In the Hawaiian Islands, planners and public officials have decided recently to raise the permissible level of urban development in central Oahu. The decision is opposed by many on the grounds that it threatens agricultural land as well as the sustainability of aquifers. A two-part procedure is presented for exploring the impact of such development and designing urban-expansion patterns that minimize them. First, a water-balance simulation model is used to calculate groundwater recharge as it varies with land use and location within the area. The difference between recharge and withdrawal is computed, and any changes are then estimated for different land uses. Second, this information is incorporated into multiobjective programming models with objectives related to agricultural land retention, groundwater balance, and residential population growth. The models generate alternative land-use expansion plans and show the tradeoffs among the objectives. The consideration of slightly suboptimal (dominated) solutions allows a significant expansion in the range of such alternatives. The results suggest that if future agricultural development does not occur on currently nonagricultural land, then both agricultural land and groundwater sustainability will suffer significant adverse effects under the new population limits.
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URBANIZATION, LAND-USE PLANNING, AND GROUNDWATER MANAGEMENT IN CENTRAL O'AHU, HAWAI'I

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ABSTRACT

In the Hawaiian Islands, planners and public officials have decided recently to raise the permissible level of urban development in central O'ahu. The decision is opposed by many on the grounds that it threatens agricultural land as well as the sustainability of aquifers. A two-part procedure is presented for exploring the impact of such development and designing urban-expansion patterns that minimize them. First, a water-balance simulation model is used to calculate groundwater recharge as it varies with land use and location within the area. The difference between recharge and withdrawal is computed, and any changes are then estimated for different land uses. Second, this information is incorporated into multiobjective programming models with objectives related to agricultural land retention, groundwater balance, and residential population growth. The models generate alternative land-use expansion plans and show the tradeoffs among the objectives. The consideration of slightly suboptimal (dominated) solutions allows a significant expansion in the range of such alternatives. The results suggest that if future agricultural development does not occur on currently nonagricultural land, then both agricultural land and groundwater sustainability will suffer significant adverse effects under the new population limits.
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</tbody>
</table>
INTRODUCTION

Land and fresh water are two commodities often in short supply on small tropical islands, a situation of pivotal concern to residents of O'ahu, the most populous of the Hawaiian Islands. Now experiencing a severe housing shortage, O'ahu's population is projected to grow by some 165,000 people over the next twenty years—a 20% increase—so planners and public officials must decide how best to accommodate this increase. Reflecting many different considerations, the Oahu General Plan was amended in early 1989 to reduce population ceilings in the Primary Urban Area, which stretches from Pearl City to Honolulu, while substantially raising the limits for the 'Ewa plain and central O'ahu (Fig. 1). Under this plan, these three areas will absorb about 85% of the expected growth. Given a major initiative to develop a new town in 'Ewa, little disagreement exists over the new ceiling for that area. The increased allocation to central O'ahu, however, is far more controversial.

The decision to open up central O'ahu to new urban development is a major departure from the strategy set forth in the previous General Plan, which set low limits on development in order to preserve prime agricultural land and maintain the area's rural character. Despite this policy, central O'ahu has been the island's greatest growth area during the past twenty years (Kresnak 1989), to the extent that the prescribed development capacity was eventually exhausted and a number of proposed developments were put on hold. The threat to agriculture and open space, the increased traffic and congestion, and the high cost of land and infrastructure development accompanying this growth were seen as reasons for directing further urban development toward the 'Ewa plain. These concerns continue to be voiced by those opposed to the new General Plan.

Another concern is water, which, in discussions of the island's "carrying capacity," is often viewed as the most significant determinant. Groundwater is the source for about 92% of O'ahu's water use, with the aquifers of the Pearl Harbor Groundwater Control Area (PHGWCA) providing water to central O'ahu and other districts (Board of Water Supply 1982). Despite a reduction in sugarcane cultivation that began in the late 1970s, and the increasing replacement of furrow irrigation by drip irrigation, rapidly growing municipal demands in tandem with drought conditions throughout most of the 1980s have meant that allocated withdrawal rights for the Pearl Harbor basin are close to, if not already exceeding, the aquifers' sustainable yields (Yuen and Associates 1988).

It was within this context that the City and County of Honolulu Planning Commission decided to raise population limits in central O'ahu. In the end, the pressure to free up land for housing outweighed desires to preserve agricultural land and minimize further demand for groundwater.
To understand the implications of this decision, one needs to know how urban development affects groundwater and agricultural land. This is a complex question because the basinwide water balance, and hence groundwater levels, are affected not only by land use and irrigation regimes but also by their specific locations within the basin. This latter factor is critical since precipitation and evapotranspiration vary greatly there. The effects upon groundwater recharge brought about by changes in land use and irrigation technology in one place may be quite different from those of similar changes elsewhere. Any assessment of hydrological impacts must therefore focus on the spatial pattern of land-use changes within the area. Furthermore, since the net effect of different land-use patterns upon groundwater and total agricultural land consumption may be similar, it follows that there may exist a variety of plans that are equally attractive vis-à-vis these concerns.

Is water really a constraint on the further urbanization of central O'ahu, and if so, how severe a constraint is it? What spatial pattern(s) of urban growth would be most desirable with respect to groundwater and agricultural land preservation, and how much flexibility would planners have in fashioning a preferred pattern? This paper presents a two-step approach to answering these questions. First, a water-balance simulation model is used to estimate the site-specific hydrological effects of changes in land use and irrigation technology. Second, these effects are integrated with other land-use concerns in a multiobjective programming model that can show the tradeoffs among the above-mentioned concerns and formulate a wide variety of different plans.
REGIONAL HYDROLOGY

Open-ocean rainfall in the vicinity of the Hawaiian Islands is estimated to be approximately 600 mm/yr (Elliott and Reed 1984). Because of the orographic and thermal effects of the land, rainfall on the islands ranges from 250 to 11 000 mm/yr, depending on location. Steep gradients in rainfall coincide with persistent orographic clouds anchored to topographic barriers. Solar radiation, temperature, and evaporation also exhibit high spatial variability related to topographic relief. On O‘ahu, high rainfall and low evaporation along the Ko‘olau mountain crest produce a substantial water surplus, most of which percolates through the porous soil and rock and recharges underlying aquifers. Leeward of the Ko‘olau, rainfall diminishes rapidly. The rates of the resulting natural recharge within the Pearl Harbor basin range from more than 4 000 mm/yr along the Ko‘olau crest at the northeast corner of the basin to less than 100 mm/yr along the leeward coastline (Giambelluca 1986).

