Guam Groundwater-Availability Study

Technical Working Group Meeting

September 20, 2011

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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*

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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

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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

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Timelines

Activity	2010				2011				2012				2013		
	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul
Data Review															
Recharge Analysis															
Water Budget Report															
Water-Level Surveys															
Regional Numerical Model															
Groundwater Availability Report															

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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

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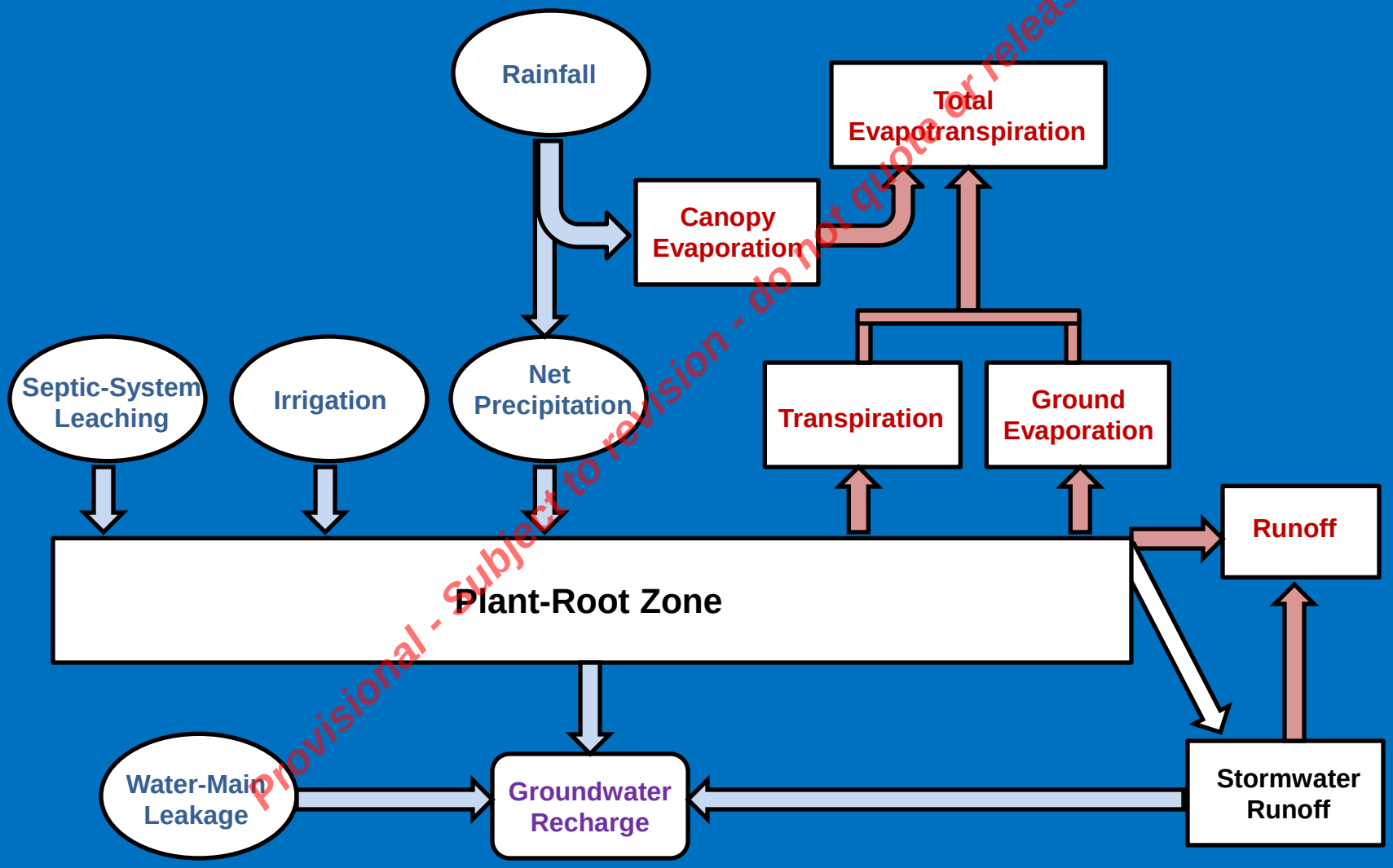
Water-budget model



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Water-budget calculation

Subarea example

Daily water fluxes

Inflow	Outflow
Rainfall	Total Evapotranspiration
Irrigation	Runoff
Septic-system leaching	
Water-main leakage	
Stormwater	
Stored soil-moisture	

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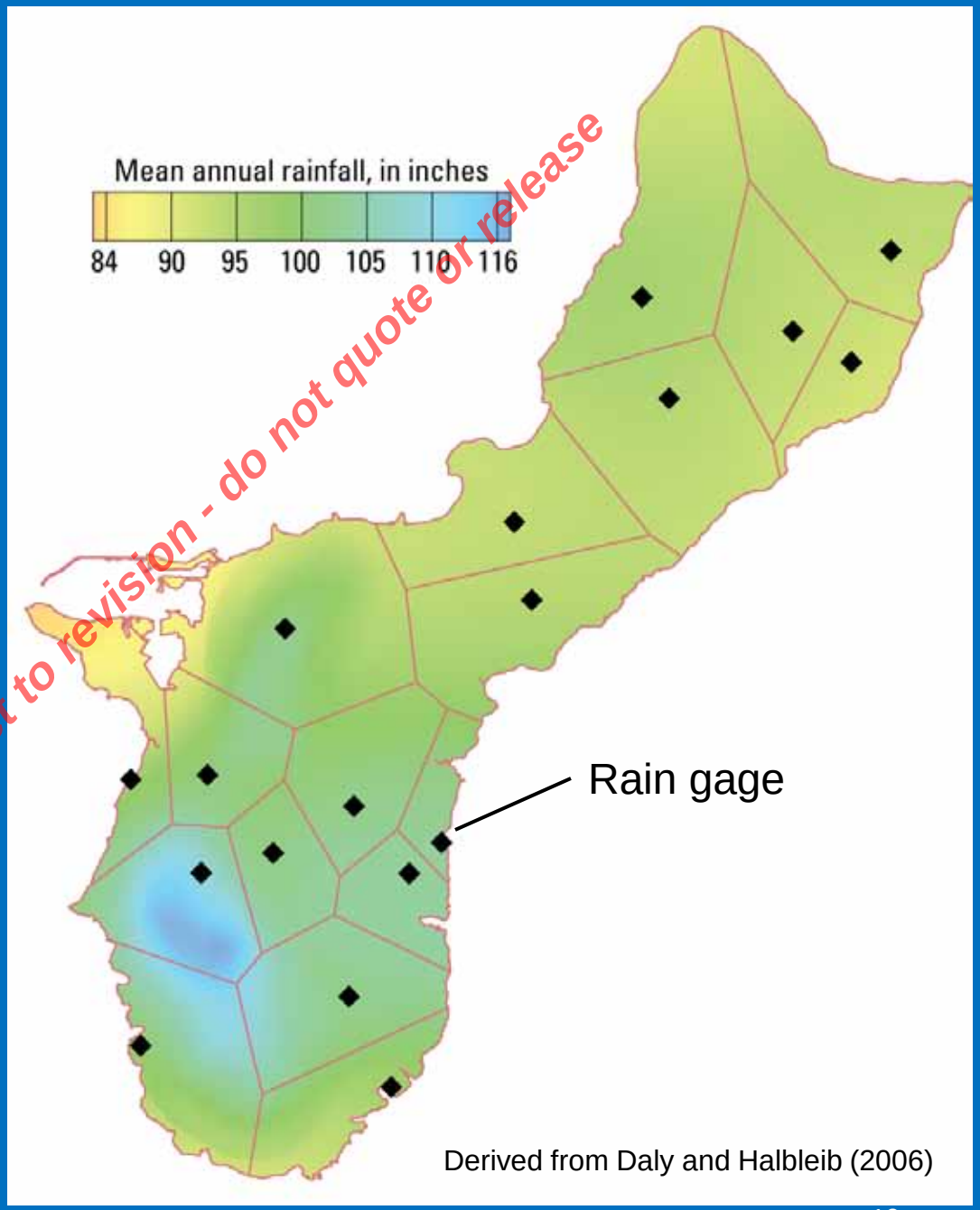
à Water-budget model quantifies these water fluxes for the entire island on a <u>daily</u> basis

