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Land-Use Change and Future Water Demand in California's Central Coast

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Received: 1 August 2020; Accepted: 9 September 2020; Published: 14 September 2020

Abstract: Understanding future land-use related water demand is important for planners and resource managers in identifying potential shortages and crafting mitigation strategies. This is especially the case for regions dependent on limited local groundwater supplies. For the groundwater dependent Central Coast of California, we developed two scenarios of future land use and water demand based on sampling from a historical land change record: a business-as-usual scenario (BAU; 1992–2016) and a recent-modern scenario (RM; 2002–2016). We modeled the scenarios in the stochastic, empirically based, spatially explicit LUCAS state-and-transition simulation model at a high resolution (270-m) for the years 2001–2100 across 10 Monte Carlo simulations, applying current land zoning restrictions. Under the BAU scenario, regional water demand increased by an estimated ~222.7 Mm^3 by 2100, driven by the continuation of perennial cropland expansion as well as higher than modern urbanization rates. Since 2000, mandates have been in place restricting new development unless adequate water resources could be identified. Despite these restrictions, water demand dramatically increased in the RM scenario by 310.6 Mm^3 by century's end, driven by the projected continuation of dramatic orchard and vineyard expansion trends. Overall, increased perennial cropland leads to a near doubling to tripling perennial water demand by 2100. Our scenario projections can provide water managers and policy makers with information on diverging land use and water use futures based on observed land change and water use trends, helping to better inform land and resource management decisions.

Keywords: land use; land cover; land change modeling; water demand; water use; California; Central Coast; state-and-transition simulation modeling; LUCAS model

1. Introduction

Water availability and human land use are inextricably tied [1]. In water limited regions, available freshwater supplies can often dictate land use intensity. However water withdrawals and diversions to support land uses, especially for irrigated agriculture, directly impact freshwater supplies [2]. Adding to the complexity are the associated feedbacks between land use, climate, and water supplies. Human land use has been attributed to widespread increases in average global temperatures, contributing to global warming [3–5], losses in species diversity, [6–9], changes in water quality [10–12], and groundwater depletion [13]. Land use models have been widely used to examine future land-use change and water resource assessments in global [14,15], national [16], and regional analyses [17–19]. Understanding potential future land-use related water demand in a region serves as a first step in assessing prospective outcomes and associated mitigation strategies to address potential vulnerabilities.

California exemplifies these issues with water, arguably the state's most contentious resource. The state boasts one of the most productive agricultural regions in the world, worth ~$50 billion [20], which consumes between 60–80% of all water supplies, while residential and industrial consumption is roughly 17% [21–23]. Surface water is over allocated, estimated at 400 billion cubic meters, 5 times the average annual runoff [24]. The state's Mediterranean climate is highly variable, characterized by long-term droughts and atmospheric river flooding events [25], contributing to inter-annual water supply uncertainty. Moreover, water demand is highest in the dry, summer months. A statewide extreme drought from 2012–2016 led to water shortages, increased reliance on groundwater pumping, and subsequent well drying [26], and contributed to saltwater intrusion in some groundwater basins [27–29].

Efforts to plan for water resource sustainability are more challenging now than ever, as these drought and flood events increase in frequency and intensity due to a changing climate [3,30,31]. While the state has long experienced periodic droughts, many climate projections show increased drought occurrence in coming decades [3,13,32–35]. Reduced surface water during drought often leads to increased groundwater pumping in the state [36–38]. Recent work also projects a 25–100% increase in extreme wet/dry events by century's end, despite only modest changes in mean precipitation [39]. Such extreme events, combined with increased evaporative water demand due to climate warming, as well as future population growth and agricultural expansion, will likely contribute to even greater water demand, posing additional challenges to an already unsustainable situation. This may lead to a pivotal juncture where water demand exceeds sustainable supply.

Oversight of California's groundwater has historically been limited. While surface water withdrawals require permits, groundwater pumping has gone largely unregulated and is managed locally [40]. Several legislative attempts have been made to incentivize groundwater management and to better integrate land use in water supply planning. In 1992, AB 3030 passed, and was modified in 2002 by SB 1938, providing procedures and incentives for local agencies to voluntarily develop groundwater management plans [41,42]. In 1995, Senate Bill (SB) 901 required that local governments conduct water supply assessments during the environmental reviews for large projects (above 500 housing units) [43]. In 2001, Senate Bills 610 and 221 required local land use authorities to demonstrate long-term water supply availability before approving new, large development projects [44,45]. Despite these restrictions, none of these laws regulated groundwater pumping. By 2014, rapidly falling groundwater tables combined with ongoing extreme drought led the state to pass the Sustainable Groundwater Management Act (SGMA; AB 1739, SB 1168, and SB 1319) [46–48]. Passage of SGMA marked the first time, local agencies were required to regulate and sustainably manage groundwater resources of critically over-drafted groundwater basins. The implementation of SGMA is ongoing, with local agencies actively designing their groundwater sustainability plans. However, many of these agencies lack the ability to quantify sustainable groundwater yield driven by future land use related water demand.

California's Central Coast is an ideal system for examining the linkages between land use change and land use driven water demand over time and exploring the long-term impacts of water laws and policies on this process, as well as impacts on groundwater supplies, and resource and community sustainability. The region has major agricultural and residential areas that are entirely reliant on local groundwater. There is limited imported surface water, primarily in San Benito and Santa Barbara counties, and groundwater overdraft (extraction exceeding recharge) occurs in an estimated 40% of basins in the region [49]. Many of the coastal aquifers have seawater intrusion, exacerbated by the recent droughts, rendering local groundwater unsuitable for drinking or irrigation [27–29]. Many of its valley floors overlie groundwater basins and support extensive agriculture, while the vast majority is largely undeveloped natural land, creating the potential for substantial new development. It is home to some of the wealthiest and poorest communities in the state, including several disadvantaged communities (annual median household incomes <80% of statewide MHI) [50]. The city of Salinas is currently the largest city at 156,259 people [51]. By 2060, the Central Coast is projected to add nearly 300,000 more people to its population [52], likely increasing water demand. Water supplies may not be able to keep pace, which could exacerbate water insecurity in already vulnerable communities and potentially spark social conflict.

To assess the trajectory of land use driven water demand for California's Central Coast and explore whether the 1992–2001 water laws and policies were correlated with the pattern of demand for the region, we ran two scenarios based on historical, empirical datasets of land use changes sampled. The first was a business-as-usual (BAU) scenario fit to land use change rates from the entire historical period, 1992–2016, while the second, recent-modern (RM) scenario only sampled from 2002–2016 rates (i.e., after the second set of laws were put in place in 2001). We simulated projected land use change and associated water demand for the years 2001–2100 at 270-m across 10 Monte Carlo simulations across these two scenarios. Our model was based on the Land Use and Carbon Scenario Simulator (LUCAS) [18,19,53–57], a stochastic, spatially explicit state-and-transition simulation model. Spatial patterning of land use change was parameterized using local zoning datasets, identifying where land change would and would not occur giving current zoning ordinances and local mandates. Our goal was to understand the region's unique potential water demand, assisting local water resource and land managers in understanding the impacts of past policies to better identify and mitigate for possible future vulnerabilities as they continue to develop and revise new groundwater sustainability plans for SGMA. While SGMA is too new to definitively determine its impact on future water demand, viewing an unregulated future with and without existing policy provides an important baseline for more targeted mitigation planning.

