Table 10.1 | Groundwater budget information for the High Plains Aquifer based on the United States Geological Survey’s Regional Aquifer System Analysis groundwater model*. (Adapted from Luckey et al. 1986.)

<table>
<thead>
<tr>
<th>Budget parameter</th>
<th>Northern High Plains</th>
<th>Central High Plains</th>
<th>Southern High Plains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary inflows (in cubic metres per year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge from precipitation on rangeland and streams</td>
<td>†5.98 × 10^8</td>
<td>†4.66 × 10^8</td>
<td>1.97 × 10^8</td>
</tr>
<tr>
<td>Recharge from precipitation on agricultural land</td>
<td>2.89 × 10^8</td>
<td>–</td>
<td>1.43 × 10^8</td>
</tr>
<tr>
<td>Groundwater irrigation return (pumpage minus crop demand)</td>
<td>2.31 × 10^9</td>
<td>2.07 × 10^9</td>
<td>3.61 × 10^9</td>
</tr>
<tr>
<td>Recharge from other human activities (e.g. seepage from reservoirs and canals)</td>
<td>2.31 × 10^9</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Recharge from other aquifers across subunit boundary</td>
<td>–</td>
<td>‡1.88 × 10^7</td>
<td>–</td>
</tr>
<tr>
<td>Totals</td>
<td>8.11 × 10^9</td>
<td>2.55 × 10^9</td>
<td>5.24 × 10^9</td>
</tr>
<tr>
<td>Primary outflows (in cubic metres per year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total pumpage</td>
<td>6.48 × 10^9</td>
<td>6.89 × 10^9</td>
<td>8.59 × 10^9</td>
</tr>
<tr>
<td>Discharge to streams and shallow water-table areas</td>
<td>2.87 × 10^9</td>
<td>4.15 × 10^9</td>
<td>–</td>
</tr>
<tr>
<td>Discharge along eastern boundary</td>
<td>–</td>
<td>6.97 × 10^7</td>
<td>1.05 × 10^8</td>
</tr>
<tr>
<td>Totals</td>
<td>9.35 × 10^9</td>
<td>7.37 × 10^9</td>
<td>8.70 × 10^9</td>
</tr>
<tr>
<td>Net residual</td>
<td>−1.24 × 10^9</td>
<td>−4.82 × 10^9</td>
<td>−3.46 × 10^9</td>
</tr>
</tbody>
</table>

* Assumptions: Inflow/Outflow values determined using 1960–1980 estimates; base of aquifer modelled as no-flow boundary; vertical flow in aquifer considered negligible on regional scale
† Recharge distributed unevenly based on soil type
‡ Additional recharge from precipitation on agricultural land because of changes in soil character due to tillage
§ Flow only from northern and southern subunits to central subunit
‖ Municipal and industrial pumpage is 3.2% of this amount
<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Pre-industrial concentration (1750)</th>
<th>Present concentration (1998)</th>
<th>Residence time</th>
<th>Annual rate of increase</th>
<th>Major sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water vapour</td>
<td>3000 ppm</td>
<td>3000 ppm</td>
<td>10–15 days</td>
<td>n.a.</td>
<td>Oceans</td>
</tr>
<tr>
<td>CO₂ (Carbon dioxide)</td>
<td>−280 ppm</td>
<td>−365 ppm</td>
<td>5–200⁰ years</td>
<td>1.5 ppm a⁻¹</td>
<td>Combustion of fossil fuels, deforestation</td>
</tr>
<tr>
<td>CH₄ (Methane)</td>
<td>~700 ppb</td>
<td>1745 ppb</td>
<td>12⁰ years</td>
<td>7.0 ppm a⁻¹</td>
<td>Rice production, cattle rearing, industry</td>
</tr>
<tr>
<td>N₂O (Nitrous oxide)</td>
<td>−270 ppb</td>
<td>314 ppb</td>
<td>114⁰ years</td>
<td>0.8 ppm a⁻¹</td>
<td>Agriculture, industry, biomass burning</td>
</tr>
<tr>
<td>CFC-11 (Chlorofluorcarbon-11)</td>
<td>0</td>
<td>268 ppt</td>
<td>45 years</td>
<td>−1.4 ppt a⁻¹</td>
<td>Aerosols, refrigeration</td>
</tr>
<tr>
<td>HFC-23 (Hydrofluorcarbon-23)</td>
<td>0</td>
<td>14 ppt</td>
<td>260 years</td>
<td>0.55 ppt a⁻¹</td>
<td>Industrial byproduct</td>
</tr>
<tr>
<td>CF₄ (Perfluoromethane)</td>
<td>40 ppt</td>
<td>80 ppt</td>
<td>&gt;50000 years</td>
<td>1 ppt a⁻¹</td>
<td>Aluminium industry</td>
</tr>
</tbody>
</table>