Rainfall

- Mean monthly rainfall maps used to distribute rainfall (PRISM: Daly and Halblieb, 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)

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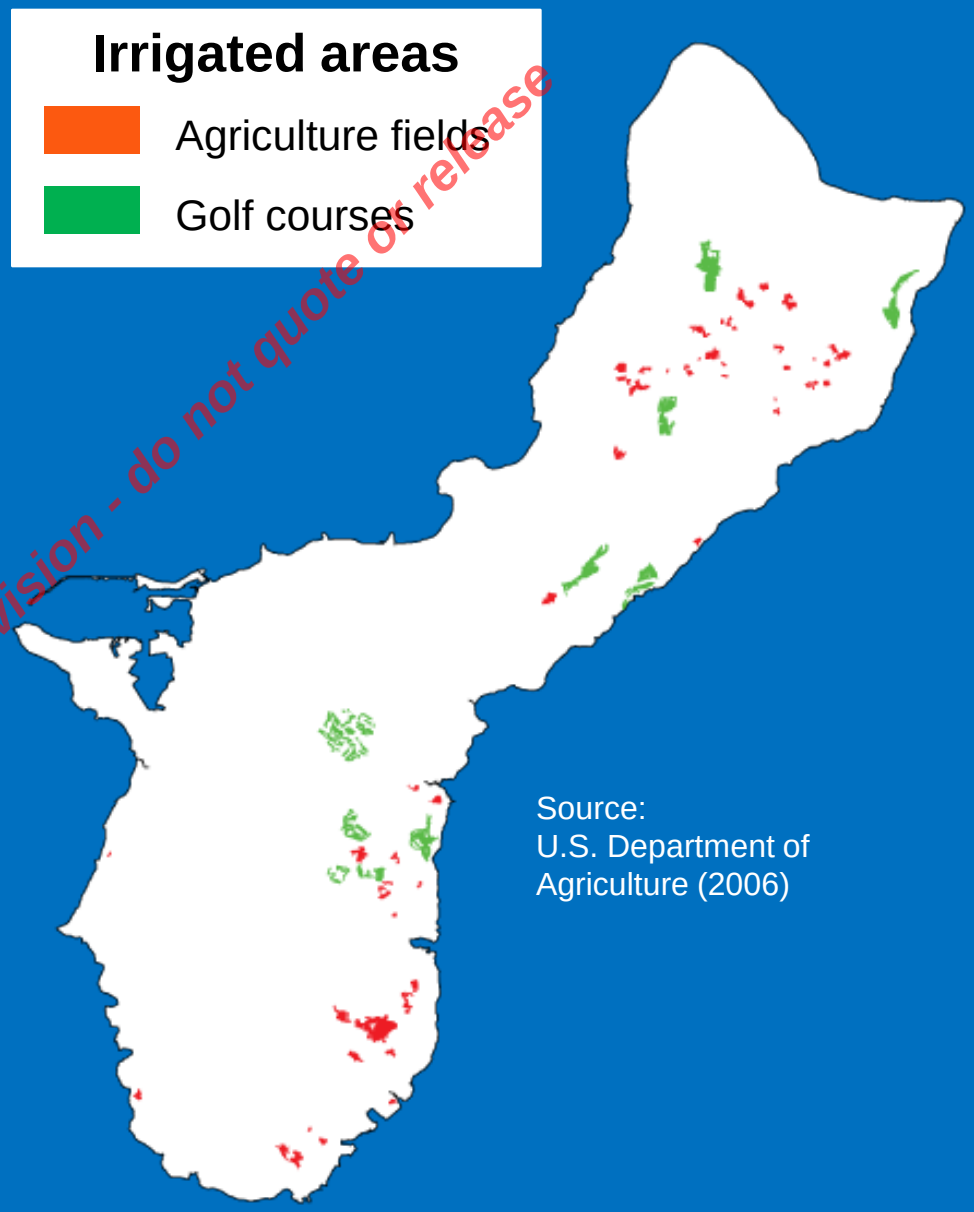
Irrigation

- Applied to all:
  - Agriculture fields
  - Golf courses
- Irrigation rates:
  - estimated based on monthly rainfall and potential evapotranspiration
  - mean annual rate: 0.8 Mgal/d



Source:
U.S. Department of Agriculture (2006)

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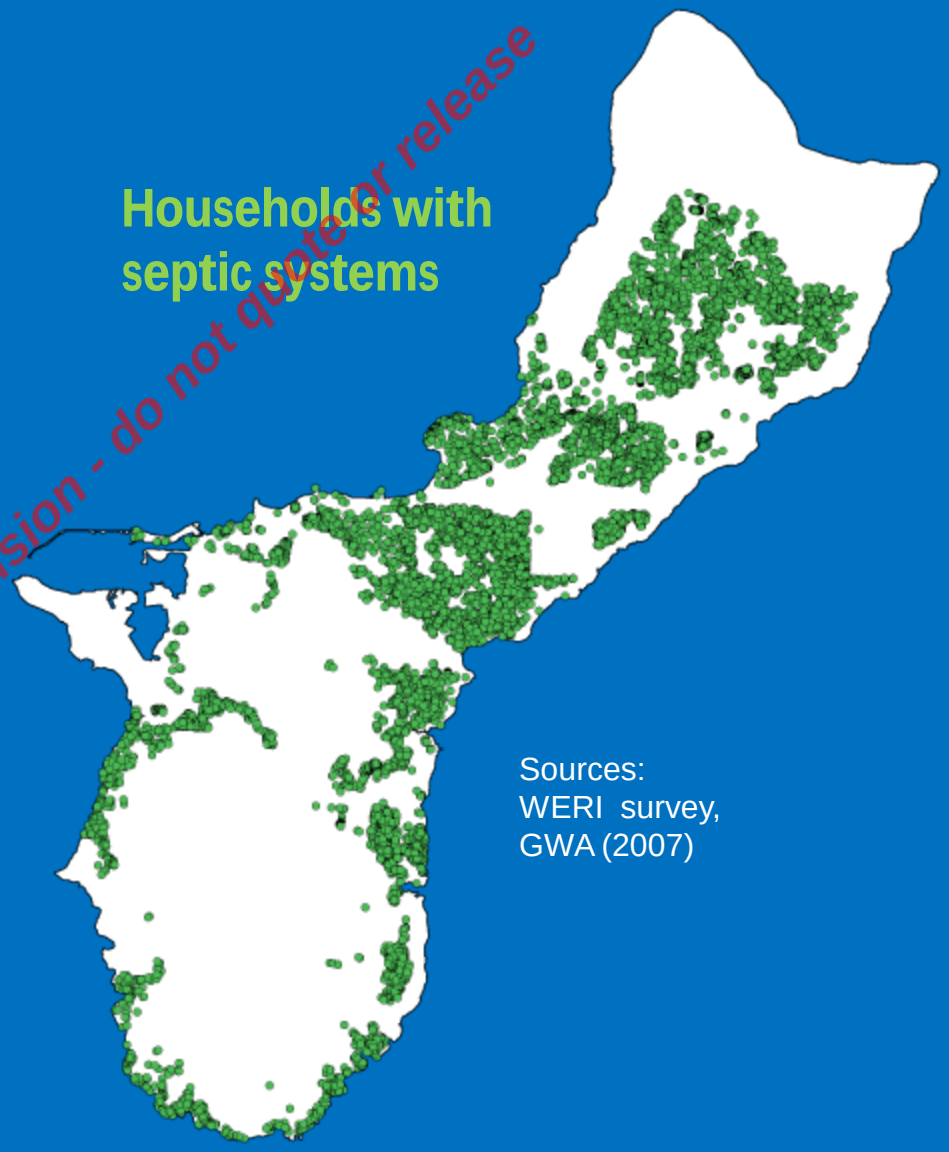
Septic systems