2. Materials and Methods

The LUCAS state-and-transition simulation model (STSM) [19,54–56] was developed and modified for our study region. An STSM is a stochastic, Markov chain, empirical simulation model used to predict how defined variables transition between different specified states over a specified timeframe [58]. An STSM can also track age structure enabling age-dependent transitions as well as age-based triggering events. STSMs have been widely used to simulate landscape level vegetation change [59] and changes in land use and land cover (LULC) over time for assessing LULC scenario impacts on population and carbon dynamics [53–55], protected areas [57], and future water resources [19,56]. The STSM divides the landscape up into spatially discrete simulation cells, each with assigned state classes (i.e., LULC) and transition types. Each state class has pre-defined transition type pathways, allowing or preventing cells to move between different state classes over time. What follows is a description of the model parameterization steps for the Central Coast region of California. For more comprehensive information on STSMs, see Daniel et al. [60]. All modeling for this study was done using the ST-SIM software application, which can be downloaded free of charge from APEX Resource Management Solutions (http://apexrms.com). All model parameters are available as (1) a Microsoft Excel file and (2) a database containing all model inputs and outputs (http://geography.wr.usgs.gov/LUCC/) and in the ScienceBase USGS catalog (https://www.sciencebase.gov/catalog/).

We held three stakeholder meetings with individuals from regional municipal governments, water agencies, and community groups while developing our models. Meetings were held at the start of model development, the midpoint, and when presenting a draft version of the final model results. Stakeholders provided information on local spatial planning datasets that were assimilated into the models (see Section 2.5) as well as interpretation of results in the context of local concerns about water sustainability and land use.

2.1. State Variables and Scale

The current study area encompasses 28,534 km^2 of the 5-county region in California's Central Coast (Figure 1a), covering Santa Cruz, San Benito, Monterey, San Luis Obispo, and Santa Barbara Counties. The region was divided into 270-m × 270-m simulation cells (391,421 total cells). Each cell was also assigned an initial LULC state class (Figure 1b) and three additional spatial identifiers including its (1) county, (2) groundwater sub-basin (Figure 1c; n = 61) [61], and (3) water service agency(s) (Figure 1d; n = 107), which are described below. Scenario simulations were initiated in 2001 and run through the year 2100. The model tracks changes in state class, age, time-since-transition, and state attributes (i.e., water demand). For each scenario simulation, we ran 10 Monte Carlo iterations to capture model variability and uncertainty in our projections.

We utilized the National Land Cover Dataset 2001 (NLCD01) [62], as our initial state class conditions, modified for our study region were as follows: (1) all four developed classes were collapsed into a single developed class and urban core areas defined per [63]; (2) the three forest classes were combined into a single forest class; (3) the woody and emergent wetlands classes were combined into a single wetlands class; (4) the agriculture and hay pasture classes were combined into a single annual agriculture class; (5) we used data from Sleeter et al. [55], for the 2001 perennial agriculture class, described in more detail below; and (6) the "Developed-Roads" class from Landfire's Existing Vegetation Cover 2001 was used to designate a transportation class [64], (Figure 1b). All datasets were resampled from 30-m to 270-m and re-projected into a NAD 1983 California Teale Albers map projection.

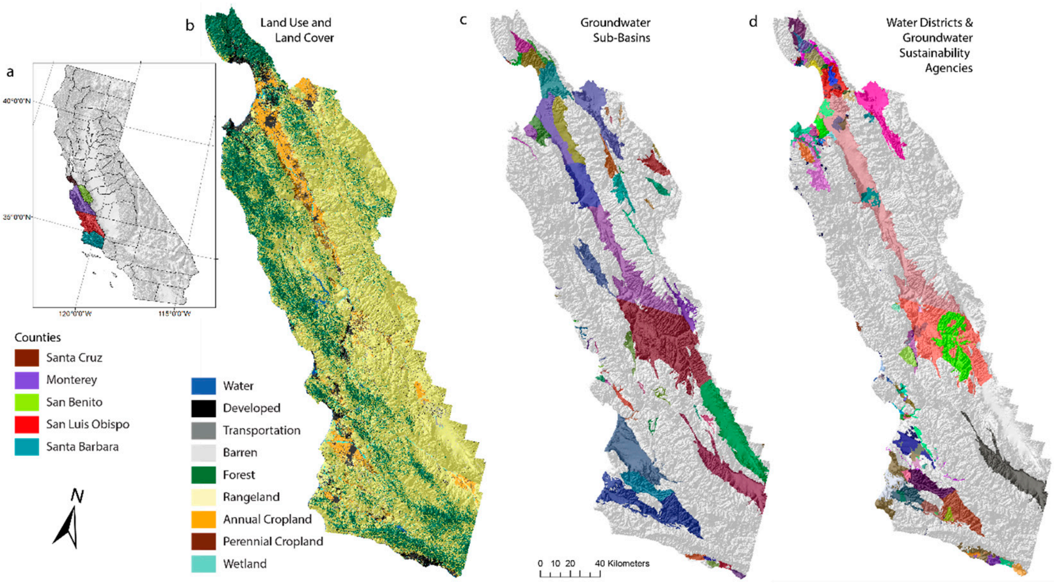

Figure 1. California's Central Coast Study Area including (**a**) counties, (**b**) land use and land cover in 2001, (**c**) groundwater sub-basins, and (**d**) aggregated water district and groundwater sustainability agency jurisdictions. Complete lists of regions included in (**c**) and (**d**) located in the Supplementary Materials Tables S1 and S2, respectively. The base map is from the U.S. Geological Survey's National Map Atlas [65].

The NLCD01 does not contain a perennial orchard and vineyard class. We used a 2001 perennial cropland cover map [55], which generated orchard and vineyard cover using a gradient boosting machine algorithm framework. Any NLCD01 pixel classified as agriculture which overlapped the 2001 perennial cover estimate was classified as perennial cropland.

The water agencies map (Figure 1d) was created by combining the Groundwater Sustainability Agency (GSA) Service Area dataset [66], and the Water Districts dataset [67]. Because polygon boundaries did not line up precisely between the two shapefiles, polygons were manually edited to remove small slivers or gaps. Multiple agencies can also have overlapping jurisdictions (e.g., local city water systems and basin-wide GSAs), so each polygon in the final dataset was assigned 0–2 GSAs and 0–2 water districts each. If GSAs were formed from pre-existing water districts with the same boundaries, we included them only as GSAs. Four county-wide water districts were not included, as counties are already represented in the LUCAS model. Lastly, water districts servicing <20 km^2 were removed, unless they were the only agency servicing that area. If so, they were included and labeled as "other small water district." This resulted in 107 unique jurisdictional combinations covering 29 GSAs and 40 water districts as well as examples of "other small water districts."