Land-Use Impacts on Hydrology

Agricultural and urban land uses in the Pearl Harbor basin greatly affect recharge rates by altering runoff and evaporation and by adding irrigation. Furrow irrigation was the dominant technology in sugarcane cultivation until the late 1970s, when most fields in the basin were converted to drip-irrigation systems. In furrow irrigation, applied water typically reached 3 m annually. The conversion to drip irrigation increased the amount of water used by the crop while reducing both irrigation requirements and recharge rate. King (1988) found that conversion to drip irrigation increased sugarcane evapotranspiration by an average of 18% and reduced recharge by 55%. For the two plantations studied, water used for irrigation decreased by an average of 32%.

The pineapple crop in Hawai‘i has a much lower water requirement than sugarcane. Ekern (1965) showed that under optimal conditions, a pineapple crop uses an average of about 20% the amount of water that a sugarcane crop uses. As a result, groundwater recharge is enhanced under pineapple cultivation. Until the recent introduction of drip irrigation in some fields, very little irrigation was applied; drip-irrigated pineapple fields now receive about 300 mm/yr.

The most obvious effect of urbanization on the water balance is the increase in surface runoff. Medium-density residential land in central O‘ahu (precipitation of 1 000 mm/yr) was estimated to produce about 2.6 times the runoff of undeveloped land (Giambelluca 1986), while high-density urbanization produced 4.2 times the undeveloped land runoff. Substantial amounts of irrigation are applied as residential lawn watering and golf-course sprinkling.
Paved surfaces reduce the evaporative surface area and tend to focus rainfall into smaller areas. The result is that urbanization may either decrease or (as in the drier areas of O‘ahu) increase groundwater recharge. Model results for central O‘ahu indicate that reduction of evaporation generally exceeds the increase in surface runoff, so that recharge is greater for urbanized surfaces than for undeveloped surfaces, and recharge generally increases with the level of urbanization (Giambelluca 1986).

**Net Groundwater Effects of Land-Use Conversions**

For the purposes of this study, a portion of the Pearl Harbor basin was selected and subdivided into seven zones (Fig. 2). The study area was one in which agricultural land uses, principally sugarcane and pineapple cultivation, are rapidly giving way to urbanization.

The regional subdivision for this study was done on the basis of natural landscape divisions: steep-sided stream gulches separating relatively flat land fit for cultivation or urban development. Other boundaries were imposed on the basis of current land use and climate. For these seven zones, the net impacts on groundwater availability of possible land-use conversions were estimated by calculating approximate groundwater recharge and water use associated with each land use and zone.

Groundwater recharge was estimated for nine land-use categories and seven regional subdivisions using a water-balance simulation model. The model was a variant of the Thornthwaite procedure (Thornthwaite and Mather 1955), as modified by Giambelluca (1986). In the model, inputs into the soil-plant system, precipitation, and irrigation were monitored. Runoff was estimated from stream-flow data and from values derived using the U.S. Soil Conservation Service (1972) runoff-curve-number method. Evapotranspiration and recharge were determined on the basis of potential evapotranspiration and the model’s running estimate of soil water content. Precipitation was determined using measurements from a dense network of gages. Irrigation for various agricultural and urban land uses was estimated from a variety of information sources, including plantation irrigation records, water-use data, and personal communication. For urban uses, a single rate was assigned to each land use. For furrow- and drip-irrigated sugarcane, spatial variation in irrigation was recognized. The water-balance simulation was run using a historical, 30-yr climate record. Separate runs were made of each zone and land-use type. Simulated groundwater recharge rates for each land use and zone are given in Table 1.

Each of the major land-use types found in central O‘ahu has an associated water demand. Based on irrigation estimates and residential and commercial water-use figures, water demand associated with each land use and zone was estimated for this study (Table 2). Groundwater-
recharge and water-demand values given in Tables 1 and 2 were used to compute the net groundwater effects of each land-use conversion.

**PROGRAMMING LAND-USE CHANGES**

Further urban development in central O'ahu will not only affect the water balance in the PHGWCA, it will undoubtedly occur at the expense of agricultural land and open space. To design patterns of land-use change that would best accommodate population growth, groundwater management, and preservation of agricultural land, an optimization-based approach was adopted. Since much uncertainty surrounds the aquifers' sustainable yields, preferred population ceilings, and the amount of land that should be retained for agricultural use, the objective of the modelling effort was to generate a range of patterns that could inform planning strategies rather than to identify the “best” one.

What follows is a two-stage modelling approach. The object of the first stage is to represent in as general a way as possible fundamental physical relationships that we feel to be of primary relevance to the issues of population, land use, and water, as presented above. We follow
### TABLE 1. GROUNDWATER RECHARGE AS A FUNCTION OF LAND USE AND ZONE

<table>
<thead>
<tr>
<th>LAND USE</th>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Low Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial &amp; Industrial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parks &amp; Golf Course</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Furrow Irrigation</td>
<td></td>
<td>127</td>
<td>394</td>
<td>270</td>
<td>437</td>
<td>232</td>
<td>322</td>
<td></td>
</tr>
<tr>
<td>Drip Irrigation</td>
<td></td>
<td>301</td>
<td>526</td>
<td>362</td>
<td>571</td>
<td>320</td>
<td>443</td>
<td></td>
</tr>
<tr>
<td>Pineapple</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Irrigation</td>
<td></td>
<td>393</td>
<td>586</td>
<td>444</td>
<td>630</td>
<td>401</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Drip Irrigation</td>
<td></td>
<td>233</td>
<td>413</td>
<td>278</td>
<td>457</td>
<td>237</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td>Vacant/Grazing/Forest</td>
<td></td>
<td>194</td>
<td>231</td>
<td>152</td>
<td>268</td>
<td>143</td>
<td>177</td>
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</tbody>
</table>

