Guam Groundwater-Availability Study

Technical Working Group Meeting

September 20, 2011
Outline of Meeting

• Project goals, products, timeline – Steve Gingerich
• Groundwater recharge study – Adam Johnson
• Water-level monitoring and analysis – Steve Gingerich
• Well database – Vivianna Bendixson
• Preliminary numerical modeling – Steve Gingerich
• Comprehensive monitoring plans – John Jenson
• Wrap up and future plans – Steve Gingerich/Travis Hylton
Guam Groundwater-Availability Study

Objectives

- Obtain a better understanding of the regional groundwater flow system in northern Guam
- Update estimates of groundwater recharge for the entire island
- Estimate effects of selected withdrawal scenarios within northern Guam, using a numerical groundwater flow and transport model, on water levels and the transition zone between freshwater and saltwater
Guam Groundwater-Availability Study

Approach

1. Compile, review, and analyze existing data
2. Collect additional groundwater data in northern Guam
3. Develop daily water budget to estimate groundwater recharge rates
4. Develop numerical groundwater flow and transport model for northern Guam
## Timelines

<table>
<thead>
<tr>
<th>Activity</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>Apr</td>
<td>Jul</td>
<td>Oct</td>
</tr>
<tr>
<td>Data Review</td>
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<tr>
<td>Recharge Analysis</td>
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<tr>
<td>Water Budget Report</td>
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<tr>
<td>Water-Level Surveys</td>
<td></td>
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<tr>
<td>Regional Numerical Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater Availability Report</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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Water-Budget Study Objectives

• Develop a daily water-budget model to estimate long-term average groundwater recharge to Guam

• Compare recharge estimates to previous studies

• Estimate recharge for drought conditions and potential land cover after military buildup

• Estimate recharge using chloride mass-balance method
Water-budget model

- Rainfall
- Total Evapotranspiration
  - Canopy Evaporation
  - Transpiration
  - Ground Evaporation

- Septic-System Leaching
- Irrigation
- Net Precipitation

- Runoff
- Stormwater Runoff
- Water-Main Leakage
- Groundwater Recharge
- Plant-Root Zone

- Groundwater Recharge

Provisional - Subject to revision - do not quote or release
### Water-budget calculation

**Daily water fluxes**

<table>
<thead>
<tr>
<th>Inflow</th>
<th>Outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>Total Evapotranspiration</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Runoff</td>
</tr>
<tr>
<td>Septic-system leaching</td>
<td></td>
</tr>
<tr>
<td>Water-main leakage</td>
<td></td>
</tr>
<tr>
<td>Stormwater</td>
<td></td>
</tr>
<tr>
<td>Stored soil-moisture</td>
<td></td>
</tr>
</tbody>
</table>

Water-budget model quantifies these water fluxes for the entire island on a **daily** basis.

Subarea example
Rainfall

• Mean monthly rainfall maps used to distribute rainfall (PRISM: Daly and Halbleib, 2006)

• Rainfall records from 18 rain gages were used to estimate daily rainfall

• Mean annual rainfall rate: about 1,000 Mgal/d

Derived from Daly and Halbleib (2006)
Irrigation

- Applied to all:
  - Agriculture fields
  - Golf courses

- Irrigation rates:
  - estimated based on monthly rainfall and potential evapotranspiration
  - mean annual rate: 0.8 Mgal/d

Septic systems

**Number:** about 15,000 houses use septic systems

**Locations:** estimated based on WERI survey, GWA (2007), and sewer lines

**Leaching rate:** 322 gal/d per septic system [95% of avg. household water-use] (GWA, 2007)

**Total annual input:** 4.8 Mgal/d

Sources: WERI survey, GWA (2007)
Water-main leakage

Leakage rates: (Final EIS, 2010)
- GWA: 10.5 Mgal/d
- Navy: 0.71 Mgal/d
- Air Force: 1.63 Mgal/d

Leakage distribution:
- Navy and Air Force: applied uniformly
- GWA: applied proportionally to regional water use