2.2. Model Formulation

The LUCAS model was formulated to simulate changes in state class variables for pathways associated with urbanization, agricultural expansion and contraction, and agricultural change (i.e., intensification associated with conversions of annual to perennial cropland).

2.3. Land Change Transitions Targets

Data from the Farmland Mapping and Monitoring Program (FMMP) [68], dataset was used to supply LULC transition targets for agricultural expansion, agricultural contraction, and urbanization in each scenario. The FMMP gathers bi-annual land change data using aerial photography and human interpretation. The FMMP does not have multiple urban or agricultural classes, justifying the aggregation of these LULC classes described in Section 2.1 above. We updated the existing historical land change record (1992–2012) from Wilson et al. [19], with newly available data, extending the record to span 24 years (1992–2016), from which both scenarios were sampled.

Changes between annual and perennial crop types (i.e., agricultural change) are typically harder to quantify. Previous work used cropland statistics to set a single agricultural change transition target, applied across a broader study area [19]. To improve upon this method and to better capture regional variability in these trends, we used available spatial datasets, including our 2001 initial conditions map and the 2018 perennial cropland map described in Section 2.5.3. Any pixel which began as annual cropland in 2001 but converted to perennial cropland by 2018 was captured. This generated a 17-year, county-level annual to perennial conversion value (2001–2018), converted into annual transition targets of 0.12 km^2 (Santa Cruz), 0.60 km^2 (San Benito), 2.59 km^2 (Monterey), 1.37 km^2 (San Luis Obispo) and 1.09 km^2 (Santa Barbara). The same approach was used for calculating yearly perennial cropland expansion into rangelands, resulting in 0.28 km^2 (Santa Cruz), 1.63 km^2 (San Benito), 3.99 km^2 (Monterey), 10.58 km^2 (San Luis Obispo), and 5.59 km^2 (Santa Barbara).

To calculate the rangeland to annual cropland transition targets, we subtracted the rangeland to perennial transition target from the overall agricultural expansion targets from FMMP. Where more rangeland to perennial occurred than was reported as agricultural expansion, it was assumed that 0 km^2 of rangeland was converted into annual cropland. We recognize this approach introduces some data loss, however, lacking wall-to-wall spatial data and “from class—to class” conversion information at higher temporal resolution, it is the most defensible approach to capture the large scale, notable shifts of natural uplands into perennial production (~375 km^2 between 2001 and 2018; [62,69,70], a trend uncommon for annual cropland in this region.

2.4. Perennial Transition Probabilities

Conversions out of the perennial cropland class are also challenging to quantify. Perennial crops are expensive to plant, cannot be fallowed, and take several years post-planting to reach maturation [71]. The average lifespan of vineyards and orchards in California is 25 years [72], after which productivity often declines. In order to capture this lifespan, we extracted age values for our 2001 perennial cropland from an age class map available from Sleeter et al., (2019). Since the LUCAS model can track pixel age and time since transition, we set the following model rules following previous work [19,54,56]: (1) a perennial pixel must reach a minimum age of 20 years before it is eligible for removal or conversion, in any model year or iteration, (2) the annual transition probability for orchard removal was sampled from a cumulative probability of 0.95 for ages 20 and 45, and (3) after removal the pixel age is reset to 1 and the cell is free to be converted into new development, agricultural contraction, or annual cropland (with annual probability set at 0.05). If the cell does not convert in this age reset year, then the model assumes it is replanted as perennial. Any perennial crop over 20 years in age has a 0.05 probability of transitioning back to annual cropland. Lacking wall-to-wall spatial data on orchard removal or comprehensive numerical data, we relied upon this previously published approach [19,54,56].

2.5. Adjacency & Spatial Multipliers

For each potential LULC transition, adjacency multipliers were applied where the relative probability of any transition increased linearly with the number of existing, neighboring "from class" cells within a 405-m × 405-m moving window [18,19,53–55]. A cell would be eligible to transition if it contained at least one neighbor of the destination class (or transitioning "to class") within a 405-m radius of the cell to be transitioned. The more neighbors of the "to class" increases the likelihood of transition, which was linearly scaled between 0–1 based on the number of "to class" neighbors present. This parameter was updated every 5 timesteps for every possible LULC transition pathway.

We developed region-specific LULC transition spatial multipliers for the each LULC transition: (1) urbanization (2) agricultural expansion, and (3) agricultural change. Spatial multipliers are raster-based, probabilistic surfaces that either increase or diminish the likelihood of the specified LULC transition type [57,73]. A probability of 1 ensures a transition will occur in that specified raster space if a transition target or multiplier is supplied, whereas a probability of 0 will prohibit the given transition from occurring in a cell. What follows is a discussion of the datasets used in the development of the LULC transition spatial multipliers.

Overall, we used national and state level land protection data from PADUS [74] to prohibit any land change on protected lands and land owned by the Department of Defense. In addition, we incorporated available county-level land use zoning data to improve the regional accuracy of projected land change. This information was used to identify areas where LULC conversions are not currently allowed or where future development is already planned and zoned for. Land use zoning has been shown to be a strong predictor of urban growth and more accurately represents land change [75]. For land change modeling, inclusion of spatial planning information generates better informed analyses [76–78]. Such an approach has been used by land change modelers to test alternative zoning scenarios [79], and as factors in LULC transition decision rules [80]. We acknowledge that zoning data can and will change over time and land area can be re-zoned with new designations. However, many zoning designations are likely to persist into the future, including open space and resource conservation areas. Alternatively, planned development areas are not likely to remain undeveloped for decades. Supplementary Materials Table S3 shows the additional zoning datasets used in the development of the spatial multipliers and their unique zoning designations. Zoning categories listed as No Conversion in Supplementary Materials Table S3 were applied as 0 values in all LULC spatial multiplier probability surfaces. We next describe each spatial multiplier in detail.

2.5.1. Urbanization

Additional constraints on the placement of new developed lands were derived from U.S. Census Bureau [81], data and county-level land use zoning information (Supplementary Materials Table S3). For conversions into new developed lands, we used the Urban Areas in 2011 dataset [81], with areas designated as core urban areas (population > 50,000) assigned a probability of 1 for urbanization transitions, while secondary urban areas or clusters (population 2500 to 50,000) were assigned a probability of 0.5. All remaining areas not classified as 0 were given a 0.25 probability of conversion. See Supplementary Materials Table S3 for a full list of data used to prohibit urbanization transitions (i.e., "No Conversion") or promote urbanization transitions (i.e., "To Developed").

2.5.2. Agricultural Expansion

Areas designated as protected in the urbanization multiplier were also considered as unavailable for transitions into new agricultural lands. For county-level zoning datasets, this included open space, public recreation facilities, parks, protected lands, preserves, and more. See the "No Conversion" category in Supplementary Materials Table S3 for all areas prohibited from conversion into agricultural land uses for more detail. Agricultural expansion transitions into new perennial croplands were supplied the spatial multipliers described in Section 2.5.3.