### TABLE 2. WATER DEMAND AS A FUNCTION OF LAND USE AND ZONE

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<tr>
<th>LAND USE</th>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Density*</td>
<td></td>
<td>895</td>
<td>895</td>
<td>895</td>
<td>895</td>
<td>895</td>
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<td>895</td>
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<tr>
<td>Medium Density*</td>
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<td>1169</td>
<td>1169</td>
<td>1169</td>
<td>1169</td>
<td>1169</td>
<td>1169</td>
<td>1169</td>
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<tr>
<td>Commercial &amp; Industrial†</td>
<td></td>
<td>1027</td>
<td>1027</td>
<td>1027</td>
<td>1027</td>
<td>1027</td>
<td>1027</td>
<td>1027</td>
</tr>
<tr>
<td>Parks &amp; Golf Course</td>
<td></td>
<td>317</td>
<td>317</td>
<td>317</td>
<td>317</td>
<td>317</td>
<td>317</td>
<td>317</td>
</tr>
<tr>
<td>Sugar</td>
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<td></td>
<td></td>
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<td></td>
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<td>Furrow Irrigation</td>
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<td>2168</td>
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<td>2486</td>
<td>2689</td>
<td>2458</td>
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<tr>
<td>Drip Irrigation</td>
<td></td>
<td>1576</td>
<td>1879</td>
<td>1524</td>
<td>1794</td>
<td>1479</td>
<td>1849</td>
<td>1554</td>
</tr>
<tr>
<td>Pineapple</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>0</td>
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<td>0</td>
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</tr>
<tr>
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<td>305</td>
</tr>
<tr>
<td>Vacant/Grazing/Forest</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Consumption rates for low-density residential land were computed using the rate of 425 gal/unit/day, based on data for single-family residences; rates for medium-density residential land were based on the rate of 230 gal/unit/day, corresponding to data for multifamily residences (Board of Water Supply 1982).

†Commercial water consumption was based on a design criterion of 3000 gal/acre/day = 21 m³/1000 m²/day.

Ignizio (1982) in terming the result the "baseline" model. In the second stage, the "operational" phase, we deal with the practical difficulties faced in solving the baseline model, including the need to provide preference and other judgmental information.
TABLE 3. LAND-USE TRANSITIONS CONSIDERED IN PROGRAMMING MODELS I-IV

<table>
<thead>
<tr>
<th>FROM LAND USE (Zone No.)</th>
<th>TO LAND USE</th>
<th>SF</th>
<th>SD</th>
<th>PN</th>
<th>PD</th>
<th>PG</th>
<th>VG</th>
<th>RL</th>
<th>RM</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF (2,6)</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>SD (2,4,6,7)</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>PN (2,3,4,5)</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>PD (7)</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>PG (1,4,5)</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
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<tr>
<td>VG (1,2,3,5,6,7)</td>
<td></td>
<td>*</td>
<td>*</td>
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<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
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<td>*</td>
</tr>
</tbody>
</table>

Note: SF = Furrow-irrigated sugar  PD = Drip-irrigated pineapple  RL = Low-density residential
SD = Drip-irrigated sugar  PG = Park/Golf Course  RM = Medium-density residential
PN = Nonirrigated pineapple  VG = Vacant/Grazing/Forest  CI = Commercial and industrial.

Optimal Land-Use Configurations

The following vector optimization problem was formulated as the baseline model. Let $x_{ijk}$ be the amount of land ($m^2 \times 10^3$) to change from use $i$ to use $j$ in zone $k$. These variables correspond to the transitions shown in Table 3. We then wish to find $x$, the set of values for $x_{ijk}$ that optimizes $z = [z_1, z_2, z_3]$, where

1. $z_1 = AGCONV$ (conversion of agricultural land [ha])
2. $z_2 = NETGW$ (net change in groundwater recharge minus withdrawal [gal/d $\times 10^3$])
3. $z_3 = NEWPOP$ (new population to be accommodated)

subject to:

1. All land accounted for and supply not exceeded:
   \[ \sum_{j} x_{ijk} = L_{i,k} \text{ for all } i,k \]  (4)
   where $L_{i,k}$ is the amount of land currently under use $i$ in zone $k$.

2. Computing the net change in recharge with a change in land use:
   \[ \sum_{ijk} r_{ijk} x_{ijk} - MORERCHG + LESSRCHG = 0 \]  (5)
   where $r_{ijk}$ is the net change (mm/yr) and MORERCHG and LESSRCHG are, respectively, the net increase and decrease (m$^3$/yr).

3. Computing net rise (m$^3$/yr) in residential water use (RESWAT):
   \[ \sum_{ik} (w_1 x_{i7k} + w_2 x_{ijk}) - RESWAT = 0 \]  (6)
   where $w_1$ is the use (m$^3$/yr) per unit of low-density residential land (type 7 use) and $w_2$ the use per unit of medium-density residential land (type 8 use).
4. Computing net rise (m³/yr) in commercial water use (COMWAT):

\[ \sum_{ik} c x_{ijk} - \text{COMWAT} = 0, \]  

(7)

where \( c \) is the use (m³/yr) per unit of new commercial land (type 9 use).

5. Computing net change in irrigation (m³/yr):

\[ \sum_{ijk} t_{ijk} x_{ijk} - \text{MOREIRR} + \text{LESSIRR} = 0, \]  

(8)

where \( t_{ijk} \) is the net change (mm/yr) per unit of land change \( ijk \), and \( \text{MOREIRR} \) and \( \text{LESSIRR} \) the cumulative net increase and decrease in irrigation (m³/yr), respectively.

6. Computing total net change (gal/d × 10³) in groundwater recharge minus withdrawal (NETGW):

\[ [(0.724)(\text{MORERCHG} + \text{LESSIRR} - \text{LESSRCHG} - \text{MOREIRR} - \text{COMWAT} - \text{RESWAT})] - 1000 \text{NETGW} = 0. \]  

(9)

7. Calculating conversion of agricultural land (AGCONV):

\[ \sum_{ijk} x_{ijk} - 10 \text{AGCONV} = 0, \]  

(10)

where \( i \) is an agricultural use, \( j \) nonagricultural.