Assumed to be direct recharge

Sources: Final EIS (2010), GWA
## Water-inflow comparison

<table>
<thead>
<tr>
<th>Water-budget parameter</th>
<th>Mean annual rate (Mgal/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>999.0</td>
</tr>
<tr>
<td>Irrigation</td>
<td>0.8</td>
</tr>
<tr>
<td>Septic-system leaching</td>
<td>4.8</td>
</tr>
<tr>
<td>Water-main leakage</td>
<td>12.8</td>
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</table>

*Less than 2% of total water inflow*
Runoff

Rainfall that runs off the land surface to the ocean or Fena Reservoir

Subdivided island into runoff regions based on
- geology
- soils
- topography
- land cover

North:
- mostly limestone
- high permeability
- no streams

South:
- mostly volcanic
- low permeability
- many streams

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Areas with no runoff

Include:
- most of northern Guam
- Orote Peninsula
- southeast coast
- drainage areas of large closed contour depressions

Areas where runoff was assumed to be zero
Runoff regions

- 9 regions in the south

- Runoff was estimated from stream-gaging stations

- Runoff calculated as a fraction of rainfall
  - annual runoff: 18 to 40 percent of annual rainfall
Stormwater runoff

Water that flows off impervious surfaces

Possible destinations considered:

1) nearby pervious areas

2) captured by storm-drain systems and disposed to:
   • ocean
   • drywells
   • Harmon Sink
Stormwater runoff to ocean

- Water captured by storm-drain systems is routed to the ocean

- Based on:
  - Guam storm-drainage manual (1980)
  - Stormwater implementation plan for the Guam road network (FEIS, 2010)
Stormwater runoff to drywells

- Water captured by storm-drain systems is routed to the drywells

- Captured water is added as direct recharge

- Based on:
  - Earth Tech, Inc. (1999)
  - Ogden Environmental and Energy Services, Inc. (1995)
  - Brian Ho (AECOM)
Stormwater runoff to Harmon Sink

- Water captured by storm-drain systems is routed to the Harmon Sink
- Captured runoff is added as direct recharge to Harmon Sink
- Based on:
  - Guam storm-drainage manual (1980)
  - Stormwater implementation plan for the Guam road network (FEIS, 2010)
  - Moran and Jenson (2004)
Evapotranspiration (ET)

Sum of canopy evaporation, transpiration, and ground evaporation

Estimated based on:

1. atmospheric conditions
2. land cover
3. soil-moisture content

Most previous water-budget studies on Guam estimated ET based only on atmospheric conditions
Canopy evaporation

Rainfall that is intercepted by leaves, trunks, or stems, and evaporates before reaching the ground

Canopy evaporation in tropical forests is typically between 10 and 30 percent of rainfall
Canopy evaporation in forests

- Assumed to be 15 percent of annual rainfall

- Based on canopy evaporation studies in areas with forests and climates that are similar to Guam (Biden and Chappell, 2004; Asdak and others, 1998)

- Not directly accounted for in previous water budgets on Guam

Reference evapotranspiration

- Evaporative power of the atmosphere

- Calculated from daily weather observations according to Allen and others (1998)
  - solar radiation, air temperature, humidity, and wind speed measurements at Guam airport and former WSMO at Taguac

- Assumed to be uniform across the island

- Analogous to pan evaporation
Potential evapotranspiration

- Maximum ET rate for given land cover

- For each land cover:
  potential ET = (reference ET) x (crop coefficient)

- Crop coefficients estimated from published ET rates for similar vegetation types

- All previous studies assumed a uniform ET rate for all land covers

Potential ET was estimated for each land cover on Guam

Potential and actual evapotranspiration

Potential ET/ Reference ET:
- Savanna complex = 1.23
- Limestone forest = 0.69

Actual ET rate calculated based on daily soil-moisture content:
- high moisture ‡ potential ET rate
- low moisture ‡ reduced ET rate
Moisture-storage capacity

