 nodes. As it turns out, the number of unique self-avoiding corridors which must be evaluated to deterministically solve the MOCL is thought to scale as 2.638^n .⁶⁵ Clearly then, in the context of such vast problem specifications, the use of conventional deterministic approaches would be computationally infeasible.

In order to broach this issue, a novel parallel implementation of an existing genetic algorithm for the MOCL problem was developed which enabled us to leverage modern multicore processing hardware to generate near optimal solutions with a reasonable amount of time/effort.⁶³ This algorithm was deployed in the cloud using the Google Compute Engine platform to allow for simultaneous and continuous solution runs. An in depth discussion of the mechanics of this algorithm as well as benchmark analysis of its runtime performance and output solution quality can be found in the SI. The Go programming language source code for this new implementation of Zhang et al.'s algorithm has been made freely available by the authors at the following host repository: <https://github.com/ericdfournier/corridor>.

Each MOCL problem specification requires three different cost surfaces: a slope based cost, an existing landuse disturbance based cost, and an accessibility based cost. Each surface was generated using an ordinal scale with values ranging from 1 to 10. The slope cost surface imposes higher cost values on areas with steeper slopes. This incentivizes the minimal accumulation of slope along the corridor's length, to minimize the energy required to deliver reclaimed water up gradient. The existing landuse disturbance cost layer imposes higher cost values on areas with sensitive or intensive existing land uses. This incentivizes the avoidance of areas that might be significantly negatively impacted by the introduction of a major new water distribution pipeline. Finally, the accessibility cost imposes higher costs on areas that are located away from access roads and throughways. This incentivizes the routing of corridors along roads and highways that would make the construction and maintenance of a pipeline easier and more cost-effective for its managing agency.

The slope based cost surface was derived from the same NED source data set used to generate the slope based site suitability score used in the WOA model. Similarly, the landuse disturbance based cost surface was derived from the same

NLCD data set used to produce the existing landuse disturbance score used for the WOA model; albeit using a modified transformation scheme. The accessibility based cost surface was derived from the U.S. Census Bureau's TIGER road network data set using the follow cost transformation scheme: major roads = 10, streets = 5, and off-road = 1.

Interestingly, the accessibility and disturbance objectives were observed to be fairly strongly inversely spatially correlated with one another within the case study regions investigated. The computed correlation coefficients (ρ) between the two layers for each case study site were: Fresno and Tulare: -0.39 , Oxnard: -0.35 , Santa Barbara: -0.41 , Santa Ana and San Bernadino: -0.47 , San Diego: -0.52 (p -values = 0.0000). This feature challenges the corridor selection algorithm to make explicit trade-offs between the two during its search for the best possible corridor.

Figure 2 provides a graphical illustration of the data inputs and a set of output corridor solutions generated by the genetic

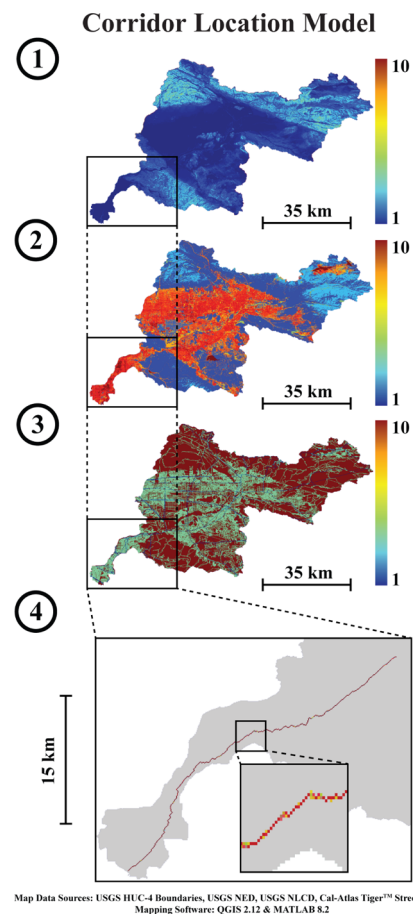


Figure 2. Graphical illustration of a multiobjective corridor location problem specification with input cost surfaces and output corridor solutions for the case study region comprising the cities of San Bernadino and Santa Ana. Figure elements include Slope cost (1), disturbance cost (2), accessibility cost (3), solution corridors (4).

algorithm used in the MOCL problem specification for the same sample case study region comprising the cities of Santa Ana and San Bernadino. Figure 2 elements ① - ② - ③ depict the three input cost surfaces for slope, existing landuse disturbance, and accessibility objectives, respectively. Element ④ depicts a set of corridor solutions generated as output for a single run of the genetic algorithm. These corridor solutions link the end

point WWTP source to the surface spreading basin destination referenced previously in Figure 1.