8. Calculating total population increase (NEWPOP):

\[ \sum_{ik} (p_1 x_{i7k} + p_2 x_{i8k}) - \text{NEWPOP} = 0, \]  

(11)

where \( p_1 \) and \( p_2 \) are, respectively, the average number of people per unit of low-density and medium-density residential land.

9. Calculating the amount (ha) of new commercial and industrial land (COMLAND):

\[ \sum_{ijk} x_{ijk} - 10 \text{COMLAND} = 0, \]  

(12)

where \( i \) is noncommercial land and \( j \) commercial.

10. Calculating the amount (ha) (LANDRL) and medium-density (LANDRM) residential land:

\[ \sum_{ik} x_{i7k} - 10 \text{LANDRL} = 0 \]  

(13)

\[ \sum_{ik} x_{i8k} - 10 \text{LANDRM} = 0. \]  

(14)

11. Calculating additional commercial and industrial land required to accompany residential development:

\[ \text{COMLAND} - m_1 \text{LANDRL} - m_2 \text{LANDRM} \geq 0, \]  

(15)

where \( m_1 \) and \( m_2 \) represent multiplier effects.
Reliable data on multiplier effects were not available when this study was done. Further, given patterns of commuting and shopping, one cannot say where such commercial land would naturally be developed (i.e., if no locational constraints were operating) in response to additional residential land development. This makes problematic the computation of such multipliers for particular subareas of O'ahu. In addition, the number of additional residents most likely must cross some minimum threshold before additional commercial land development is triggered.

Despite these problems, possible multiplier effects must be addressed and incorporated in such a model. One solution was to use plausible values exhibited in empirical cases: based on the then-proposed Waiawa development, we let \( m_1 \) and \( m_2 \) equal 0.1 and 0.2, respectively. We noted in doing so that locational constraints are abundant and severe, many deriving from zoning and other planning regulations, and that insofar as such regulations require certain percentages of commercial land to accompany new residential development, they reflect or are informed by multiplier effects believed to be operative. For simplicity, as well as for lack of data, we chose to ignore threshold effects. This allowed the entire model to remain linear. However, it is easy and straightforward to represent minimal thresholds by using a binary variable in the manner employed to model constraints on minimum batch size (e.g., see Wagner 1975). Similarly, other values could be used as desired.

This baseline model is a multiobjective land-allocation model that differs from baseline single-objective models in important ways. Most obviously, it assumes that people judge the attractiveness of a given land-use pattern along various dimensions, with no single one able to supplant or represent all others. In the case at hand, this means that, for at least some people, knowing the effect upon water of a particular land-use change will not by itself enable an adequate appraisal of that change; information on the consequences for population accommodation and agricultural land use would also matter. In contrast, single-objective models assume that people would happily base their appraisals on only a single criterion. Consequently, the builders of such models must decide the criterion to optimize. That decision may be made by (1) selecting, with varying degrees of arbitrariness, one criterion from those that have been proposed; (2) formulating or selecting a criterion that reflects a particular theory or normative principle, such as the net economic benefits criterion often favored by economists; or (3) using a criterion that reflects the preferences of a given decision maker, analyst, or other party interested in the issue. In all cases, the other candidate objectives are treated as constraints, merely monitored as state (accounting) variables, or ignored altogether.

Common examples of the single-objective approach are models that strive to maximize some measure of output, such as production or revenue, subject to availability of resources, two of which may be land and water. In such representations, resources are considered to be
only means to an end; they have no value other than that of their contribution to the maximal attainment of the (single) objective. As such, there is no acceptable tradeoff between resources conserved and the further attainment of the objective; there is no limit to the amount of resources used to achieve an additional unit of output.

The distinction between multiobjective and single-objective philosophies can also appear in the operational model. (Of course, where the baseline model is single-objective, the operational one will be too, and the baseline-operational distinction disappears altogether. This is invariably true in conventional linear programming, but exceptions may occur in nonlinear, integer, and combinatorial programming, where analytical or computational challenges can often be confronted in a variety of tactical ways.) The conflicts between the objectives in the multiobjective case can be dealt with operationally in two principal ways. One approach is to construct a multidimensional function that incorporates all the relevant criteria as well as the relative preference for, or importance of, each one. Such a function is often called a (multiattribute) utility or value function, the construction and properties of which are based on utility or value theory (Keeney and Raiffa 1976; von Winterfeldt and Edwards 1986). Other approaches reflect the view that such a function is in practice difficult and time-consuming to formulate (Saaty 1990), may not be unique, and may not even exist for a single person (e.g., the decision maker), let alone for a group (Zeleny 1982). In this second set of approaches, various tacks are available (Cohon 1978; Steuer 1986). Three common ones are: (1) setting targets for each objective and minimizing the deviation from them; (2) optimizing one objective while relegating the others to the constraint set; and (3) optimizing the weighted sum of the objectives. Although this last method also involves constructing a superobjective, it differs from the utility-function approach in that the weighted-sum objective is used only to generate nondominated candidate solutions and is not postulated to represent the overall utility (attractiveness) of any particular one. In a similar spirit, the second method treats objectives as constraints also for the purpose of generating nondominated solutions; in so doing, it is not subordinating those objectives to the one appearing in the criterion function.

The approach taken here is multiobjective in both the baseline and the operational models. It seems clear that none of the three concerns identified above clearly and unequivocally dominates the others. Nor does it appear that one can use any normative theory to formulate a single criterion function that would accurately reflect society's preferences regarding these three issues. For example, given the poor data presently available and the known deficiencies of prices as measures of public preference as well as of resource scarcity (Nijkamp 1977; Pearce and Turner 1990), an economic production function would be a poor choice for such a single-objective function; likewise, the construction of a utility function begs the question of whose utility is being represented and inevitably leads to the analytically awesome (if at all possible)
and pragmatically impossible task of building a group utility function. Finally, the multiple-stakeholder nature of public planning, and the negotiation and bargaining that arise out of it, suggest clearly the hazards of selecting a single-objective function on the basis of a single party's (e.g., the analyst's) interest—even assuming that such a party has but one interest.