Depends on:
1) available water capacity
2) root depth

Available water capacity varies by soil type (USDA, 2009)

Root depth varies by vegetation (various sources)

Recharge occurs when soil moisture exceeds moisture-storage capacity
Water-budget model results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean annual rate (Mgal/d)</th>
<th>Percent of water input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total water input</td>
<td>1017</td>
<td>100%</td>
</tr>
<tr>
<td>Rainfall</td>
<td>999</td>
<td>98%</td>
</tr>
<tr>
<td>Runoff</td>
<td>130</td>
<td>13%</td>
</tr>
<tr>
<td>Total evapotranspiration</td>
<td>495</td>
<td>49%</td>
</tr>
<tr>
<td>Recharge</td>
<td>392</td>
<td>38%</td>
</tr>
</tbody>
</table>

for entire island and “baseline conditions”

- annual rainfall from 1961 to 2005
- 2004 land cover (USDA, 2006)
Mean annual recharge distribution

- Limestone areas have highest recharge
- Volcanic areas have lowest recharge
- Storm-drain systems redistribute water
Mean annual recharge distribution

Recharge can be enhanced by
- water-main leakage
- septic-system leaching
- stormwater runoff at Harmon Sink

Annual recharge (in/yr)
Recharge, percent of water inflow

most limestone areas: 40 to 60%

most volcanic areas: less than 30%
Comparisons to previous water-budget studies on Guam

<table>
<thead>
<tr>
<th>Study</th>
<th>Time step</th>
<th>Study area</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Northern Guam Lens Study” (CDM Inc., 1982)</td>
<td>Mean monthly</td>
<td>Part of northern Guam</td>
</tr>
<tr>
<td>Mink (1991)</td>
<td>Mean monthly</td>
<td>Most of northern Guam</td>
</tr>
<tr>
<td>Jocson and others (2002)</td>
<td>Daily</td>
<td>Part of northern Guam</td>
</tr>
<tr>
<td>Habana and others (2009)</td>
<td>Daily</td>
<td>Part of northern Guam</td>
</tr>
<tr>
<td>This study</td>
<td>Daily</td>
<td>Entire island</td>
</tr>
</tbody>
</table>
Comparison to “Northern Guam Lens Study” (NGLS)

(Camp Dresser and McKee, Inc., 1982)

Recharge computed as mean monthly rainfall minus mean monthly ET

ET estimated from daylight hours and air temperature

Estimated annual recharge relative to the NGLS by aquifer subbasin (%)

<table>
<thead>
<tr>
<th>NGLS</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>159</td>
</tr>
</tbody>
</table>

+42%

Total recharge to NGLS subbasins (Mgal/d)
Comparison to Mink (1991)

Recharge computed as mean monthly rainfall minus monthly ET

Monthly ET assumed to be:
- 73 percent of rainfall from January to May
- 3.3 inches from June to December

Estimated annual recharge relative to northern aquifer sectors (%)

Total recharge to northern aquifer sectors (Mgal/d)

<table>
<thead>
<tr>
<th></th>
<th>Mink</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>254</td>
<td>238</td>
</tr>
</tbody>
</table>
Comparison to Jocson and others (2002)

Recharge computed as daily rainfall minus daily pan evaporation

Implicit assumptions:
1) ET is zero on days with no rain
2) no moisture stored in soil for more than a day

Did not directly account for canopy evaporation

‡ ET estimated by Jocson and others (2002) is much lower than this study

Estimated annual recharge relative to Jocson study area (%)

Total recharge to Jocson study area (Mgal/d)

<table>
<thead>
<tr>
<th>Jocson</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>87</td>
</tr>
</tbody>
</table>

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Comparison to Habana and others (2009)

Developed a daily water-budget model to estimate recharge

Main differences from this study:
1) Unique land cover potential ET rates not quantified

2) Canopy evaporation not directly accounted for

‡ ET estimated by Habana and others (2009) is slightly lower than this study

Total recharge to Habana study area (Mgal/d)