2.5.3. Conversions to Perennial—Historical and Projected

Historical perennial cropland expansion in the Central Coast has been spatially disparate and has not occurred near existing cropland areas [62,69,70]. Most new perennial crops have been planted in previously open rangeland and valley uplands. In order to capture this spatially anomalous historical trend with observed data, we developed a "To Perennial 2018" spatial multiplier for the historical period (through 2018) by combining two spatial datasets. We used the Crop Mapping 2014 dataset from the California Natural Resources Agency for orchard and vineyard classes [69]. We combined this with parcel-level orchard and vineyard data, aggregating avocado groves, citrus groves, orchards, and vineyards into a single perennial class with a probability of 1 for conversion into perennial cropland during this timeframe [70]. All other pixels were set with a probability of 0 to force new perennial crops into known locations.

In 2019 or the first projection year (i.e., year for which we do not know where new perennial crops occurred), we developed a "To Perennial 2019" multiplier, based on the 2018 multiplier to include probabilities of 0 for the "No Conversion" regions identified in Supplementary Materials Table S3, and 1's for the known historical locations. In addition, all other pixels classified as annual cropland or rangeland in 2001 were assigned a probability of conversion into perennial cropland. We calculated these probabilities of perennial conversion for each county based on the proportion of historical conversion from each class, based on the conversion rates defined in Section 2.3.

2.6. Water Demand

In addition to tracking state class variables, the model was parameterized to track water use by county and state class type using data from Wilson et al. [19]. They calculated average county level applied water use for the annual and perennial cropland classes by reclassifying the USDA Cropland Data Layer (CDL) [82], by cropland categories associated with the California Department of Water Resources (CDWR) Agricultural Land & Water Use 1998–2010 dataset [83]. These were then aggregated into annual and perennial cropland classes and assigned an area-weighted average applied water use value for each combination of county and state class type. For the developed class, they derived applied water use from a national dataset of water use in 2010 developed by various sectors [23]. Applied water use for the developed state class was calculated as a sum of public supply freshwater and industrial self-supplied water and divided by the total developed area in each county based on the NLCD 2011 [84]. The NLCD 2011 most closely aligned with the 2010 water data for generating a water use per unit area estimate and captured both residential and industrial use values for each county.

2.7. Land Use and Land Cover Scenarios

Two LULC change scenarios were modeled to examine how projections of future land change based on longer term land change would compare to projections based only on modern land change trajectories. The first scenario, referred to hereafter as the Business-As-Usual (BAU) scenario, randomly samples from the full 1992–2016 FMMP land change record. The second Recent-Modern (RM) scenario samples from 2002–2016 FMMP record alone. The RM scenario is intended to both capture land use policies implemented in 2001, restricting development in some regions, while also capturing recent drought-related trends. Each model run was initiated in 2001 and the model uses the actual FMMP LULC transition targets for the specified historical model year (2001–2016). For each scenario projection year (i.e., 2017 and after), LUCAS randomly samples a single year, from the range of available historical years (i.e., 24-year record was used for BAU; a 14-year record was used for RM), sampling all associated LULC transitions, preserving LULC change covariance from this sampled historical year.

2.8. Model Validation

The same LUCAS model using the FMMP historical data has been validated as capable of reproducing the desired amount of FMMP transition area based on the historical distributions for each transition group in previous efforts at both the regional [19,56], and state level [54]. The LUCAS model consistently produces the expected historical outcome (2001–2016) with mean modeled results matching the input FMMP transition target amounts (Supplemental Materials Table S4). Modeled averages demonstrate that the model has accurately replicated historical rates; however, for any timestep and Monte Carlo simulation, the modeled estimate could have been slightly higher or lower than the FMMP data. Lacking thematically, spatially, and temporally consistent data prohibits a more thorough pixel-to-pixel comparison for validation. Modeled water demand for the years 2005 and 2010 compared to the USGS water data [85] for the same years show modeled water demand closely matching the empirical water data (Supplemental Materials Table S5).

3. Results

3.1. Projected Land Use and Land Cover Change

General LULC change trajectories were similar between scenarios but the overall magnitude of change was markedly different (Figure 2). In both scenarios rangelands and annual cropland declined, being outcompeted by development and perennial cropland expansion through 2100. The declines were dramatic with BAU annual cropland declines averaging 80% (1029 km^2) across Monte Carlo simulations, while the RM lost 81.4% (1046 km^2). The BAU projected greater increases in developed land, yet lower losses of rangeland overall. In comparison, the RM scenario projected lower rates of development and greater increases in perennial cropland. Perennial expansion in the region continued its robust historical trend, with planting of these specialty crops nearly doubling in the BAU and nearly tripling in the RM scenario. On average, the BAU was projected to gain 710 km^2 of new perennial cropland by 2100, with the RM scenario gaining 1084 km^2 (Figure 2). Overall cropland totals—the sum of both annual and perennial cropland—increased slightly (37.4 km^2) in the RM scenario but declined an average of 19.3% in the BAU (Figure 2). Developed lands increased in both scenarios across simulations but were approximately 11.7% higher in the BAU (843.3 km^2) than in the RM (666.6 km^2) (Figure 2).

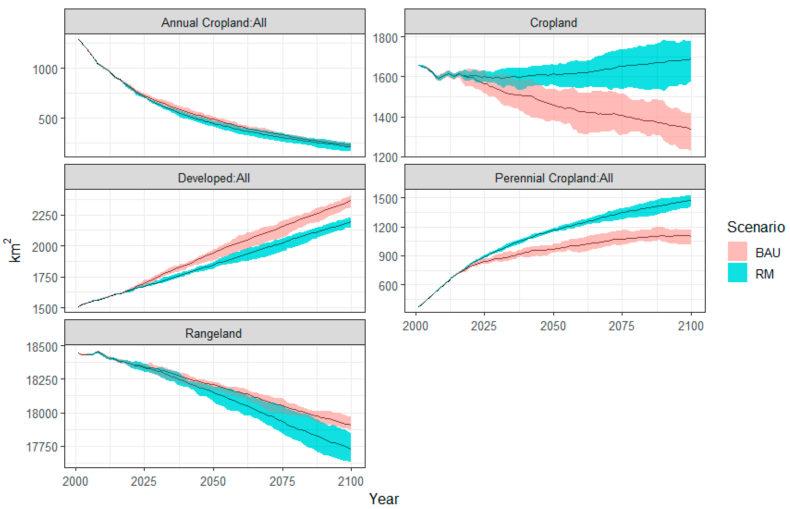

Figure 2. Projected land use and land cover change from 2001–2100 under a business-as-usual (BAU; red) and recent modern (RM; blue) scenarios for the California Central Coast, including Annual Cropland, Cropland (sums Annual Cropland and Perennial Cropland), Developed, Rangeland, and Perennial Cropland. Dark center trendline is the mean for each scenario and shaded area represents the minimum and maximum value ranges across 10 Monte Carlo simulations.