Estimating Reuse System Pump Energy Requirements. After a valid corridor has been generated linking the site of the existing WWTP to that of the proposed site for the surface spreading basin, the process of addressing *Challenge-3*, involving the evaluation of the proposed system's net energy-water usage efficiency, can finally proceed. One of the primary benefits associated with investing all of the effort required to generate near optimal corridors is that the resulting detailed route information can then be used to derive estimates for the system's pump energy requirements using the well established civil engineering computational techniques.⁶⁶

These techniques begin with assumptions about the basic characteristics regarding the pipeline's physical structure such as pipe section length, cross sectional area, materials, etc. For the purposes of this analysis the pipelines were modeled as being constructed of standard concrete pipe sections with a cross sectional area that was sufficiently large so as to ensure that the maximum flow speed through the pipeline did not exceed a maximum velocity of 7 m/s. The number and location of fitting elements modeled as part of each pipeline system were derived from each case study's detailed pipeline corridor specification. All other relevant assumptions as well as a detailed overview of the computation procedure itself are provided in the SI.

Estimating Reuse System Process Energy Related Water Demands. The corresponding water required to generate the energy needed to pump the water (P) can be estimated by referencing the technology composition of the local grid mix to literature values for the water intensity of various electricity generation technologies. For the purposes of this analysis, the composition of the local average grid mix in each case study region was taken from values published in the UC Berkeley Water for Energy Sustainability Tool (WWEST) web based life cycle inventory modeling tool.^{45,67–70} Based upon the relative geographic location of the case study sites, three different grid mix values, corresponding to three separate utility providers operating within the state of California, were ultimately used. The water intensity of electricity generation for each of the different production technologies were taken from a National Renewable Energy Laboratory (NREL) review of the operation water consumption and withdrawal factors for electricity generating technologies.⁴⁴ The values contained in this study were selected because they reflect the most recent consensus based assessment of a dynamic and complicated field, one which is the focus of continued active research.^{71–75}

RESULTS AND DISCUSSION

Case Study Corridor Solutions. We investigated the net energy-water usage characteristics of five hypothetical new reuse systems, assuming 100% reuse of the existing WWTP's National Pollutant Discharge Elimination System (NPDES) permitted maximum daily flow capacity; an assumption which corresponds to the worst case scenario in terms of system scale. Five hydrologically distinct regions distributed throughout Central and Southern California were selected, each of which is depicted graphically in the map set at the top portion of Figure 3. These five regions comprise the level 8 HUC sub-basin zones containing the following cities (each referenced to their corresponding figure elements): Santa Barbara ①, Ventura and Oxnard ②, Fresno and Tulare ③, Santa Ana and San Bernadino ④, and San Diego ⑤. These locations were selected on the basis of the dissimilarity of their local geographic