MODEL I. Two factors were important in developing an operational model of equations (1) to (15). First, the relative importance of each objective could not be determined a priori due to the highly politicized nature of land development on O'ahu and the uncertainty of the levels at which the three objectives might be attained. Second, notwithstanding this uncertainty, it was clear that the problem was neither to maximize nor minimize \( Z_2 \) (NETGW) or \( Z_3 \) (NEWPOP), but rather to aim for desirable, and yet unknown, targets; minimization would only make sense with respect to \( Z_1 \) (AGCONV). In conjunction with the need to identify a variety of land-use patterns, these considerations suggested a generating approach, where \( Z_2 \) and \( Z_3 \) would be constrained to meet certain minimum values. Thus, the baseline model became Model I:

\[
\begin{align*}
\text{min } & \quad Z_1 = \text{AGCONV} \\
\text{s.t. } & \quad Z_2 = \text{NETGW} \geq L_2 \\
& \quad Z_3 = \text{NEWPOP} \geq L_3 \\
& \quad x \in F,
\end{align*}
\]

where (1-4) simply denotes the feasibility constraint set (eqq. [4]–[15]).

As a first step, a payoff table (Table 4) was developed to give an idea of the range of values each objective could attain. The table suggests that satisfactory levels of AGCONV and NEWPOP might well be attainable without lowering groundwater heads significantly; indeed, it would seem possible even to augment groundwater storage.

Systematically varying the values of \( L_2 \) and \( L_3 \) over the ranges shown in their respective columns of the payoff table (Table 4) will generate a variety of solutions to Model I. When \( Z_2 \) and \( Z_3 \) are binding, the solutions will be nondominated (Cohon 1978). Many values within these ranges, however, would be unrealistic vis-à-vis the planning problem, so information in the General Plan and other sources was used to narrow the range of values and thus identify plausible solutions.

Two pieces of information were particularly pertinent. First, the Oahu General Plan was recently revised to allow a population increase of 41 000 people in the central O'ahu planning district (Kresnak 1989), markedly greater than the previous allowable increase of 11 500. With frequent and vociferous cries to maintain the original ceiling, the amendment still faces considerable opposition. Second, a recent reappraisal of the PHGWCA's sustainable yield (Table 5) resulted in a reduction from its 1985 level of 208 mgd to 181 mgd (Yuen and
TABLE 4. PAYOFF TABLE FOR THREE OBJECTIVES

<table>
<thead>
<tr>
<th>OPTIMIZED OBJECTIVE</th>
<th>AGCONV (ha)</th>
<th>NETGW (mgd)</th>
<th>NEWPOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_1$: AGCONV</td>
<td>145.2</td>
<td>-25.3</td>
<td>109 342</td>
</tr>
<tr>
<td>$z_2$: NETGW</td>
<td>2 345.2</td>
<td>13.0</td>
<td>7 404</td>
</tr>
<tr>
<td>$z_3$: NEWPOP</td>
<td>5 353.1</td>
<td>-136.8</td>
<td>686 715</td>
</tr>
</tbody>
</table>

TABLE 5. GROUNDWATER ALLOCATION, USE, AND SUSTAINABLE YIELD IN PEARL HARBOR GROUNDWATER CONTROL AREA

<table>
<thead>
<tr>
<th>Authorized Total Draft</th>
<th>Koolau Aquifer (mgd)</th>
<th>Waianae Aquifer (mgd)</th>
<th>Total (mgd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Draft (983–986)</td>
<td>184</td>
<td>20</td>
<td>204</td>
</tr>
<tr>
<td>Sustainable Yield</td>
<td>164</td>
<td>17</td>
<td>181</td>
</tr>
<tr>
<td>Sustainable Authorized</td>
<td>-20</td>
<td>-3</td>
<td>-23</td>
</tr>
<tr>
<td>Current Use</td>
<td>15</td>
<td>2</td>
<td>17</td>
</tr>
</tbody>
</table>


Using the new estimate, sustainable yield is calculated to be 23 mgd short of the withdrawals already authorized, although it exceeds actual use by 17 mgd (Yuen and Associates 1988). Thus, a relatively conservative strategy would be to keep the difference between recharge and withdrawal at current levels, pending additional information on the exercise of use rights and corroboration of sustainable-yield estimates. Although political and hydrogeologic uncertainty renders these figures tentative, they do suggest reasonable values for $L_2$ and $L_3$, thus narrowing the search for plausible solutions.

With these assumptions, (I-2) and (I-3) become

$$z_2 : \text{NETGW} \geq 0$$  \hspace{1cm} (I-2a)
$$z_3 : 11 500 \leq \text{NEWPOP} \leq 60 000$$ \hspace{1cm} (I-3a)

The range of $L_3$ values corresponds to the uncertainty of allowable population growth. Solving Model I-A, the modified version of Model I, we can identify a range of different solutions and elucidate tradeoffs between agricultural land conversion and population growth. Nondominated solutions correspond to those where $37 938 \leq \text{NEWPOP} \leq 60 000$, with the tradeoff being constant throughout almost the entire range.