n.a. not applicable

a Rate is calculated over the period 1990 to 1999
b No single lifetime can be defined for CO₂ because of the different rates of uptake by different removal processes
c Rate has fluctuated between 0.9 ppm a⁻¹ and 2.8 ppm a⁻¹ for CO₂ and between 0 and 13 ppb a⁻¹ for CH₄ over the period 1990–1999
d This lifetime has been defined as an ‘adjustment’ time that takes into account the indirect effect of the gas on its own residence time
Table 10.3 Classification scheme for environmental droughts and consequences for groundwater resources.
(Adapted from Mawdsley et al. 1994. Reproduced with permission of British Hydrological Society.)

<table>
<thead>
<tr>
<th>Class of drought</th>
<th>Duration</th>
<th>Return period</th>
<th>Groundwater impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate</td>
<td>Short</td>
<td>5–20 years</td>
<td>Reduced spring and river flows; drying out of floodplain areas</td>
</tr>
<tr>
<td></td>
<td>Long¹</td>
<td></td>
<td>Reduced spring and river flows; drying out of floodplain areas and wetlands; well yields may decrease</td>
</tr>
<tr>
<td>Serious</td>
<td>Short</td>
<td>20–50 years</td>
<td>Reduced spring and river flows; wetlands and ponds dry up</td>
</tr>
<tr>
<td></td>
<td>Long¹</td>
<td></td>
<td>Reduced spring and river flows; rivers become influent; wetlands and ponds dry up; saline intrusion in coastal aquifers</td>
</tr>
<tr>
<td>Severe</td>
<td>Short</td>
<td>&gt;50 years</td>
<td>Springs and rivers dry up; wetlands and ponds dry up; well yields decrease as groundwater levels fall</td>
</tr>
<tr>
<td></td>
<td>Long¹</td>
<td>&gt;50 years</td>
<td>Springs and rivers dry up; wetlands and ponds dry up; well yields fail as groundwater levels fall substantially; saline intrusion in coastal aquifers</td>
</tr>
</tbody>
</table>

¹ Longer than one groundwater recharge season

Table 10.4 Scenarios of climate and groundwater use change effects considered for the Edwards Aquifer, south-central Texas.
(Adapted from Loáiciga 2003. Reproduced with permission of Association of American Geographers.)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>I: Base</th>
<th>II: Climate change effect</th>
<th>III: Groundwater use change effect</th>
<th>IV: Total effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate (recharge)</td>
<td>$R_{1978-89}$</td>
<td>$2 \times CO_2/1 \times CO_2$</td>
<td>$R_{1978-89}$</td>
<td>$2 \times CO_2/1 \times CO_2$</td>
</tr>
</tbody>
</table>

Notes:

a Historical recharge (R) during 1978–1989 (mean = $0.949 \times 10^9 \text{m}^3 \text{a}^{-1}$)
b Historical recharge scaled to $2 \times CO_2$ climate conditions
c Average groundwater use between 1978–1989 = $0.567 \times 10^9 \text{m}^3 \text{a}^{-1}$
d Groundwater use forecast for 2050 = $0.784 \times 10^9 \text{m}^3 \text{a}^{-1}$

Table 10.5 Simulated minimum spring flows in the Edwards Aquifer, south-central Texas, for climate and groundwater use change effects listed in Table 10.4. (Adapted from Loáiciga 2003. Reproduced with permission of Association of American Geographers.)