<table>
<thead>
<tr>
<th></th>
<th>Habana</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>58</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>
## Recharge scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Rainfall</th>
<th>Land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1961 – 2005</td>
<td>2004</td>
</tr>
<tr>
<td>Future land cover</td>
<td>1961 – 2005</td>
<td>After military buildup</td>
</tr>
<tr>
<td>Future land cover and drought</td>
<td>1969 – 1973</td>
<td>After military buildup</td>
</tr>
</tbody>
</table>

1969 • 1973 had the lowest 5-year rainfall average since 1961
Future land-cover changes

Includes potential land-cover changes incurred by:

- proposed military buildup
- normal background growth

Sources:

- Final EIS (2010)
- Database of approved development projects from Guam Bureau of Statistics and Plans (Victor Torres)
Comparison to baseline recharge

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Entire island</th>
<th>Northern aquifer sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future land cover</td>
<td>+1%</td>
<td>+1%</td>
</tr>
<tr>
<td>Drought</td>
<td>-34%</td>
<td>-31%</td>
</tr>
<tr>
<td>Future land cover and drought</td>
<td>-32%</td>
<td>-30%</td>
</tr>
</tbody>
</table>

Baseline recharge is long-term average recharge.
Drought scenario

Annual rainfall is 20 percent less than mean annual rainfall

All parameters except rainfall kept the same as baseline

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Drought</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mgal/d)</td>
<td>238</td>
<td>164</td>
</tr>
</tbody>
</table>

-31%

Total recharge to northern aquifer sectors

Provisional - Subject to revision - do not quote or release
Chloride mass-balance method

Recharge = \( C_p (P - R) / C_{gw} \)

<table>
<thead>
<tr>
<th>Equation variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p )</td>
<td>Chloride concentration of rain infiltrating into the ground</td>
</tr>
<tr>
<td>( P )</td>
<td>Annual rainfall</td>
</tr>
<tr>
<td>( R )</td>
<td>Annual runoff</td>
</tr>
<tr>
<td>( C_{gw} )</td>
<td>Chloride concentration of groundwater</td>
</tr>
</tbody>
</table>
Chloride samples

March 2010 to May 2011:

$C_p$ measured at five bulk-deposition stations

$C_{gw}$ measured at five groundwater sites

Recharge estimated at each bulk-deposition site
## Chloride mass-balance recharge results

### Recharge, as a percent of annual rainfall

<table>
<thead>
<tr>
<th>Bulk-deposition station</th>
<th>Chloride mass-balance method</th>
<th>Water-budget model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jinapsan</td>
<td>26%</td>
<td>55%</td>
</tr>
<tr>
<td>Y-15</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>Beng Bing</td>
<td>40%</td>
<td>50%</td>
</tr>
<tr>
<td>Airport</td>
<td>36%</td>
<td>54%</td>
</tr>
<tr>
<td>Almagosa</td>
<td>20%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Runoff assumed to be zero at all stations except for Almagosa
Uncertainties in chloride mass-balance method

- historically, sea spray deposited from tropical cyclones has devastated vegetation on Guam (Guard and others, 1999)
- there were no heavy storms during sampling period

recharge was possibly underestimated
Water-Budget Summary

1. Recharge estimated for the northern aquifer subbasins is 32% to 49% greater than recharge estimated by the Northern Guam Lens Study (1982)

2. Recharge is about 40%-60% of water input in limestone areas and less than 30% in volcanic areas

3. Potential land-cover changes incurred during the proposed military buildup likely will not reduce overall recharge to Guam

4. Compared to long-term average recharge, recharge is 34% lower during the lowest 5-year rainfall period

5. Recharge distribution maps will be used in a numerical groundwater model of Guam’s freshwater-lens system
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Water-Level Monitoring

- Measure water levels in selected areas for several months
- Characterize distribution of aquifer properties (tidal analysis)
- Define spatial distribution of water levels (model-calibration target)
- Identify long-term monitoring needs
Water-Level Data Consistency