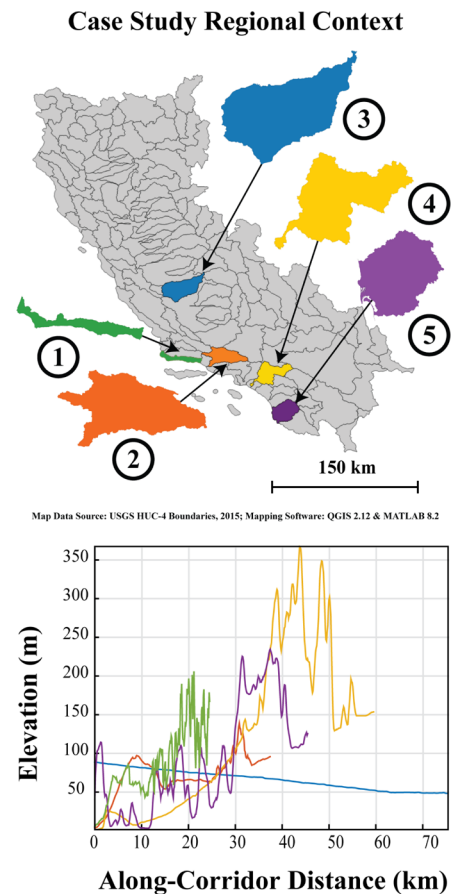


Figure 3. Overview map depiction of five case study regions plotted relative to the along-corridor elevation profiles associated with each region's corresponding output solution corridor. Santa Barbara (1), Oxnard and Ventura (2), Fresno and Tulare (3), Santa Ana and San Bernadino (4), San Diego (5).

contexts (i.e., end point separation distance, regional topography, region landuse, etc.) as well as the demonstrated interest of their corresponding water management authorities in the reuse of treated wastewater for the artificial recharge applications.

At the lower portion of Figure 3 is a plot illustrating the elevation profiles associated with the corridor solutions generated by the genetic algorithm for each of the five case study regions. The color of each plot series corresponds to the color of each of the case study regions depicted in the map panel. The vertical axis references the elevation relief which occurs along the length of each proposed corridor in meters. The horizontal axis references the along-path distance of each corridor in kilometers.

In four of the five case study regions, corresponding to Figure 3 elements ① - ② - ④ - ⑤, the slope of the along-corridor elevation profile is net positive. This is because, each of these HUC zones are coastal and their corresponding WWTP are situated at the lowest elevation point in the basin to take advantage of gravity in the collection of sewage. In the HUC sub basin containing Fresno and Tulare, however, element ③, the slope of the along-corridor elevation profile is net negative. This is because this HUC sub basin is landlocked (i.e., internally drained) and the WWTP is not positioned at the lowest elevation point within the basin.

As the elevation profile plot illustrates the length of each corridor and thus the distance that the water must be pumped depends in part upon the absolute area of the subbasin and in part upon the relative position of the source WWTP relative to the site selected for the surface spreading basin. The Ventura and Oxnard case study region, plotted in orange, comprises a relatively large land area. However, the site deemed to be most suitable for the location of a surface spreading basin was positioned fairly close to the site of the WWTP. Therefore, the total along-corridor distance associated with the Ventura and Oxnard case study region is shorter than that for the San Diego region which, in terms of area, is comparatively larger in size.

Another interesting observation which can be made from this figure is the relative roughness (i.e., the second derivative of slope) associated with each of the proposed solution corridors. For example, the elevation profile for the Santa Barbara case study region's corridor is characterized by a high degree of roughness. The explanation for this feature has to do with the structure of the different objective variables within the search domain area. In Santa Barbara for example, the WWTP is separated from the proposed surface spreading basin site by a large amount of high value land-uses. These land-uses therefore correspond to high disturbance costs which must be weighed relative to the slope based costs during the multiobjective optimization process. Thus, the high degree of roughness in the Santa Barbara watershed along the corridor elevation profile indicates the algorithm trades off a smoother elevation profile for one that is characterized by a lower degree of landuse disturbance and/or a higher degree of accessibility.

Case Study Energy–Water Usage Efficiency Estimates. The electric utility provider which services this region is Southern California Edison (SCE). The portfolio of electric generation technologies in use by this utility provider in 2011 is depicted graphically by the pie chart in the upper portion of Figure 4. As the plot shows, the dominant production technologies are natural gas (48%), coal (12%), nuclear (19%), hydro (9%), and geothermal (9%); with the remainder (~4%) comprised of a mixture of renewable generation technologies.⁷⁰

In terms of the water intensity of electricity production it has been observed that generation technologies which require process water for cooling tend to have higher water withdrawal and consumption factors than for renewable processes. The water intensity, measured in terms of water withdrawals and consumption, for SCE's grid mix are described graphically by the combination of plots contained in Figure 4 using data from the NREL literature review. The absence of a plot series for any column in either of these figures indicates an estimated consumption/withdrawal factor of 0 m³/MWh. For the purposes of this analysis, mean factor values (horizontal red bars) were used to compute the net energy-water usage efficiencies for proposed reuse systems in each of the five case study regions.