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)

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Water-main leakage

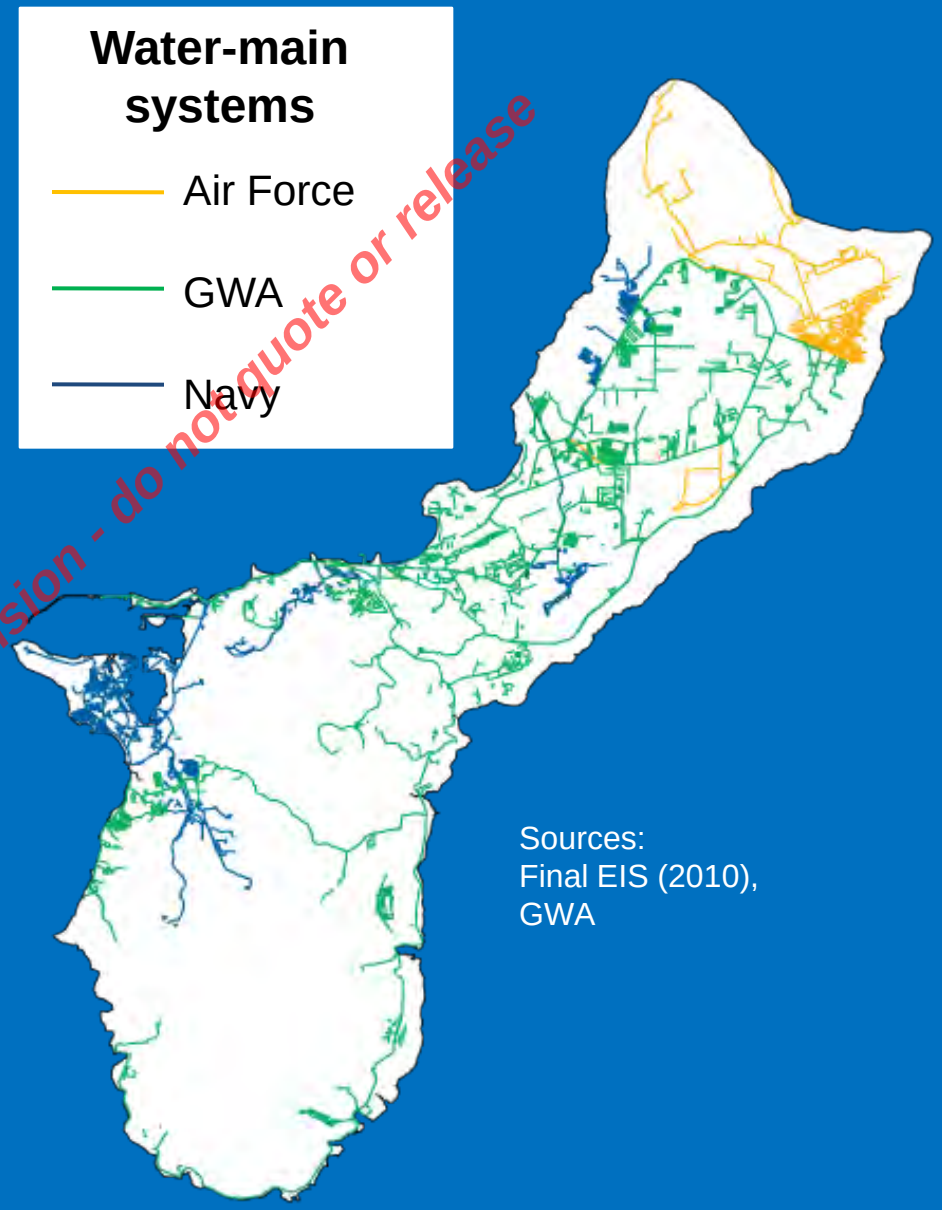
Leakage rates: (Final EIS, 2010)

- 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

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Water-inflow comparison

Water-budget parameter	Mean annual rate (Mgal/d)
Rainfall	999.0
Irrigation	0.8
Septic-system leaching	4.8
Water-main leakage	12.8

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Water-inflow comparison

Water-budget parameter	Mean annual rate (Mgal/d)
Rainfall	999.0
Irrigation	0.8
Septic-system leaching	4.8
Water-main leakage	12.8

less than 2% of total water inflow

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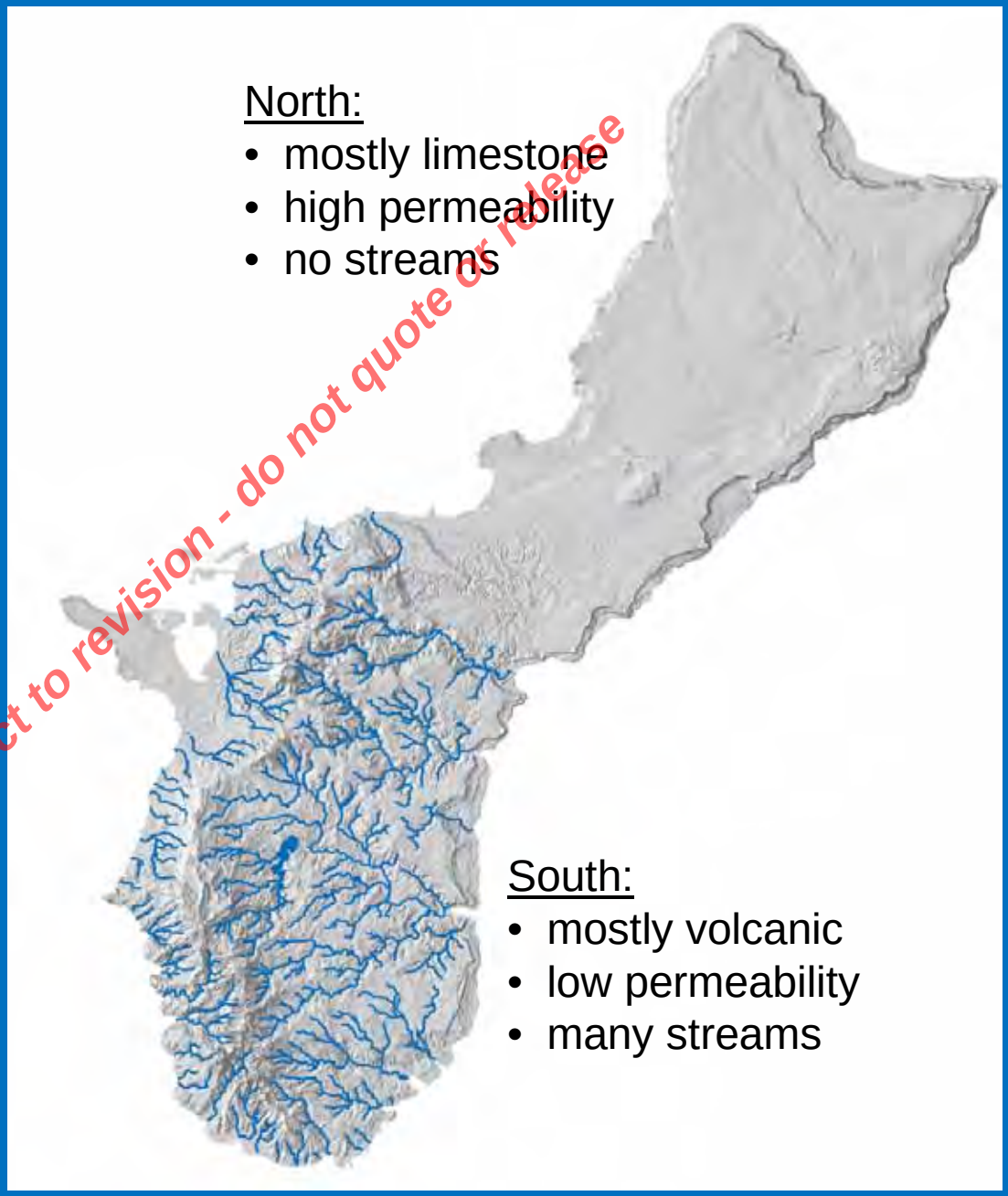
Runoff