At the county scale, the greatest declines in annual cropland were projected in Monterey and Santa Barbara Counties (Figure 3). The greatest increases in both developed and perennial cropland occurred in Monterey and San Luis Obispo Counties, predominantly at the expense of rangeland (Figure 3) which declined between 181–186 km^2 (BAU-RM) and 365–479 km^2 (BAU-RM), respectively. In Monterey County, developed land increased between 21.6% (RM) and 28.0% (BAU) by 2100. In both scenarios, development in San Luis Obispo increased an average 28.5%. County-level trends varied greatly between scenarios losses in rangelands. When accounting for overall percent loss from 2001–2100, Santa Cruz County was projected to lose between an average 25.9% (RM) and 27.4% (BAU) of its rangelands. Conversely, San Benito County had projected increased natural lands in rangeland, following recent FMMP trends in agricultural contraction. Figure 4 shows the mapped LULC projections under the RM scenario to demonstrate spatial placement of change.

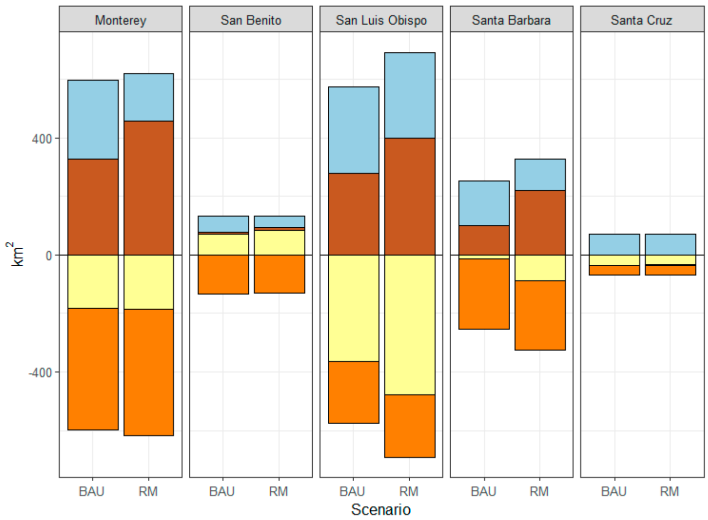

Figure 3. Projected change in land use and land cover from 2001–2100 under a business-as-usual (BAU) and recent modern (RM) scenario for each county in the California's Central Coast region, expressed as average net change in annual cropland (orange), perennial cropland (brown), development (blue), and rangeland (yellow) across the modeled period and 10 Monte Carlo simulations.

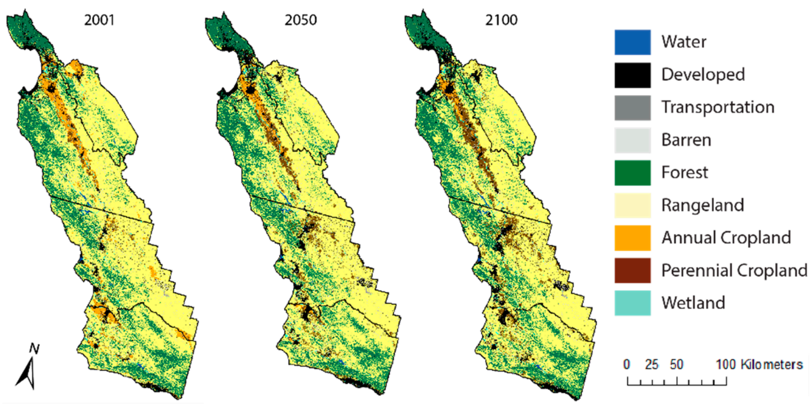

Figure 4. Projected land-use and land-cover (LULC) change from 2001–2100 in 50-year increments for California's Central Coast region under the Business-As-Usual (BAU) scenario. Each map represents one out of 10 possible Monte Carlo simulations modeled for each time step.

3.2. Projected Future Water Demand

From 2001 to 2100, overall land-use related water demand was projected to increase between 222.7 and 310.6 million cubic meters (Mm^3) in the BAU and RM scenarios, respectively (Figure 5). In 2001, the Central Coast water demand was approximately 1.3 billion cubic meters (Bm^3). By 2100, our model shows water demand projected to rise between 1.5–1.6 Bm^3 on average across Monte Carlo simulations and scenarios by 2100 (Figure 5). This represents a 16.4% to 22.8% increase in water demand by the end of this century, assuming current land use trends persist. Continuing trends in perennial cropland expansion led to a projected 222.7 Mm^3 increase in water demand in the BAU (Figure 6). This increase is small in comparison to the near tripling of perennial water demand in the RM scenario over 2001 use levels, rising by an estimated 359.2 Mm^3, concentrated primarily in Monterey, San Luis Obispo, and Santa Barbara counties (Figure 6). Water demand from developed land uses was projected to increase 290.4 Mm^3 (53.8%) in the BAU and 230.8 Mm^3 (42.7%) in the RM scenario. The only demand declines projected were for annual cropland cover, with dramatic projected decreases from between 339.3 Mm^3 (77.9%) in the BAU and 344.8 Mm^3 (79.2%) in the RM in all counties (Figure 6). Opposite demand increase trends are seen between the BAU and RM scenarios, as the BAU shows increased demand higher for development than for perennial crops, whereas the RM shows higher perennial demand and lower demand caused by developed land uses.

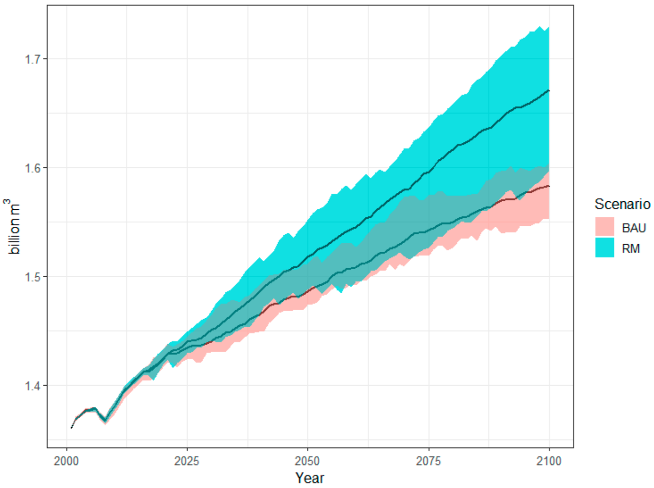

Figure 5. Projected land-use related water demand in billions of cubic meters (Bm^3) from 2001–2100 in California's Central Coast under a business-as-usual (BAU; red) and recent modern (RM; blue) scenarios. Darker center lines represent the mean and shaded area represents the maximum and minimum values across 10 Monte Carlo simulations.

Figure 6. Net change in water demand in millions of cubic meters (Mm^3) from 2001–2100 by land use and land cover class and county for the business-as-usual (BAU) and recent modern (RM) scenarios.

Potential Changes in Groundwater Basin Overdraft

Projections of future land-use related water demand showed some groundwater sub-basins experiencing much greater increases than others. Figure 7 shows the percent change in total water demand per sub-basin, calculated as (Demand—Demand$_{2001}$)/(Demand$_{2001}$ + 10). Table 1 summarizes these results for each groundwater sustainability agency (GSA) and Table 2 summarizes them for other Non-GSA water districts.