The population limit allowed under the amended General Plan was taken as the most likely case, and the solution obtained when $\text{NEWPOP} \geq 40 000$ (from Model I-A) was examined further (Table 6). The minimum AGCONV value would be 216.6 ha, and the additional
TABLE 6. SELECTED CHARACTERISTICS OF OPTIMAL SOLUTION TO MODEL I-A AND OF FIVE SOLUTIONS GENERATED BY MODEL IV

<table>
<thead>
<tr>
<th>Solution</th>
<th>AGCONV (ha)</th>
<th>NETGW (mgd)</th>
<th>NEWPOP</th>
<th>LANDRL (ha)</th>
<th>LANDRM (ha)</th>
<th>MOREGOLF (ha)</th>
<th>Sum PNPD (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fig. 3.1</td>
<td>216.6</td>
<td>0</td>
<td>40 000</td>
<td>0</td>
<td>331</td>
<td>101</td>
<td>857</td>
</tr>
<tr>
<td>Suboptimal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fig. 3.2</td>
<td>227.0</td>
<td>-1</td>
<td>38 000</td>
<td>0</td>
<td>314</td>
<td>209</td>
<td>0</td>
</tr>
<tr>
<td>Fig. 3.3</td>
<td>227.0</td>
<td>-1</td>
<td>38 000</td>
<td>255</td>
<td>190</td>
<td>127</td>
<td>544</td>
</tr>
<tr>
<td>Fig. 3.4</td>
<td>227.0</td>
<td>-1</td>
<td>38 000</td>
<td>67</td>
<td>281</td>
<td>104</td>
<td>179</td>
</tr>
<tr>
<td>Fig. 3.5</td>
<td>227.0</td>
<td>-1</td>
<td>38 000</td>
<td>76</td>
<td>277</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>Fig. 3.6</td>
<td>227.0</td>
<td>-1</td>
<td>38 000</td>
<td>0</td>
<td>314</td>
<td>104</td>
<td>0</td>
</tr>
</tbody>
</table>

NOTE: LANDRL = additional land for low-density residential
LANDRM = additional land for medium-density residential
MOREGOLF = additional land for parks and golf courses
Sum PNPD = total land being converted from nonirrigated pineapple to drip-irrigated pineapple.

population would be accommodated entirely in medium-density development in zones 2 and 6 (Fig. 3.1). Except with the conversion of 6 ha of nonirrigated pineapple land to commercial use in zone 5, in this model loss of agricultural land always occurs at the expense of sugarcane.

The existence of 16 nonbasic land-use-transition variables with zero reduced costs indicated the existence of alternate optima. When fashioning plans to satisfy a variety of stakeholders, alternate and highly distinct optima are clearly important. One way to identify such varied optima is first to discover all corresponding extreme-point solutions, and then, since each solution is a vector of decision-variable values, select from these a subset that are distant from each other in decision space. Unfortunately, identifying all optimal extreme points is very difficult and requires a special code. Steuer discusses the problem, describes an algorithm to find such solutions, and provides a code (ADBASE) that is also capable of filtering the set of optima to identify the maximally varied subset (Steuer 1986, 1989).

The method used here does not require a special code and was motivated by the “Hop, Skip, and Jump” (HSJ) procedure developed by Brill, Chang, and Hopkins (1982) as a means of identifying significantly different suboptimal solutions. In the following two models, the HSJ method was adapted to search for radically different optima.

MODEL II. The parameters and values of Model II were as follows:

\[
\begin{align*}
\text{max } \sum_{n} x_n \\
\text{s.t. } x \in F \\
z_1 : \text{AGCONV} \leq 216.6 \\
z_2 : \text{NETGW} \geq 0
\end{align*}
\]
3.1. Optimal distribution of new residential population of 40,000

3.2. Suboptimal distribution of new residential population of 38,000: Pattern 1

Figure 3. Alternative patterns of residential expansion under limit of 40,000 new residents
3.3. Suboptimal distribution of new residential population of 38,000: Pattern 2

3.4. Suboptimal distribution of new residential population of 38,000: Pattern 3
3.5. Suboptimal distribution of new residential population of 38,000: Pattern 4

3.6. Suboptimal distribution of new residential population of 38,000: Pattern 5
\[ z_3 : \text{NEWPOP} \leq 40\,000 \]

\[ x_n \in N, N \subseteq \{x_{ijk} \text{ nonbasic with zero reduced costs at optimality} \}. \]

Although a very large number of combinations of \( x_n \) can be identified and used to define different objective functions, only five were explored. Each set contained only those \( x_n \) corresponding to new residential development in zones 1, 3, 4, 5, or 7, that is, in areas not previously assigned such transitions. An alternative to attempting to drive currently nonbasic transitions into solution is to try to force some of the nonzero assignments out of the currently optimal basis. This was attempted with Model III, where the basic variables in question were those representing residential expansion into zones 2 and 6.

**MODEL III.** The parameters and values of Model III were as follows:

\[
\begin{align*}
\text{min} & \quad \sum_b x_b \\
\text{s.t.} & \quad x \in F \\
& \quad z_1 : \text{AGCONV} \leq 216.6 \\
& \quad z_2 : \text{NETGW} \geq 0 \\
& \quad z_3 : \text{NEWPOP} \geq 40\,000 \\
& \quad x_b \in B, B \subseteq \{x_{ijk} \text{ basic at optimality} \}.
\end{align*}
\]

Although in this application 5 new land-use-transition variables (out of 29 basic ones) came into solution in every case, residential development showed negligible differences: zone 2 received almost 38% of the population, zone 6 received 62%, and a few individuals were assigned variously to the other zones. No residential development was ever allocated to zone 5, and the total amount of land being converted to residential use was invariant at 330 ha, the entirety always at medium density. However, whereas under the initial optimal plan (Model I-B) much of the nonirrigated pineapple land would have to become drip irrigated, several of the new solutions did not require such a change. Clearly, such a qualitative difference potentially is of great importance.

**Suboptimal Land-Use Configurations**

The solutions examined so far are Pareto optimal with respect to the baseline model. It may be useful, however, intentionally to consider plans that are suboptimal if in so doing a wider range of solutions can be identified (Brill, Chang, and Hopkins 1982; Chang, Brill, and Hopkins 1982; Harrington and Gidley 1985). If slightly degrading a nondominated solution leads to a plan that is nearly as good with respect to objective attainment and yet far more acceptable (e.g., implementable), the tradeoff might well be worth considering.
MODEL IV. The HSJ approach was employed to generate such nearly optimal solutions as those just described. A new model, Model IV, was formulated by loosening the constraints on objective attainment in Model III—about 5% of $z_1$ and $z_3$, and 1 mgd in the case of $z_2$:

$$\min \sum_b x_b$$

s.t.