- Accurate water-level data is needed to determine spatial changes.
- Errors can be a large fraction of water-level difference between wells in Guam’s freshwater lens.
- Water-level tape accuracy.
- Water-level measuring point with updated elevation surveyed to a common datum.
- Important for data sharing among all agencies.
Water-Level Tape Calibration

- Used master calibration tape
- Calibrated new tapes to establish baseline
- Re-calibrate on a regular schedule
- Calibrated over a range of depths
- Accounted for environmental factors
- Recommended retiring tapes out of calibration (> 0.05% error usually due to kinking)
- Involved all agencies collecting water-level data

Correction table:

<table>
<thead>
<tr>
<th>From (feet)</th>
<th>To (feet)</th>
<th>Add to Depth to Water (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>24.88</td>
<td>0.00</td>
</tr>
<tr>
<td>24.89</td>
<td>74.64</td>
<td>0.01</td>
</tr>
<tr>
<td>74.65</td>
<td>124.40</td>
<td>0.02</td>
</tr>
<tr>
<td>124.41</td>
<td>174.17</td>
<td>0.03</td>
</tr>
<tr>
<td>174.18</td>
<td>223.93</td>
<td>0.04</td>
</tr>
<tr>
<td>223.94</td>
<td>273.69</td>
<td>0.05</td>
</tr>
<tr>
<td>273.70</td>
<td>323.46</td>
<td>0.06</td>
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<tr>
<td>323.47</td>
<td>373.22</td>
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<td>373.23</td>
<td>422.99</td>
<td>0.08</td>
</tr>
<tr>
<td>423.00</td>
<td>460.13</td>
<td>0.09</td>
</tr>
<tr>
<td>460.14</td>
<td>472.75</td>
<td>0.09</td>
</tr>
<tr>
<td>472.76</td>
<td>550.00</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Values in blue are extrapolations beyond deepest test measurement (460.13 ft)
Aquifer Properties of Northern Guam

- Measure water levels in selected areas for several months
- Compile long-term continuous water levels
- Digitize historic water levels
- Characterize distribution of aquifer properties by analyzing tidal response in wells

by Kolja Rotzoll, John Jenson, Steve Gingerich, and Aly El-Kadi
Distribution of Monitoring Wells

EXPLANATION
- Groundwater subbasin
- Volcanic basement at sea level

Water-level observations
- Ocean tide
- USGS long-term continuous record
- Additional wells monitored for this study
- Historic continuous water levels

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Tidal Response in Monitoring Wells

With increasing distance from the coast:
- amplitude decays exponentially
- time lag increases linearly
Tidal Efficiency

With increasing distance from the coast: amplitude decays exponentially.
With increasing distance from the coast: time lag increases linearly.
Aquifer Diffusivity

Effective Diffusivity = \(2.4 \times 10^8\) ft\(^2\)/d

1.0 \times 10^7\) ft\(^2\)/d
Next Steps in Water-Level Analysis

• Find alternative explanation for damping effects at the boundary other than sediment capping

• Delineate areas of similar aquifer properties

• Analyze groundwater responses to long-period ocean water-level fluctuations (El Niño)
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# Well Database

![Well Database Excel Spreadsheet](image.png)

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Model grid showing thickness of limestone aquifer below sea level
Model grid showing wells and drains

Volcanics above sea level
Model grid showing observed heads

Volcanics above sea level
Model grid showing example hydraulic conductivity distribution
Model grid showing modeled heads
Model grid showing potential groundwater flow lines
Next Steps

Groundwater flow model - Modflow
• Match tidal efficiency and lag data
• Match observed water levels and gradients

Solute transport model – SUTRA/SEAWAT/SWI
• Match chloride and pumping data
• Model future pumping and recharge scenarios
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Next Steps

• Review and publish Water-Budget report by end of March 2012
• Write up aquifer test analysis by end of December 2011
• Continue developing numerical groundwater model
• Formulate future pumping scenarios
• Develop a long-term monitoring plan for NGLA