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



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Areas with no runoff

Include:

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

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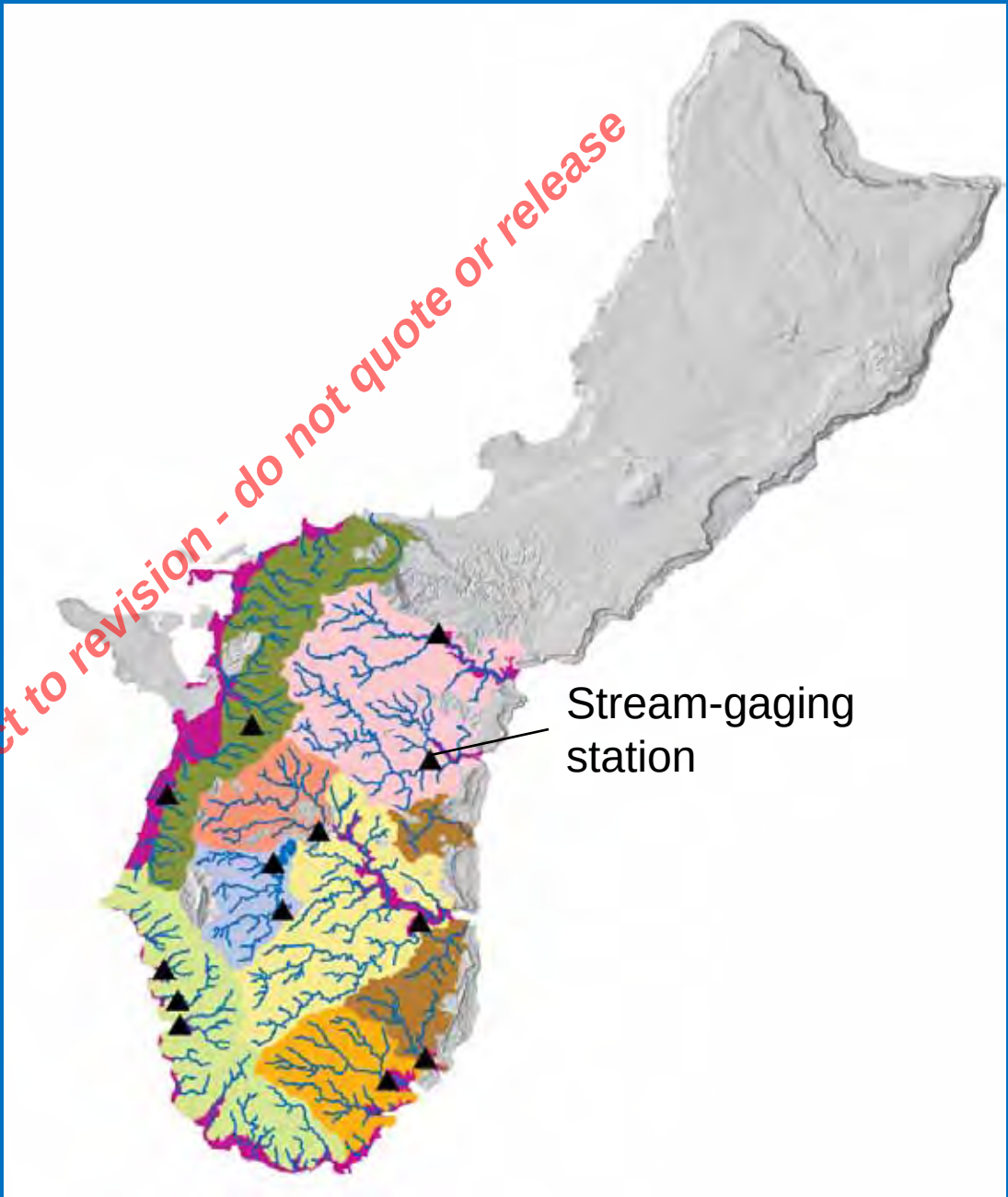
Runoff regions

- 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



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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

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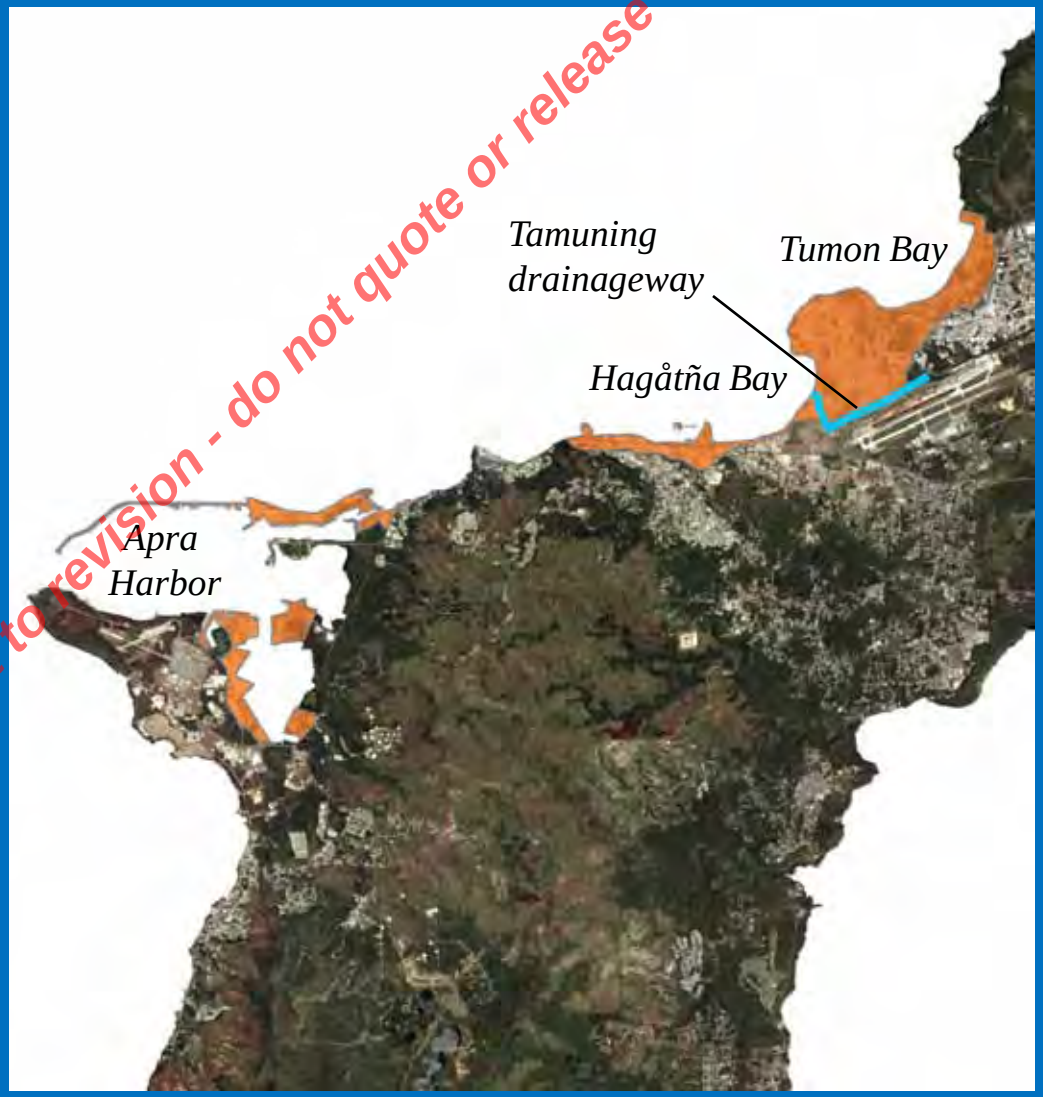
Stormwater runoff to ocean

- 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)