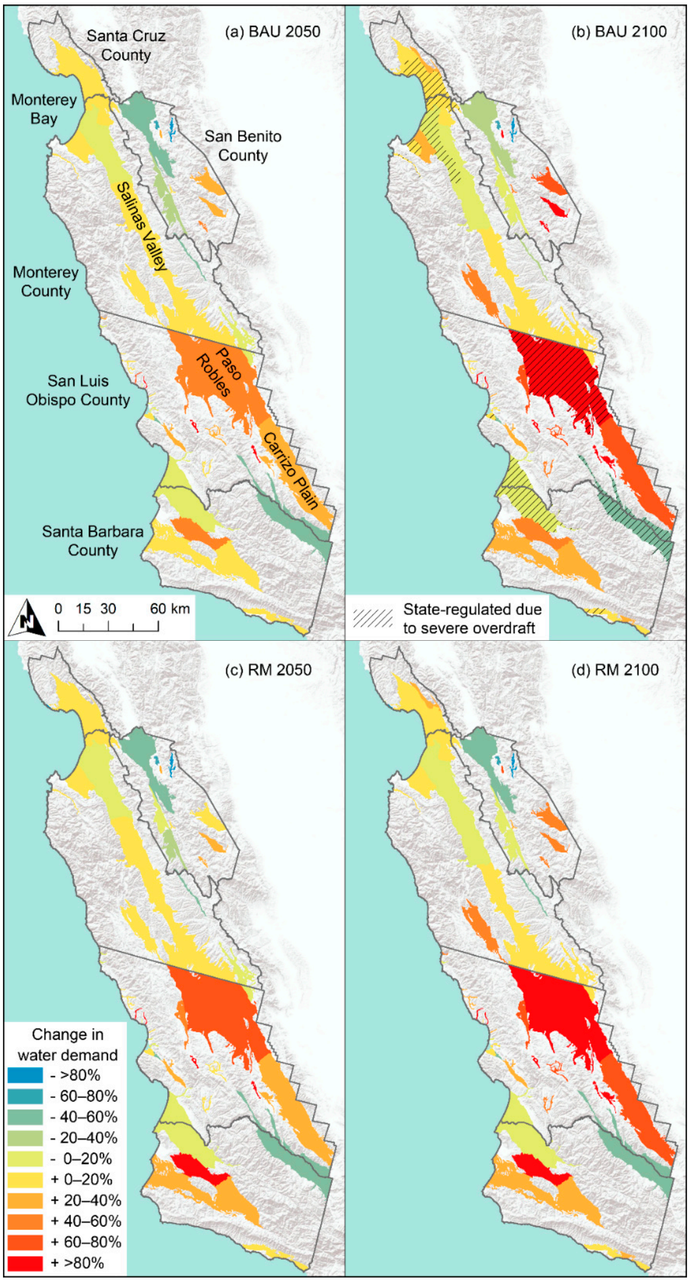

Figure 7. Projected change in water demand for groundwater sub-basins from the (**a**) business-as-usual (BAU) by 2050, (**b**) BAU by 2100, (**c**) recent modern (RM) by 2050, and (**d**) RM by 2100. Hatched lines shown in (**b**) represent existing state-regulated groundwater basins already experiencing overdraft. The base map is from ESRI World Terrain Base [86].

Table 1. Projected percent (%) change in water demand for SGMA groundwater sustainability agencies of the Central Coast by 2050 and 2100 under two scenarios, a Business-as-Usual (BAU; fit to 1992–2016 land use change rates) and Recent-Modern (RM; fit to 2002–2016).

Groundwater Sustainability Agency	**BAU**		**RM**	
	2050	**2100**	**2050**	**2100**
Arroyo Seco GSA	−7.10	−8.40	−9.74	−11.54
Atascadero Basin GSA	30.39	58.03	18.42	42.30
City of Arroyo Grande GSA	47.55	68.24	47.84	70.63
City of San Luis Obispo GSA	0	0	0	0
Cuyama Basin GSA	9.24	12.94	8.02	11.06
Goleta Fringe GSA	−2.28	−3.47	−2.11	−2.96
Montecito Groundwater Basin GSA	17.71	17.64	16.80	16.85
Paso Basin—County of San Luis Obispo GSA	6.77	10.57	6.90	10.07
Salinas Valley Basin GSA	23.43	19.88	26.72	24.11
San Antonio Basin GSA	15.49	17.01	15.66	18.82
San Benito County Water District GSA	8.61	11.06	7.63	11.06
San Luis Obispo Valley Basin—County of San Luis Obispo GSA	11.15	11.90	10.85	11.90
Santa Maria Basin Fringe Areas—County of San Luis Obispo GSA	9.24	9.81	9.14	10.03
Santa Maria Basin Fringe in Santa Barbara County GSA	1.51	1.51	1.51	1.51
Santa Ynez River Valley Basin Central Management Area GSA	−4.15	0.38	−5.53	−2.87
Santa Ynez River Valley Basin Eastern Management Area GSA	9.52	11.37	8.64	11.37
Santa Ynez River Valley Basin Western Management Area GSA	53.43	76.80	53.13	77.10
Shandon-San Juan GSA	15.89	20.76	15.57	20.23
City of Paso Robles	12.50	14.09	12.23	14.37
County of San Luis Obispo	6	7.33	4.78	6.66
County of Santa Cruz	3.34	3.34	3.34	3.34
Heritage Ranch Community Services District	15.34	15.20	14.74	14.75
Marina Coast Water District	69.04	82	77.80	81.97
Monterey Peninsula Water Management District	44.75	40.83	84.96	102.01
Pajaro Valley Water Management Agency	9.79	10.38	9.49	10.38
San Miguel Community Services District	19.59	25.80	16.24	24.16
Santa Clara Valley Water District	178.78	383.94	157.66	374.79
Santa Cruz Mid-County Groundwater Agency	2.28	2.54	2.28	2.54
Santa Margarita Groundwater Agency	26.33	35.41	24.47	34.50

Table 2. Projected percent (%) change in water demand in water districts of the Central Coast (excluding GSAs and county agencies) by 2050 and 2100 under two scenarios, a Business-as-Usual (BAU; fit to 1992–2016 land use change rates) and Recent-Modern (RM; fit to 2002–2016).