$x \in F$

$z_1 : AGCONV \leq 227$

$z_2 : NETGW \geq -1000$

$z_3 : NEWPOP \geq 38000$

$x_b \in B, B \subseteq \{x_{ijk} \text{ basic at optimality}\}.$

In this application, all variables with nonzero values in the optimal solution to Model III were placed in the objective function. Basic variables appearing in the solution of Model IV that were not in the objective function were then added to it, defining a new problem, whereupon the procedure was repeated. It should be noted, however, that Model IV does not require the objective function to include all basic variables from a preceding solution, but rather any subset of them. For example, one might wish to minimize only the basic variables corresponding to land-use change in zones 2 and 6.

The procedure was repeated fifteen times, and the cumulative number of different nonzero land-use transitions grew from 28 to 110, spawning a great variety of different plans. Table 6 shows the variation among five of the plans along four different dimensions, other than those pertaining to the three objectives, which would likely be significant in any evaluation. In at least one plan, considerable residential expansion—accommodating at least 20% of total population increase—occurred in each zone, with zones 2 and 6 often allocated less residential development than other areas (Figs. 3.2–3.6). Total land area being converted to residential use now ranged from 314 ha to 444 ha, with low-density development accounting for as much as 254 ha in some cases. Whereas in the optimal plans the amount of land destined for use as parks or golf courses always rose by exactly 100 ha, the increases in the nearly optimal cases ranged from 33 ha to 303 ha. Since the different land-use programs exhibit even greater variety than do these gross indicators, the deliberate consideration of slightly suboptimal plans has allowed the generation of a far greater array of options.

These results suggest that it may well be possible to accommodate considerable urban growth while adhering to constraints imposed by groundwater management and agricultural land preservation. However, any optimization model for land-use plan design makes assumptions regarding the acceptability and plausibility of future land-use transitions. In the
models described thus far, for example, changes from nonagricultural uses to agricultural ones are permitted. Since pineapple cultivation yields moderate groundwater recharge (Table 1) yet demands little or no irrigation (Table 2), expansion of pineapple acreage increases NETGW. In all models, significant amounts of acreage were therefore converted from vacant or grazing land to pineapple fields. Yet is it realistic to assume an increase in pineapple cultivation?

**TABLE 7. PAYOFFS FOR THREE OBJECTIVES WHEN AGRICULTURAL DEVELOPMENT ON CURRENTLY NONAGRICULTURAL LAND IS DISALLOWED**

<table>
<thead>
<tr>
<th>Optimized Objective</th>
<th>AGCONV (ha)</th>
<th>NETGW (mgd)</th>
<th>NEWPOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_1 = \text{AGCONV}$</td>
<td>145.2</td>
<td>-2.2</td>
<td>7 404</td>
</tr>
<tr>
<td>$z_2 = \text{NETGW}$</td>
<td>2 345.2</td>
<td>6.8</td>
<td>7 404</td>
</tr>
<tr>
<td>$z_3 = \text{NEWPOP}$</td>
<td>5 353.1</td>
<td>-136.5</td>
<td>686 715</td>
</tr>
</tbody>
</table>

**Constraining Agricultural Expansion**

**MODEL V.** To examine the implications of not increasing agricultural acreage, a new model, Model V, was created by appending to Model I a constraint eliminating conversions of non-agricultural to agricultural uses. Optimizing each objective in turn produced the payoffs shown in Table 7. Since AGCONV ($z_1$) only concerns land parcels that are removed from agricultural use and is not affected by new agricultural development, which might be viewed as compensating for losses of agricultural land incurred elsewhere, its values remain unchanged from those used in Model I (Table 4). Also unaffected is NEWPOP ($z_3$), since the amount of land available for residential use remains unaltered. What does change is NETGW ($z_2$), as withdrawal increases by roughly 3 to 7 mgd (depending on the additional population to be accommodated) relative to recharge. For example, with the additional constraints of 40 000 more residents and minimal agricultural land loss (a combination not shown in Table 7), NETGW ($z_2$) would decline by 5.3 mgd.

The greater impact on groundwater under these new, perhaps more realistic, conditions makes one less sanguine about the prospect of continuing intense urban development in central O‘ahu. Figure 4 shows the tradeoff between agricultural land conversion and additional residential population if NETGW remains unchanged. Allowing 40 000 new residents in the area would now result in a near tripling of agricultural land loss ($z_1 = 596$ ha), while recharge would fall by 3.5 mgd relative to withdrawal (i.e., $z_2 = -3.5$ mgd). An optimal residential land-use expansion pattern corresponding to these values is shown in Figure 5.1. In addition to the higher price now paid in terms of $z_1$ and $z_2$, the settlement pattern is quite different: residential
Figure 4. Tradeoff between agricultural land loss and residential population increase, optimally distributed, when net groundwater recharge equals or exceeds withdrawal.

growth is now distributed over four zones rather than two, and only zone 2’s assignment of 38% of the new population is common to both plans.

Again, the HSJ procedure was used to generate very different configurations. Allowing for slight degradations in the attainments of each of the three objective functions—AGCONV \( z_1 \) \( \leq 626 \) ha, NETGW \( z_2 \) \( \geq -4 \) mgd, and NEWPOP \( z_3 \) \( \geq 38,000 \) people—a wide range of options again could be identified (Figs. 5.2–5.6).

In view of the greater adverse impacts that this model suggests would accompany the much higher level of urban development prescribed by the amended General Plan, it may be enlightening to consider the impacts corresponding to the population limits set by the previous General Plan. Figure 6 shows the tradeoffs between agricultural land loss and the difference between groundwater recharge and withdrawal when only 11,500 additional residents are accommodated. Keeping agricultural land conversion at a minimum of 145.2 ha would result in a net loss to the aquifer of 2.3 mgd, while a policy of no increase in withdrawal relative to recharge would mean that more than four times the minimum, or 615.4 ha, would cease to be used for agriculture. Compared to the optimum under the new population ceiling of 40,000, the original policy of minimizing agricultural land conversion would result in only one-quarter of the agricultural land loss while cutting by one-third the drop in recharge relative to withdrawal.