Tamuning drainageway



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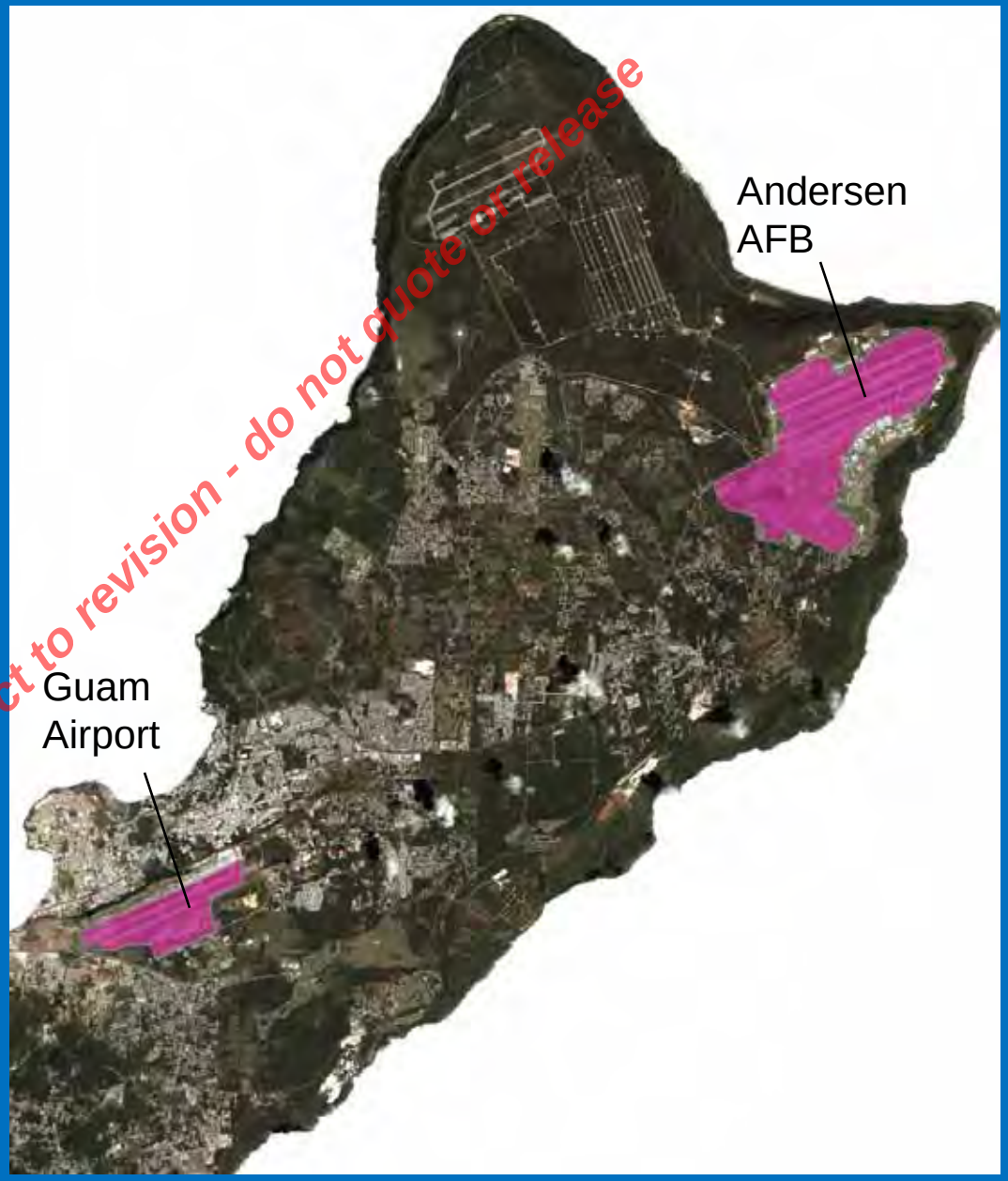
Stormwater runoff to drywells

- 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)



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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)

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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

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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

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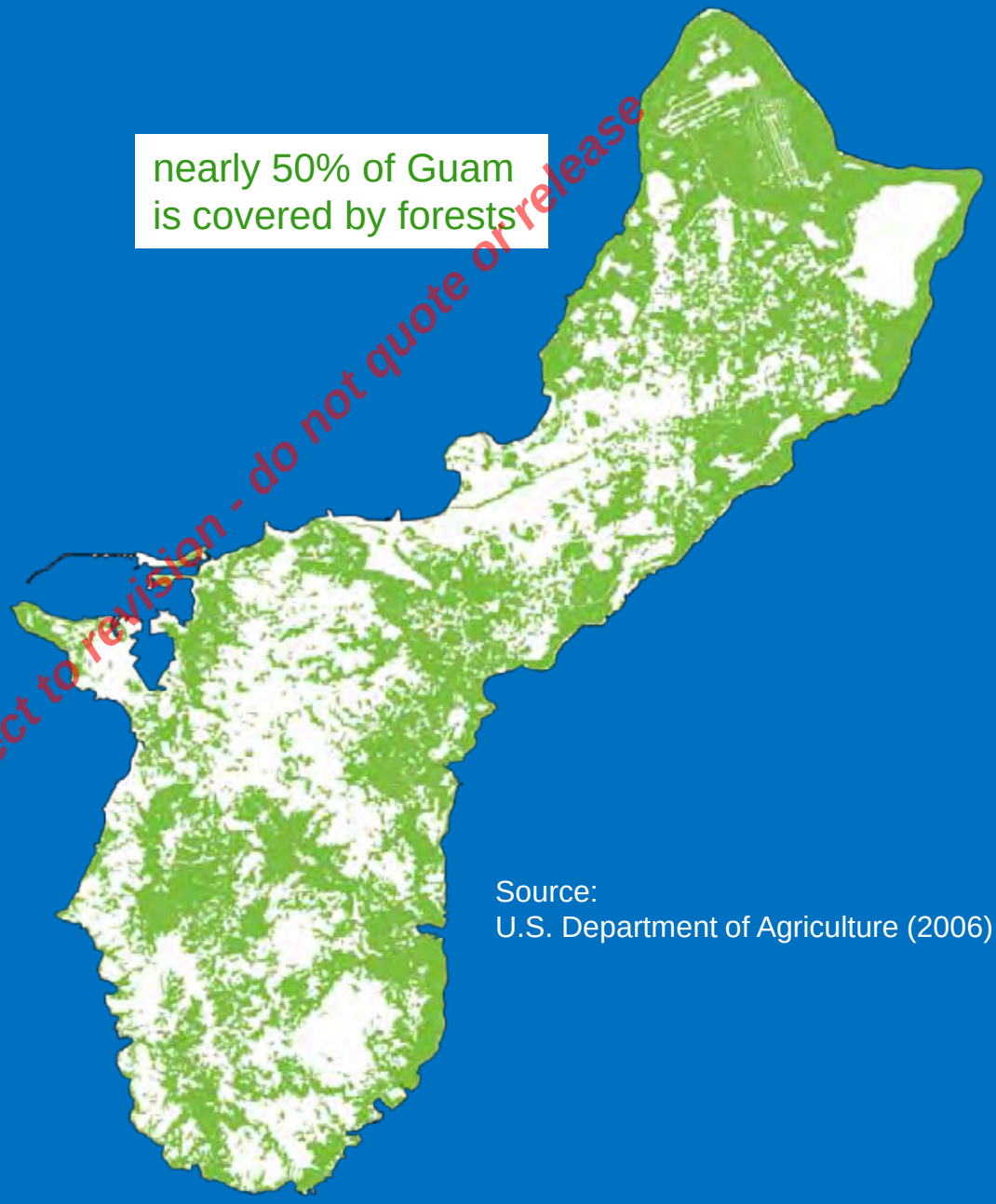
Canopy evaporation in forests

- 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



Source:
U.S. Department of Agriculture (2006)

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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

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Potential evapotranspiration