Water District	**BAU**		**RM**	
	2050	**2100**	**2050**	**2100**
Alco Water Service	−7.10	−8.40	−9.74	−11.54
Aromas Water District	30.39	58.03	18.42	42.30
Atascadero Mutual Water Company	47.55	68.24	47.84	70.63
CA Parks and Recreation Department—Hollister Hills SVRA	0	0	0	0
California American Water Company—Monterey District	9.24	12.94	8.02	11.06
California Water Service Company—Salinas	−2.28	−3.47	−2.11	−2.96
California Water Service Company—Salinas Hills	17.71	17.64	16.80	16.85
Cambria Community Services District	6.77	10.57	6.90	10.07
Carpinteria Valley Water District	23.43	19.88	26.72	24.11
Central Coast Water Authority	15.49	17.01	15.66	18.82
Central Water District	8.61	11.06	7.63	11.06
City of Arroyo Grande	11.15	11.90	10.85	11.90
City of Goleta	9.24	9.81	9.14	10.03

Table 2. *Cont.*

Water District	BAU		RM	
	2050	2100	2050	2100
City of Grover Beach	1.51	1.51	1.51	1.51
City of Lompoc	−4.15	0.38	−5.53	−2.87
City of Morro Bay	9.52	11.37	8.64	11.37
City of Paso Robles	53.43	76.80	53.13	77.10
City of Pismo Beach	15.89	20.76	15.57	20.23
City of San Luis Obispo	12.50	14.09	12.23	14.37
City of Santa Barbara	6	7.33	4.78	6.66
City of Santa Cruz	3.34	3.34	3.34	3.34
City of Watsonville	15.34	15.20	14.74	14.75
Golden State Water Company—Edna	69.04	82	77.80	81.97
Golden State Water Company—Lake Marie	44.75	40.83	84.96	102.01
Golden State Water Company—Los Osos	9.79	10.38	9.49	10.38
Golden State Water Company—Orcutt	19.59	25.80	16.24	24.16
Heritage Ranch Community Service District	178.78	383.94	157.66	374.79
Los Osos Community Services District	2.28	2.54	2.28	2.54
Montecito Water District	26.33	35.41	24.47	34.50
Monterey County Recycling Project	−7.06	−16.89	−6.74	−16.49
Oceano Community Service District	5.20	5.81	5.40	5.60
Other Small Additional District	21.05	30.90	18.79	29.33
Pajaro Community Service District	−8.23	−13.46	−9.60	−17.05
San Lorenzo Valley Water District	4.46	5.46	4.05	5.46
Santa Lucia Preserve Water System	0	0	0	0
Santa Maria Valley Water Conservation District	−22.80	−37.25	−27.00	−37.78
Scotts Valley Water District	1.44	1.80	0.99	1.80
Soquel Creek Water District	4.38	4.38	4.38	4.38
Templeton Community Services District	58.51	73.66	54.91	73.19
Unmanaged	−7.10	−8.40	−9.74	−11.54

Across both scenarios, increased water demand by 2100 was greatest in San Luis Obispo County (Figure 7). This is largely due to perennial agriculture replacing rangeland in many areas, creating unprecedented (percent increases >1000%) new perennial cropland water demand in Carrizo Plain basin and other small basins in the area, and roughly doubling total water demand in the Paso Robles area. In general, increasing urban water demand was uniformly spread across the study area, with median increases of ~50% per sub-basin (range 0–215%). In the major sub-basins around Monterey Bay, many of which are already critically overdrafted (Figure 7b), total water demand increased only slightly. An exception was the critically overdrafted "180/400-foot" sub-basin of the Salinas Valley, which underlies part of the disadvantaged city of Salinas and experienced a decrease in water demand of −11% in both scenarios. This restrained growth or even reduction in total water demand was due to urban expansion into previous annual agriculture resulting in a net loss of water. The greatest decreases in total water demand was in San Benito County. This was particularly notable in the RM scenario, where dramatically declining annual agriculture coupled with modest increases in urban water demand, led to an overall decreasing water demand in most sub-basins (median decrease of −8% in both scenarios). Increasing water demand was projected in basins where encroachment of water-dependent human land uses occurred in previously open rangeland (Figure 1b, Figure 7).

4. Discussion and Conclusions

Overall, our scenario results suggest that water supply challenges, overdraft, and overdraft-driven seawater intrusion in the Central Coast region are likely to continue absent changes in groundwater and/or land-use management.

4.1. Projected Water Demand Trends

Projections show increasing land-use related water demand by 2100 of between 222.7 and 310.6 Mm^3 in the BAU and RM scenarios, respectively. Increased demand was driven by continued perennial cropland expansion and urbanization, even as annual cropland water use declined. Additional increased demand from continued urbanization leads to additional residential and industrial water use needs. For the BAU scenario development-related increases in water demand outpaced increased demand from perennial cropland, while the opposite was the case in the RM. This difference illuminated trends noted in the historical FMMP dataset, showing marked declines in urbanization beginning around 2003. The RM scenario only sampled from FMMP-based LULC change in the years 2002–2016, thus capturing land use changes likely associated with legislative mandates which imposed water use restrictions for new development. We sought to capture this declining urbanization trend as well as the unprecedented 2011–2016 drought in our RM scenario projections. Despite slower rates of development and a historic drought, the RM scenario showed a 22.8% increased water demand overall, much higher than the 16.3% increase projected in the BAU. Notably, despite an historically unprecedented drought, perennial cropland expansion was projected to nearly double (BAU) and triple (RM), which may be cause for concern in a predominantly groundwater dependent region with already strained water supplies.

These same trends in agriculture intensification have been occurring statewide for decades. Between 1960 and 2009, while the amount of harvested acreage in California declined by more than a half million acres, the proportion of fruit and nut crops (i.e., not field crops, vegetable, or melons) more than doubled from 14% to 33% of all acres harvested [71]. Between 2004 and 2013 alone, statewide harvested acres for almonds, pistachios, grapes, cherries, berries, and olives nearly doubled as well [71]. Cropland reports for the Central Coast show annual field and row crops dominating the landscape; however, grape acreage between 2002 and 2017 expanded by nearly 25,000 acres (~100 km^2) [87].

Neither the perennial nor urban expansion trends are likely to persist indefinitely into the future, particularly given new water limitations under SGMA, increasing water scarcity, and the likelihood of additional policies and management. Shifts in future development patterns due to other local economic factors and demand for affordable housing, changing dietary preferences, and a warming climate are likely to further deviate future rates from simply continuing historical trajectories. Specialty perennial crops could slow their expansion, as high value annual crops retain their value and market demand. Annual cropland losses are likely to be much lower than projected as market forces would drive continued planting of high value, short-lived, multiple harvest annual crops (i.e., lettuce, kale, spinach). Despite these limitations, these scenarios projections do provide an understanding of the challenges facing the region if current trends persist and if water resources were unlimited, providing a baseline from which additional mitigation and management scenarios can be developed, to explore alternative potential futures.

4.2. Land Use and Water Use Sustainability Implications

Expansion of orchard and vineyard crops leads to the greatest increased water demand and most perennial crops require year-round watering. Given limited water supplies, regional growers have had to increasingly rely on advanced technology for watering vineyards, such as pressure chambers to detect water needs through leaf moisture, soil moisture probes, and groundwater moisture meters [88], as well as water recycling [89]. Implementation of the Sustainable Groundwater Management Act could also incentivize greater reductions on groundwater pumping by perennial growers or improved efficiencies.