<table>
<thead>
<tr>
<th>Climate change and groundwater use scenario</th>
<th>Edwards Aquifer springs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Comal</td>
</tr>
<tr>
<td>I</td>
<td>4.84</td>
</tr>
<tr>
<td>II</td>
<td>12.7 (+162%)</td>
</tr>
<tr>
<td>III</td>
<td>0 (−100%)</td>
</tr>
<tr>
<td>IV</td>
<td>1.31 (−73%)</td>
</tr>
</tbody>
</table>

Notes:

Spring flows are given in $10^6 \text{m}^3 \text{month}^{-1}$
The numbers in parentheses represent the percentage increase (+) or decrease (–) caused by a scenario relative to the base condition (I)
### Table 10.6 Types of adaptation options for surface water and groundwater supply and demand. (Adapted from IPCC 2008. Reproduced with permission.)

<table>
<thead>
<tr>
<th>Supply-side</th>
<th>Demand-side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase storage capacity by building reservoirs and dams</td>
<td>Improve water-use efficiency by recycling water</td>
</tr>
<tr>
<td>Desalinate seawater</td>
<td>Reduce water demand for irrigation by</td>
</tr>
<tr>
<td>Expand rain-water storage</td>
<td>changing the cropping calendar, crop mix,</td>
</tr>
<tr>
<td>Remove invasive non-native vegetation from riparian areas</td>
<td>irrigation method and area planted</td>
</tr>
<tr>
<td>Prospect and extract groundwater</td>
<td>Promote traditional practices for sustainable water use</td>
</tr>
<tr>
<td>Develop new wells and deepen existing wells</td>
<td>Expand use of water markets to reallocate water to highly valued uses</td>
</tr>
<tr>
<td>Maintain well condition and performance</td>
<td>Expand use of economic incentives including metering and pricing to encourage water conservation</td>
</tr>
<tr>
<td>Develop aquifer storage and recovery systems</td>
<td>Introduce drip-feed irrigation technology</td>
</tr>
<tr>
<td>Develop conjunctive use of surface water and groundwater resources</td>
<td>License groundwater abstractions</td>
</tr>
<tr>
<td>Develop surface water storage reservoirs filled by wet season pumping from surface water and groundwater</td>
<td>Meter and price groundwater abstractions</td>
</tr>
<tr>
<td>Develop artificial recharge schemes using treated wastewater discharges</td>
<td></td>
</tr>
<tr>
<td>Develop riverbank filtration schemes with vertical and inclined bank-side wells</td>
<td></td>
</tr>
<tr>
<td>Develop groundwater management plans that manipulate groundwater storage, e.g. resting coastal wells during times of low groundwater levels</td>
<td></td>
</tr>
<tr>
<td>Develop groundwater protection strategies to avoid loss of groundwater resources from surface contamination</td>
<td></td>
</tr>
<tr>
<td>Manage soils to avoid land degradation to maintain and enhance groundwater recharge</td>
<td></td>
</tr>
</tbody>
</table>

### Table 10.7 Percentage change in mean annual potential groundwater recharge values calculated using four GCMs (HadCM3, CGCM2, CSIRO2 and PCM) for the 2020s, 2050s and 2080s ‘high’ gas emissions scenarios compared with the baseline period, 1961–1990, for five study areas (Denmark, England, France, Spain and Italy). Negative percentage changes indicating a decrease in annual groundwater recharge are shown in bold. (Adapted from Hiscock et al. 2011. Reproduced with permission from Taylor & Francis.)