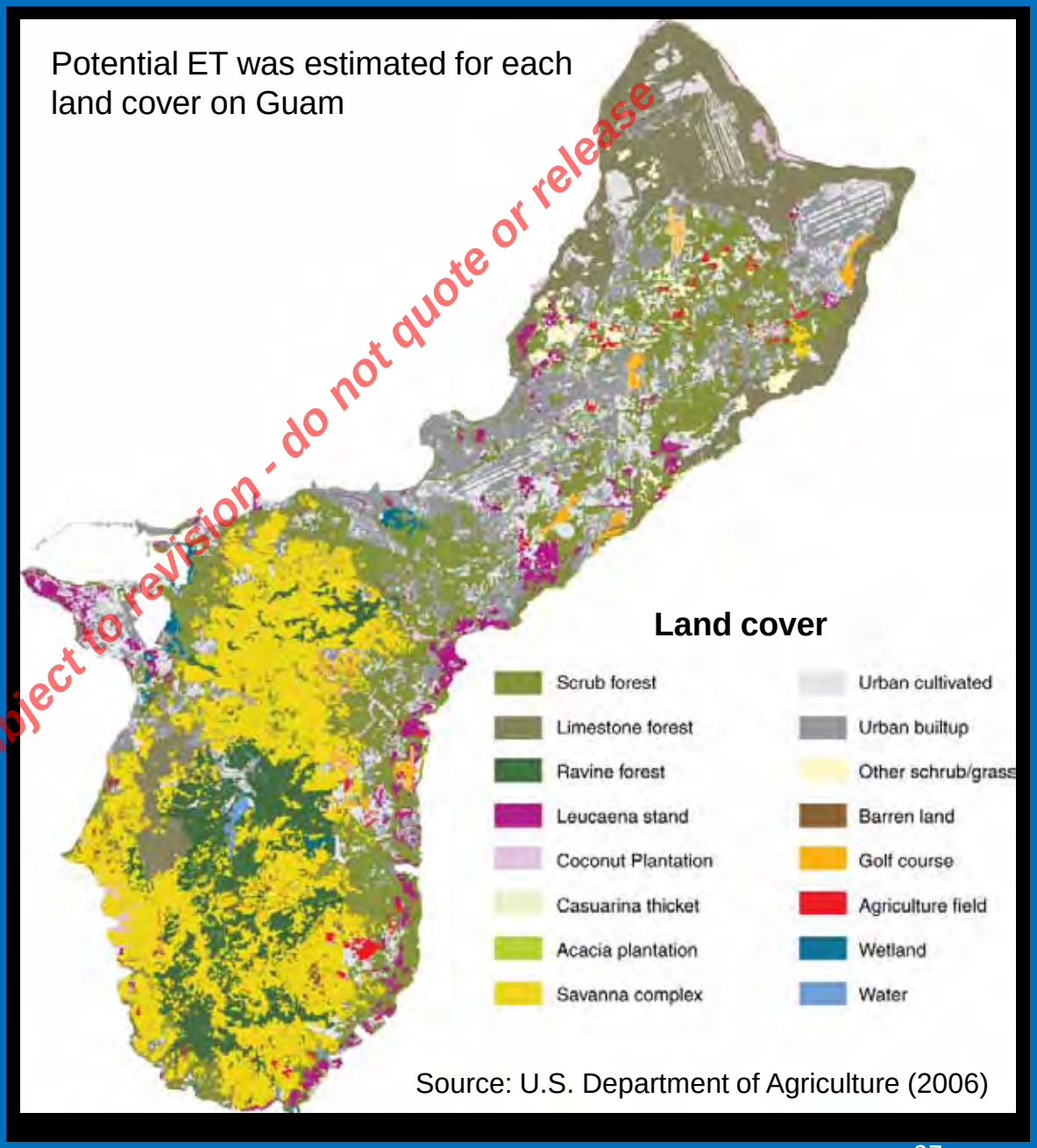
- Maximum ET rate for given land cover

- <u>For each land cover:</u>

  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



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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 à potential ET rate
- low moisture à reduced ET rate

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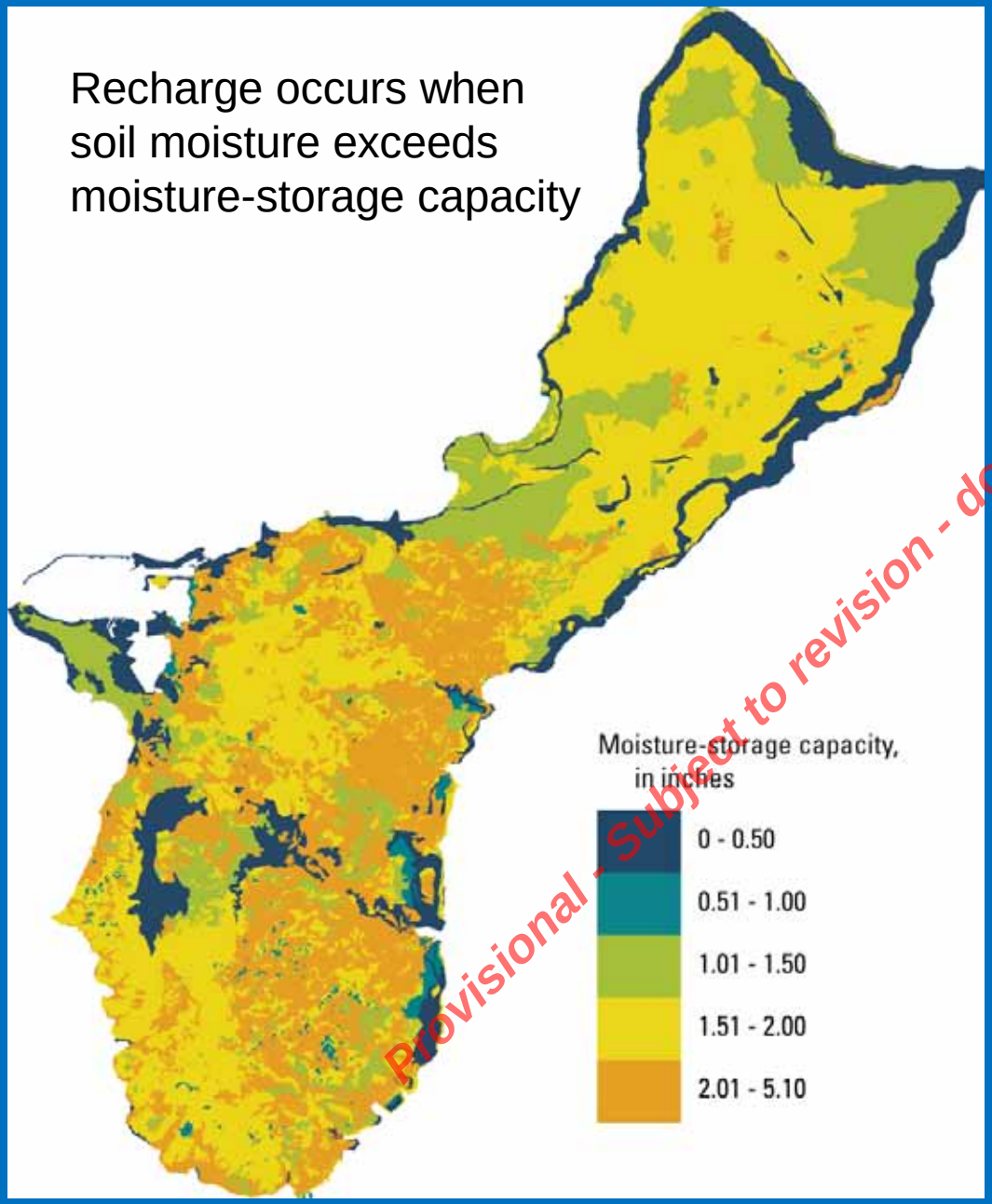
Moisture-storage capacity



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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)

Water-budget model results

Parameter	Mean annual rate (Mgal/d)	Percent of water input
Total water input	1017	100%
Rainfall	999	98%
Runoff	130	13%
Total evapotranspiration	495	49%
Recharge	392	38%

for entire island and "baseline conditions"