Given the 20–30 year lifespan of most of specialty perennial crops, their resilience to a changing climate and shifting water availability is also limited [90]. Central Coast specialty crops show high sensitivity to changing temperature under future climate projections [91]. Specifically, wine grapes, strawberries, and lettuce—dominant crops in the Central Coast—had higher relative magnitude of negative impacts from increased temperatures of the top 14 value-ranked specialty crops in the state [91]. Yield declines have also been predicted with warmer winters and hotter summers [90].

However, agricultural intensification also has many other benefits and drawbacks. It often leads to (1) a higher investment and return per acre, (2) the creation of more jobs and demand for related support industry and housing, (3) the creation of more land use conflicts at the agriculture/urban interface, (4) technological innovation, and (5) improvements in irrigation efficiency [92]. These competing factors could influence a market-driven demand for improved water use efficiency.

New developed lands often generate additional water demand, potentially creating increased competition over ever-limited water resources. Well-drying and self-reported water supply shortages were already reported during the 2011–2016 drought and through 2019, and were highest in San Luis Obispo, with 201 reports submitted since 2014 [93]. By all accounts this represents only a small fraction of the total number households which likely experienced shortages, as vast under-reporting is suspected given limited outreach [93]. By contrast, where urban growth was projected to spread into existing cropland, such transitions were demand-neutral and sometimes even led to reduced overall water demand as seen in areas around the Monterey Bay and San Benito County. Such growth patterns conflict with the conservation of prime agricultural lands, a major goal of regional and state land management [94], and this conflict was also reported by stakeholders. Future development patterns over time may include urban redevelopment and infill with higher density which would preserve existing farmland. New upland regions in non-prime farmland could also be targeted for additional housing.

The region's disadvantaged communities may be least resilient in a water limited future. Between 2007 and 2015, California's median income fell by 6% between 2007 and 2015, while the average water bill, after adjusting for inflation, rose by 45% [95]. The combined pressures of climate variability, water quality, and aging infrastructure could potentially lead to further price increases, up to four times current rates in coming decades [96]. In addition, the increased frequency of atmospheric river events [25,39], could generate additional costs to improve storm water treatment infrastructure, which would likely be passed on to consumers [97,98]. Our scenario projections could help inform effective water resource management plans to balance projected LULC water demand with available supplies, preventing water insecurity and safeguarding communities from potential water shortages [99].

4.3. Assessment of Historic Policy Impacts

Between 1990–2006, over two–thirds of cities and counties in coastal California's metropolitan areas adopted policies explicitly aimed at limiting urban development by restricting housing growth [100]. Additionally, laws adopted between 1992–2001 required the demonstration of a sustainable water supply for new suburban and urban housing developments. Our projections showed a clear drop in rates of development following the passage of these laws, suggesting that they were effective. Our scenarios also illustrated that while likely limiting development, these policies were nevertheless unable to achieve long-term groundwater sustainability in the Central Coast. FMMP data was not available prior to 1992, and thus the impact of these laws on different LULC rates could not be directly assessed, but they did not prevent LULC from increasing water demand overall in overdrafted basins. Thus, the 1992–2001 water laws restricting urban development, while effective at slowing rates of urban growth, were unable to promote water sustainability because they did not impact the agricultural expansion, particularly of perennial crops.

Our results can be used to inform the development of groundwater sustainability plans by local groundwater sustainability agencies (Table 1) in critically overdrafted basins, as required under SGMA (AB 1739, SB 1168, and SB 1319, passed in 2014) [40]. Our results indicate the previous approach of regulating urban and suburban development is unlikely to address water demand challenges posed by the expansion of perennial agriculture. If perennial water demand projections continue to rise, then multi-pronged conservation and technology implementation strategies will likely be needed to avoid continued groundwater depletion and to meet the sustainability goals outlined in SGMA [46–48].

4.4. Future Directions

Additional scenario development, which includes continued feedback from local and regional stakeholders, including individual land holder and farmers, will be needed to test alternative regional mitigation strategies and their associated outcome on water demand change. Projections of future land change and water demand would also greatly benefit from more advanced, fully coupled modeling approaches, involving climate-driven hydrological models and the LUCAS land change model. Such an integrated system would facilitate more informed, process-based interactions and dynamic feedbacks between models during a model run, between timesteps and iterations. This would enable the direct utilization of established climate projections with hydrologic modeling to examine human-environment system feedbacks and stressors. The LUCAS framework is already based on the open source ST-SIM model platform [60], which includes a module to facilitate information passing between integrated systems using a Python or R code interface [101]. Such an approach could include more accurate, process-based analysis of cropland water demand, a more detailed cropland classification scheme, and could serve to identify couplings between human land-use related water demand and climate forced changes to the regional hydrologic system.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/9/9/322/s1, Table S1: List of Groundwater Sub-Basins, Table S2: List of water districts and groundwater sustainability agencies, Table S3: Spatial datasets and zoning categories used in land use and land cover transition spatial multipliers, Table S4: Comparison of historical land use and land cover empirical data (2001–2016) with mean modeled results for the same time period, Table S5: Comparison of modeled regional water demand and historical water use data in 2005 and 2010 for model validation.

Author Contributions: Conceptualization, T.S.W., N.D.V.S., and R.L., methodology, T.S.W.; software, T.S.W.; validation, T.S.W. and N.D.V.S.; formal analysis, T.S.W. and N.D.V.S.; investigation, T.S.W. and N.D.V.S.; resources, T.S.W., N.D.V.S., and R.L.; data curation, T.S.W.; writing—Original draft preparation, T.S.W.; writing—Review and editing, T.S.W., N.D.V.S., and R.L.; visualization, T.S.W. and N.D.V.S.; supervision, T.S.W.; project administration, T.S.W. and R.L.; funding acquisition, R.L and T.S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the California Strategic Growth Council Climate Change Research Program Grant # CCRP0023 and the U.S. Geological Survey's Climate and Land Use Research Program.

Acknowledgments: We are grateful for the detailed and thoughtful internal peer review provided by Paul Selmants as well as our anonymous peer reviewers. All modeling for this study was done using the ST-SIM software application which can be downloaded, free of charge, from APEX Resource Management Solutions (http://apexrms.com). All model parameters are available as (1) a Microsoft Excel file and (2) a database containing all model inputs and outputs (http://geography.wr.usgs.gov/LUCC/) and in the U.S. Geological Survey's ScienceBase catalog (https://www.sciencebase.gov/catalog/item/5e5e9d53e4b01d5092513ccf). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This work supports research objectives outlined by the California Strategic Growth Council and also directly aligns with the U.S. Department of the Interior's (DOI) Strategic Plan to conserve our land and water by utilizing water science to support decisions and activities and to help better manage water storage and delivery to resolve conflicts and expand capacity. Additionally, this work supports the DOI goal to ensure emergency preparedness by providing science to safeguard communities from natural hazards including water shortages and drought. This work also supports directives from the (1) U.S. National Intelligence Community which identifies water stress as a potential driver of regional insecurity and social unrest and (2) U.S. Department of Homeland Security which places managing regional water loss, natural disasters impacting available water quantity, and the lack of recognition of the water sector as a "lifeline sector" as the Most Significant Risk to water infrastructure.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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