Figure 5 plots the estimated ratios of energy derived water expenditures, measured in terms of both withdrawals and consumption, to the volume of water recovered for proposed reuse systems in each of the five case study regions. The horizontal red line depicts the net water savings threshold for a proposed reuse system; defined as the point at which the volume of water recovered is equal to the volume of water withdrawn/consumed to supply the process energy for the reuse activities. The range of ratios is determined by

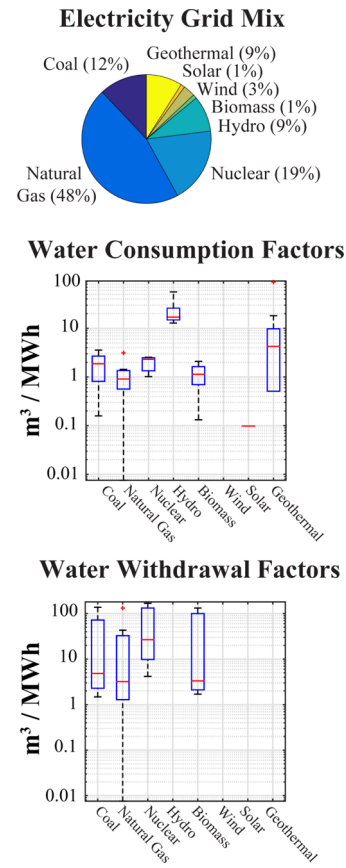


Figure 4. Breakdown of the production technology mix in use by the local electric utility provider: Southern California Edison plotted relative to the ranges of water consumption and withdrawal factors associated with each production technology category.

Ratio of Water Expenditures for Reuse to Water Recovered Via Reuse

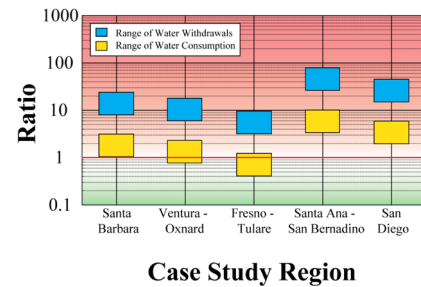


Figure 5. Ranges for the ratios of energy derived water expenditures, measured in terms of both withdrawals and consumption, to water recoveries for proposed reuse systems in each of the five case study regions.

propagating the uncertainty regarding the power efficiency of the pump systems in use for each system (50–90%).

Of the five case study regions investigated only one reuse system, located in the inland sub-basin containing the cities of Fresno and Tulare, was found to provide an estimated net water savings when the embedded water consumption associated with the systems' process energy was taken into account. This result can be explained, in large part, by the unique spatial orientation of the pipeline corridor end points in this case study region. For, in this region alone, the elevation of

the proposed site for the surface spreading was lower than that of the WWTP; a feature which allowed the water being sent along the pipeline corridor to be modeled as flowing downhill under the force of gravity, thus requiring only minimal pump energy to overcome frictional losses.

In two of the five case study regions, those containing the cities of San Bernadino and Santa Ana, and San Diego, the water consumption requirements associated with each systems estimated pump energy demands were sufficiently high to negate the water savings associated with the reuse activities nearly ten times over. The range of water withdrawals is even worse, exceeding the volume of water recovered by reuse in these locations by nearly 2 orders of magnitude. The explanation for the large size of these values again stems from the characteristics of the proposed pipeline corridor at the case study sites: with each exhibiting long along-corridor distances and large net elevation gradients between the corridor end points.

Model Component Validation. A model validation exercise was undertaken to evaluate the effectiveness of the first two components of our modeling approach, the WOA site suitability model and the corridor location model. The researchers were unable to validate the method for estimating the net energy-water usage efficiencies of the proposed reuse systems due to the lack of public availability of real world facility operational data for existing systems. For both components of this validation exercise, publicly available information about the structural components of an existing reuse system with the Santa Ana and San Bernadino case study basin were used for reference. The first validation component involved an investigation of the quality of the WOA model predicted destination site selections for the location of an artificial groundwater recharge infiltration basin.