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

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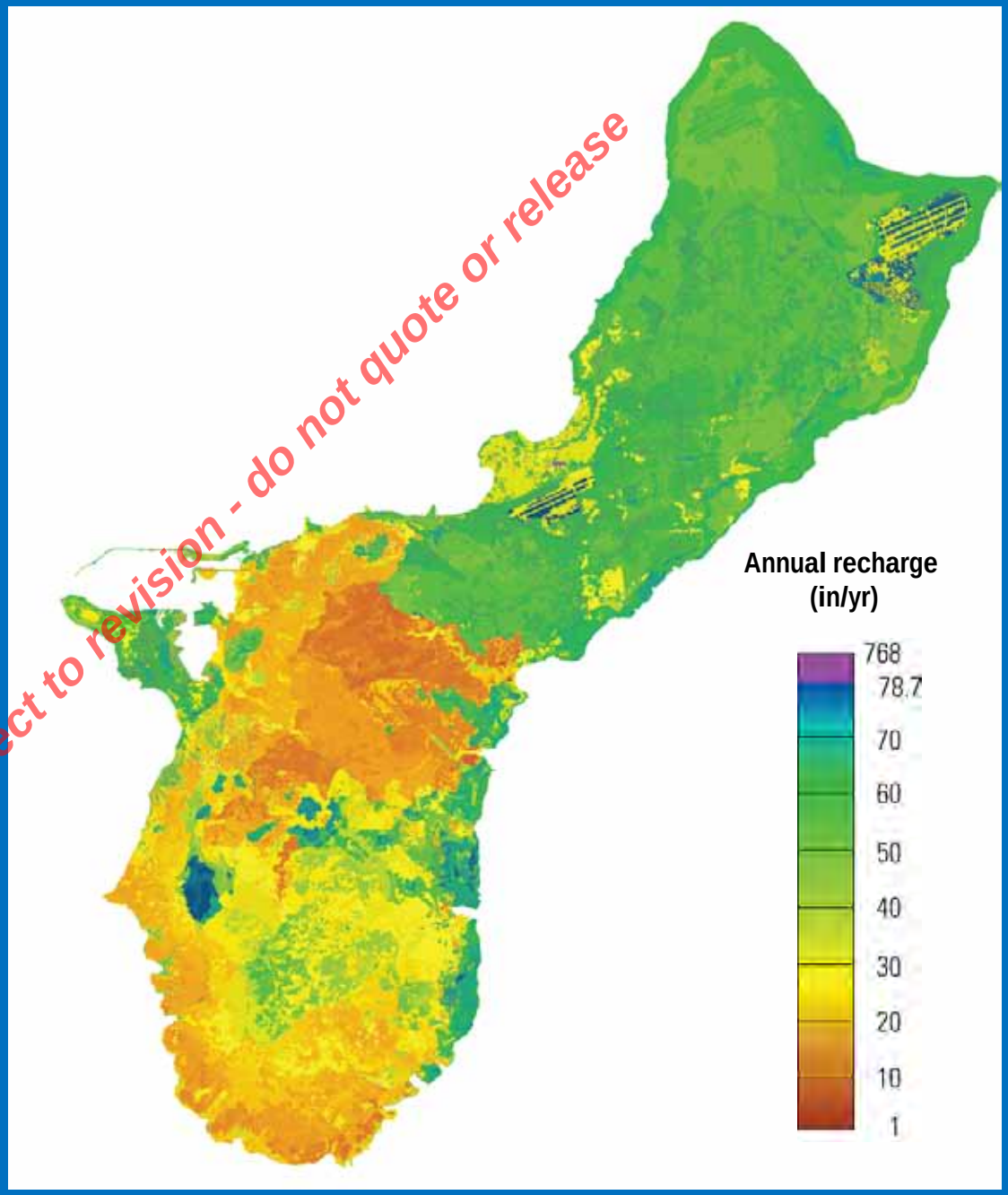
Mean annual recharge distribution

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



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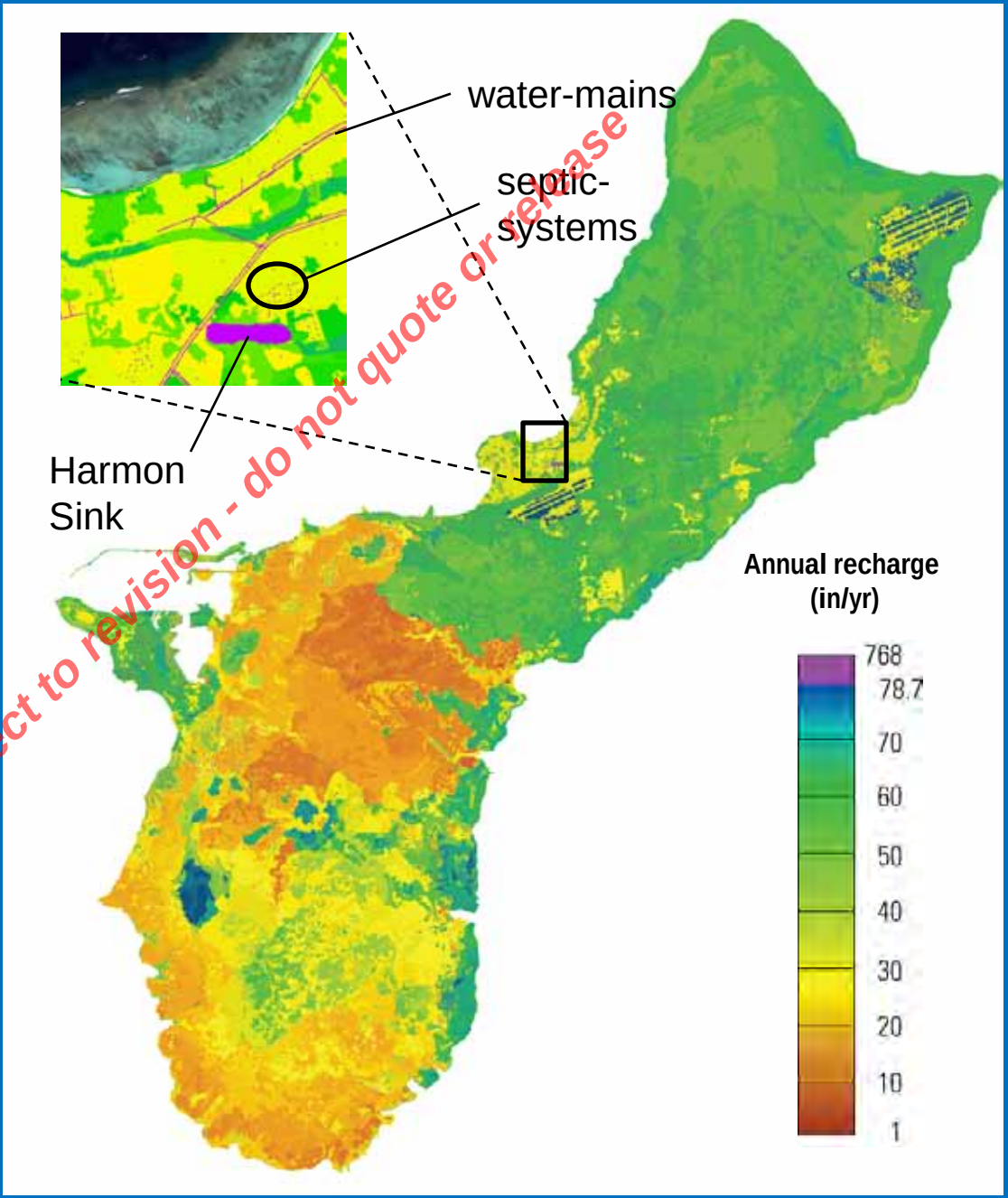
Mean annual recharge distribution