<table>
<thead>
<tr>
<th></th>
<th>HadCM3</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Baseline</td>
<td>2020s</td>
<td>% change</td>
<td>2050s</td>
<td>% change</td>
</tr>
<tr>
<td>Denmark</td>
<td>279.8</td>
<td>312.0</td>
<td>11.5</td>
<td>333.6</td>
<td>19.2</td>
<td>302.3</td>
</tr>
<tr>
<td>England</td>
<td>286.8</td>
<td>301.5</td>
<td>5.1</td>
<td>284.8</td>
<td>−0.7</td>
<td>347.2</td>
</tr>
<tr>
<td>France</td>
<td>140.7</td>
<td>159.0</td>
<td>13.1</td>
<td>175.3</td>
<td>24.6</td>
<td>235.5</td>
</tr>
<tr>
<td>Spain</td>
<td>30.6</td>
<td>24.5</td>
<td>−20.1</td>
<td>30.2</td>
<td>−1.4</td>
<td>5.1</td>
</tr>
<tr>
<td>Italy</td>
<td>494.0</td>
<td>370.6</td>
<td>−25.0</td>
<td>330.3</td>
<td>−33.1</td>
<td>346.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>440.0</td>
<td>330.9</td>
<td>18.3</td>
<td>384.3</td>
<td>37.3</td>
</tr>
<tr>
<td></td>
<td>286.8</td>
<td>303.6</td>
<td>5.8</td>
<td>289.0</td>
<td>0.8</td>
<td>340.4</td>
</tr>
<tr>
<td></td>
<td>140.7</td>
<td>148.2</td>
<td>5.4</td>
<td>147.5</td>
<td>4.9</td>
<td>184.4</td>
</tr>
<tr>
<td></td>
<td>30.6</td>
<td>33.4</td>
<td>9.0</td>
<td>46.9</td>
<td>53.0</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>494.0</td>
<td>392.1</td>
<td>−20.6</td>
<td>362.0</td>
<td>−26.7</td>
<td>383.4</td>
</tr>
</tbody>
</table>

|                      | CGCM2  |          |          |          |          |          |
|                      |        | Baseline | 2020s | % change | 2050s | % change | 2080s | % change |
| Denmark              | 279.8  | 333.5    | 19.2    | 384.3    | 37.3    | 376.3    | 34.5   |
| England              | 286.8  | 303.6    | 5.8     | 289.0    | 0.8     | 340.4    | 18.7   |
| France               | 140.7  | 148.2    | 5.4     | 147.5    | 4.9     | 184.4    | 31.1   |
| Spain                | 30.6   | 33.4     | 9.0     | 46.9     | 53.0    | 12.1     | −60.6 |
| Italy                | 494.0  | 392.1    | −20.6   | 362.0    | −26.7   | 383.4    | −22.4 |
|                      |        | 440.0    | 330.9   | 18.3     | 384.3    | 37.3     | 376.3   | 34.5   |
|                      | 286.8  | 303.6    | 5.8     | 289.0    | 0.8     | 340.4    | 18.7   |
|                      | 140.7  | 148.2    | 5.4     | 147.5    | 4.9     | 184.4    | 31.1   |
|                      | 30.6   | 33.4     | 9.0     | 46.9     | 53.0    | 12.1     | −60.6 |
|                      | 494.0  | 392.1    | −20.6   | 362.0    | −26.7   | 383.4    | −22.4 |

|                      | CSIRO2 |          |          |          |          |          |
|                      |        | Baseline | 2020s | % change | 2050s | % change | 2080s | % change |
| Denmark              | 279.8  | 330.9    | 18.3    | 376.3    | 34.5    | 369.3    | 32.0   |
| England              | 286.8  | 308.6    | 7.6     | 294.4    | 2.7     | 349.2    | 21.7   |
| France               | 140.7  | 162.0    | 15.1    | 173.1    | 23.0    | 232.9    | 65.6   |
| Spain                | 30.6   | 43.2     | 41.0    | 70.6     | 130.5   | 35.8     | 16.9   |
| Italy                | 494.0  | 420.6    | −14.9   | 424.6    | −14.1   | 493.9    | 0.0    |

|                      | PCM    |          |          |          |          |          |
|                      |        | Baseline | 2020s | % change | 2050s | % change | 2080s | % change |
| Denmark              | 279.8  | 318.4    | 13.8    | 348.3    | 24.5    | 318.5    | 13.8   |
| England              | 286.8  | 297.2    | 3.6     | 268.1    | −6.5    | 302.7    | 5.5    |
| France               | 140.7  | 138.9    | −1.2    | 117.7    | −16.3   | 138.1    | −1.8   |
| Spain                | 30.6   | 37.5     | 22.4    | 57.0     | 86.1    | 22.0     | −28.1 |
| Italy                | 494.0  | 406.6    | −17.7   | 390.3    | −21.0   | 438.4    | −11.3 |