Figure 6 depicts the results of this first model component validation exercise. At the top of the figure a map of the composite site suitability scores generated from the WOA model is shown overlaid with a set of three connected points plotting the reference source, the reference destination, and the predicted destination. The euclidean distances separating each of these three points of interest are given. Additionally, at the bottom of Figure 6 is a histogram plot showing the distribution of the composite site suitability scores for the case study basin. The red and blue vertical lines on this plot depict the composite site suitability scores for the reference destination and the predicted destination, respectively. As this figure shows, according to the suitability ranking criteria introduced in our WOA approach, the predicted destination site score is significantly higher than of the reference destination.

The second validation component involved an investigation of the quality of the corridor location model solutions relative to the location of an existing pipeline corridor supplying an artificial groundwater recharge operation within the Santa Ana and San Bernadino case study region. The detailed specification of this corridor was obtained by the researchers through a manual digitization process which involved the use of high resolution satellite imagery capable of resolving individual pipeline components.

Figure 7 depicts the results of the second model component validation exercise. At the top portion of Figure 7 are a set of map panels depict the location of the top 100 output corridor solutions generated by the model (shaded in blue) relative to the reference corridor (in red). The plot at center graphically depicts the various objective scores computed for each of these

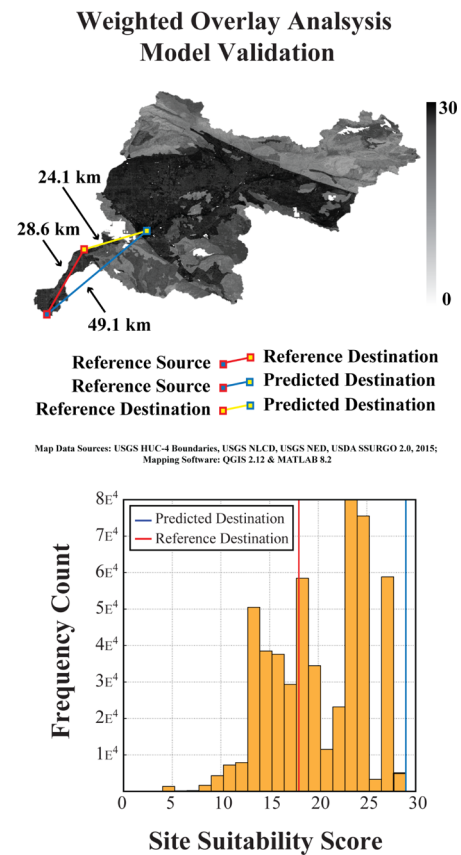


Figure 6. Weighted overlay analysis model component validation results. The map plotted at top shows the relative location—with point to point euclidean distances—of the reference source, the predicted destination, and the reference destination for the siting of a groundwater infiltration basin within the Santa Ana and San Bernadino case study region. The grayscale shading of the mapped area depicts the composite site suitability scores (0–30) for the entire case study region. Likewise, the histogram plot at bottom depicts the distribution of these same composite site suitability scores graphically.

top 100 solution corridors (solid lines) relative to the objective scores computed for the reference corridor (broken lines). As this plot shows, while the slope scores are roughly the same, the solution corridors tend to have lower accessibility scores but higher disturbance scores than the reference corridor. The plot at bottom of Figure 7 shows a histogram of the total aggregate objective scores for the top 100 solution corridors generated by the model. The blue and red vertical lines illustrate the finding that the top solution corridor exhibits a 3% improvement over the reference corridor, as measured in terms of total aggregate objective score.

As mentioned previously, the authors were unable to perform a similarly detailed validation of their predictions for the net energy-water usage efficiency of the existing reuse facility in the Santa Ana and San Bernadino case study basin. This inability was due to the lack of publicly available data for that facility's operations. Were this facility to be structured in accordance with the assumptions used throughout this analysis the authors would anticipate, generally, for it to be operating as a net water consumer due to the high predicted pump energy demands associated with the physical layout of its structural components.