As under the new General Plan, many different land-use configurations could accommodate the lower limit of 11,500 new residents, with only slight modifications of goals
5.1. Optimal distribution of new residential population of 40,000, with no agricultural expansion

5.2. Suboptimal distribution of new residential population of 38,000, with no agricultural expansion: Pattern 1

Figure 5. Alternative patterns of residential expansion under limit of 40,000 new residents, disallowing agricultural development in areas of presently nonagricultural use
5.3. Suboptimal distribution of new residential population of 38 000, with no agricultural expansion: Pattern 2

5.4. Suboptimal distribution of new residential population of 38 000, with no agricultural expansion: Pattern 3
5.5. Suboptimal distribution of new residential population of 38,000, with no agricultural expansion: Pattern 4

5.6. Suboptimal distribution of new residential population of 38,000, with no agricultural expansion: Pattern 5
concerning groundwater and agricultural land. For comparison, Figure 7.1 displays the optimal pattern of residential growth when AGCONV is minimized and NETGW = -2.3 mgd. Figures 7.2 to 7.6 show five of twenty-one different plans generated using the HSJ procedure. Although zone 2 always receives the greatest share of new residential development, accommodating 65% or more of the new population in all cases, each zone would receive new development in at least two of the twenty-one alternate plans. As indicated in Table 8, other plan attributes, such as the proportion of new residential land under low-density development, also vary appreciably. Thus, significant flexibility would be available under the old population ceiling as well. Considering values for AGCONV and NETGW different from those used in Figure 7 would yield yet many more plausible configurations, and flexibility would increase in turn.

**CONCLUSIONS**

Southern O'ahu and the areas fringing Honolulu have seen rapid urban growth throughout the past three decades. Occurring simultaneously with this growth have been reductions in sugarcane and pineapple land and changes in type and extent of irrigation. Paralleling these developments have been changes in the use and replenishment of groundwater in the Pearl Harbor basin, although the precise relationship between the basin’s water balance and shifts in land use and irrigation patterns is not a simple one. With pumpage rights possibly already
TABLE 8. SELECTED CHARACTERISTICS OF OPTIMAL AND SUBOPTIMAL SOLUTIONS TO MODEL V WITH NEW RESIDENTIAL POPULATION LIMITED TO 11,500

<table>
<thead>
<tr>
<th>New Population Pattern</th>
<th>( z_1 ) (ACCONV: ha)</th>
<th>( z_2 ) (NETGW: mgd)</th>
<th>( z_3 ) (NEWPOP: ha)</th>
<th>LANDRL (ha)</th>
<th>LANDRM (ha)</th>
<th>MOREGOLF (ha)</th>
<th>Sum PNPD (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fig. 7.1</td>
<td>145.2</td>
<td>-2.3</td>
<td>11,500</td>
<td>59</td>
<td>66</td>
<td>137</td>
<td>593</td>
</tr>
<tr>
<td>Suboptimal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fig. 7.2</td>
<td>153.0</td>
<td>-2.5</td>
<td>11,500</td>
<td>125</td>
<td>34</td>
<td>138</td>
<td>857</td>
</tr>
<tr>
<td>Fig. 7.3</td>
<td>153.0</td>
<td>-2.5</td>
<td>11,500</td>
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<td>30</td>
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<td>Fig. 7.6</td>
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<td>135</td>
<td>30</td>
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</table>

NOTE: LANDRL = additional land for low-density residential
LANDRM = additional land for medium-density residential
MOREGOLF = additional land for parks and golf courses
Sum PNPD = total land converting from nonirrigated pineapple to drip-irrigated pineapple.

exceeding the aquifers' sustainable yields, and the demand for urban land seeming to grow inexorably, there is great concern that water supply and the desire to preserve agricultural land and open space may restrict the amount of urban growth that central O'ahu can sustain.

We have explored these factors by incorporating the results of a water-balance simulation into a multiobjective land-use programming model. If it is found plausible that land currently used nonagriculturally may be used for agriculture while present-day agricultural, recreational, and vacant lands are urbanized, then, the models suggest, accommodating roughly 40,000 additional residents in central O'ahu may be accomplished while only slightly affecting the relationship between agricultural land loss and the ground-water recharge-withdrawal balance. Moreover, a variety of land-use plans could probably achieve the stated goals. On the other hand, if converting nonagricultural land to agricultural use is not found plausible, the models indicate that the larger residential population allowed under the amended General Plan can be situated within the area only at the loss of significant amounts of agricultural land and reductions in groundwater recharge relative to withdrawal. Although many different land-use configurations are tenable given these costs, agricultural land loss would, at the least, triple that necessitated under the old population ceiling, while relative groundwater withdrawal would be 50% higher.

We emphasize that these findings are only tentative, however, since the model does not pretend to address all relevant objectives and constraints and does not encompass the entire geographical area of concern to planners. Some of the land-use changes proposed in some solutions, for example, may currently be unlikely, unrealistic, or unacceptable. Nevertheless, such transitions may become more realistic under different conditions or may suggest other
7.1. Optimal distribution of new residential population of 11,500, with no agricultural expansion

7.2. Suboptimal distribution of new residential population of 11,500, with no agricultural expansion: Pattern 1

Figure 7. Alternative patterns of residential expansion under former limit of 11,500 new residents, disallowing agricultural development in areas of presently nonagricultural use
7.3. Suboptimal distribution of new residential population of 11,500, with no agricultural expansion: Pattern 2

7.4. Suboptimal distribution of new residential population of 11,500, with no agricultural expansion: Pattern 3
7.5. Suboptimal distribution of new residential population of 11,500, with no agricultural expansion: Pattern 4

7.6. Suboptimal distribution of new residential population of 11,500, with no agricultural expansion: Pattern 5
options with the same effect, such as the initiation of land-management practices to alter recharge. As Geoffrion (1976) reminded us, "the purpose of mathematical programming is insight, not numbers." By considering both optimal and near-optimal programming solutions, it is possible to formulate a wide variety of land-use plans that respond well to goals concerning population growth, water management, and agricultural land. What is required, however, is a more systematic, basinwide framework for evaluating decisions about land-use change than that currently in use.

REFERENCES CITED


------. 1989. ADBASE multiple objective linear programming package. Department of Management Science and Information Technology, University of Georgia, Athens.