Caveats and Considerations. We believe that both the modeling framework and the case studies' results presented in conjunction with this research significantly advance our

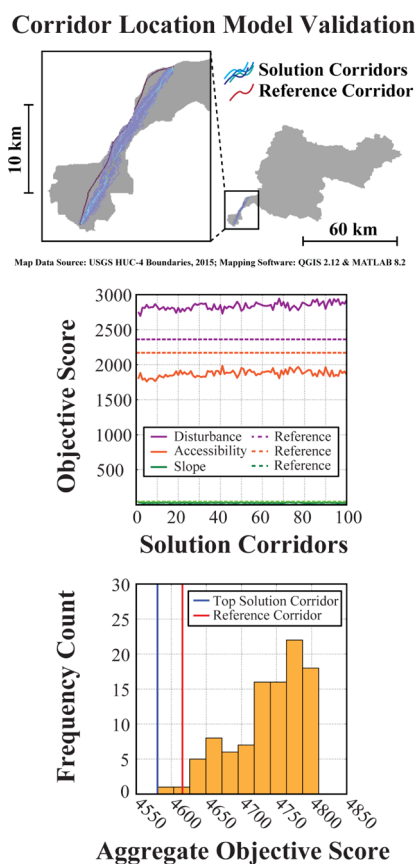


Figure 7. Corridor location model component validation results. The map panels plotted at top show the location of the top 100 output solutions generated by the corridor location algorithm relative to that of the reference corridor. The plot at center depicts the objective scores for each corridor across each of the three separate objectives. These can be compared to the scores for the reference corridor plotted as broken horizontal lines. The plot at bottom depicts the distribution of total aggregate objective scores for the top 100 solution corridor generated.

understanding of the net environmental performance of water reuse systems involving artificial groundwater recharge components. Specifically, they underscore the importance of the linkages between local geographic context, pump energy consumption, and the net water usage efficiencies of water reuse systems. While there are likely important benefits to the watershed in which water is reused, the following issues must be better understood.

First, within the state of California a nontrivial number of the power plants are strategically positioned along the coast to take advantage of the use of available seawater to supply the water intensive process of cooling. In the case of these facilities, the net energy-water usage efficiency of reuse activities can and likely should be interpreted differently from situations in which the water being used for cooling is being sourced from more conventional freshwater surface flows or groundwater reservoirs. Indeed, in these unique circumstances, it may be more appropriate to consider the net effects of large scale reuse activities as being akin to a form of virtual ocean desalination.

Another potential concern is that there are a number of modeling assumptions inherent to this analysis which stem from the core assumption that both the surface spreading basin and the underlying aquifer which it feeds would be capable of supporting both a rate and a total volume of recharge

commensurate with 100% reuse of the WWTP's maximum permitted throughput capacity. On the one hand, it is entirely possible that the existing WWTP may regularly operate at a level below this maximum permitted capacity, thus reducing the total volume destined to be recharged. On the other hand, it is also possible the either the proposed site of the surface spreading basin and/or the underlying aquifer may not be able to accommodate either the designated rate of recharge or the total recharge volume. If this were to be the case, the system must be either scaled back or decomposed into multiple separate recharge sites. In any case, addressing these issues would require highly context specific information regarding the daily treatment flow of the existing WWTP, the precise scale and infiltration rate of the proposed new surface spreading basin, the hydraulic storage capacity of the adjacent subsurface aquifer, and the nature of the vertical connectivity between the infiltration basin and the subsurface aquifer.

Finally, it is clear from this analysis that the large scale reuse of treated wastewater for artificial groundwater recharge would impose significant new electricity demands on the regional power grid. For the sake of simplicity, our framework assessed the water requirements associated with this marginal electricity demand using average grid mix data. Given recent trends toward the decarbonization of electricity production technologies and the ongoing push for the adoption of more renewable energy technologies, it is also possible that the water intensity of the marginal grid mix may be significantly different/lower than the average. Such a situation, while difficult to accurately forecast, would lead to reduced evaluations for the water intensity of these types of reuse systems, thus making them appear to provide greater net water savings.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: [10.1021/acs.est.5b04465](https://doi.org/10.1021/acs.est.5b04465).

Multiobjective corridor location algorithm runtime performance metrics, GIS data processing workflows, and detailed case study analyses result data are all available ([PDF](#))

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Notes

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