Recharge can be enhanced by

- water-main leakage
- septic-system leaching
- stormwater runoff at Harmon Sink



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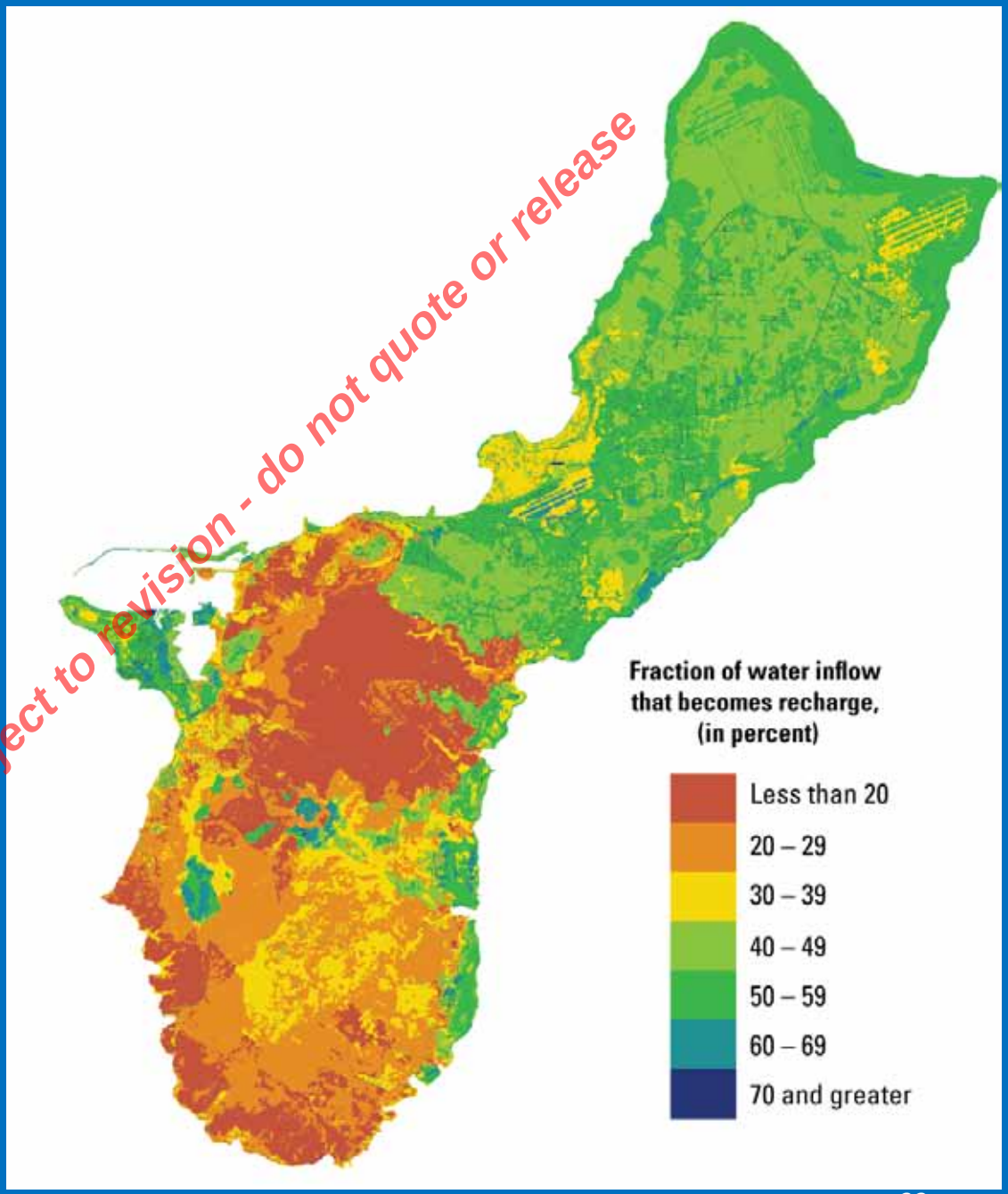
Recharge, percent of water inflow

most limestone areas:
40 to 60%

most volcanic areas:
less than 30%



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Comparisons to previous water-budget studies on Guam

Study	Time step	Study area
"Northern Guam Lens Study" (CDM Inc., 1982)	Mean monthly	Part of northern Guam
Mink (1991)	Mean monthly	Most of northern Guam
Jocson and others (2002)	Daily	Part of northern Guam
Habana and others (2009)	Daily	Part of northern Guam
This study	Daily	Entire island

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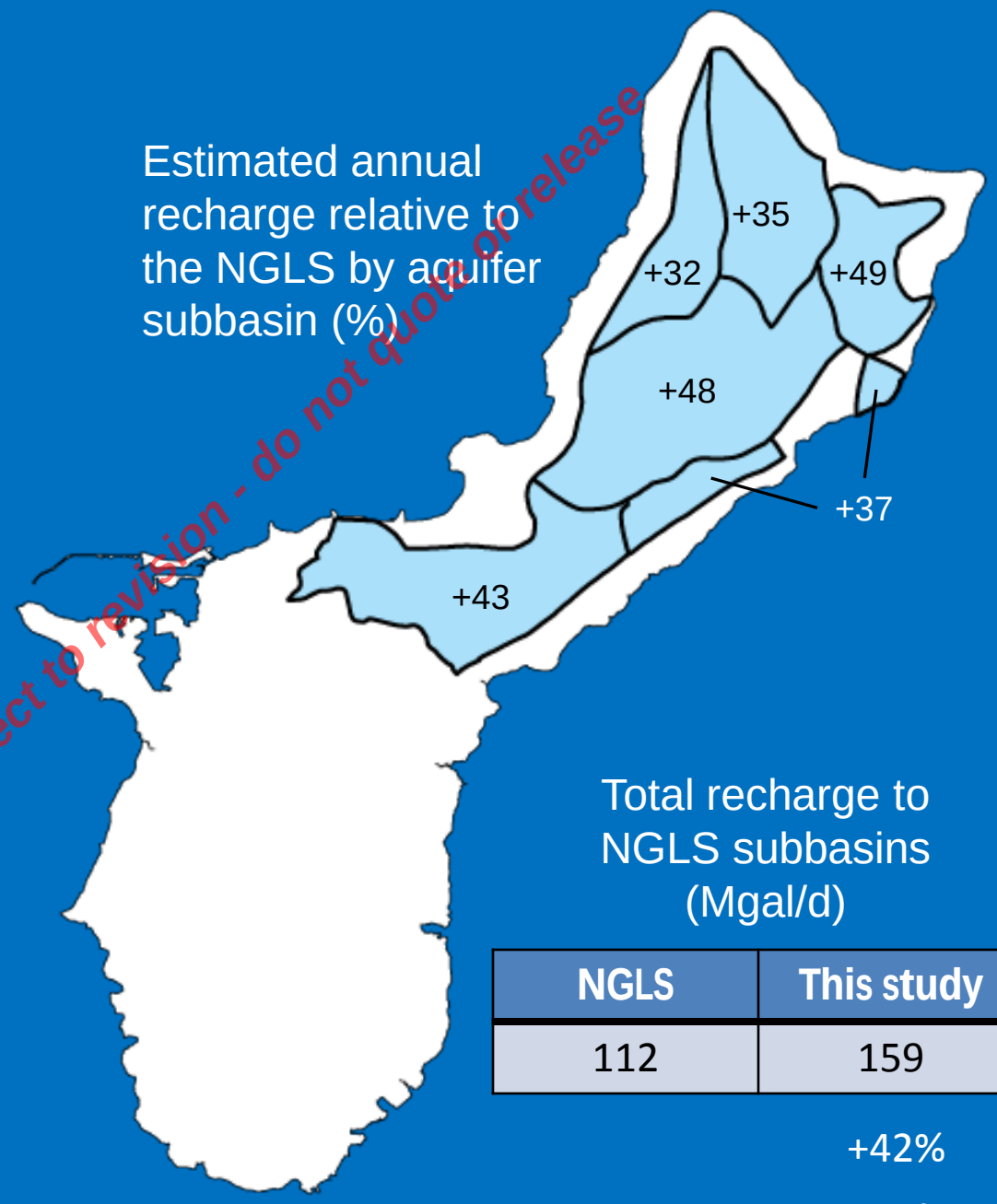
Comparison to "Northern Guam Lens Study" (NGLS)

(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 (%)



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Total recharge to NGLS subbasins (Mgal/d)

NGLS	This study
112	159

+42%

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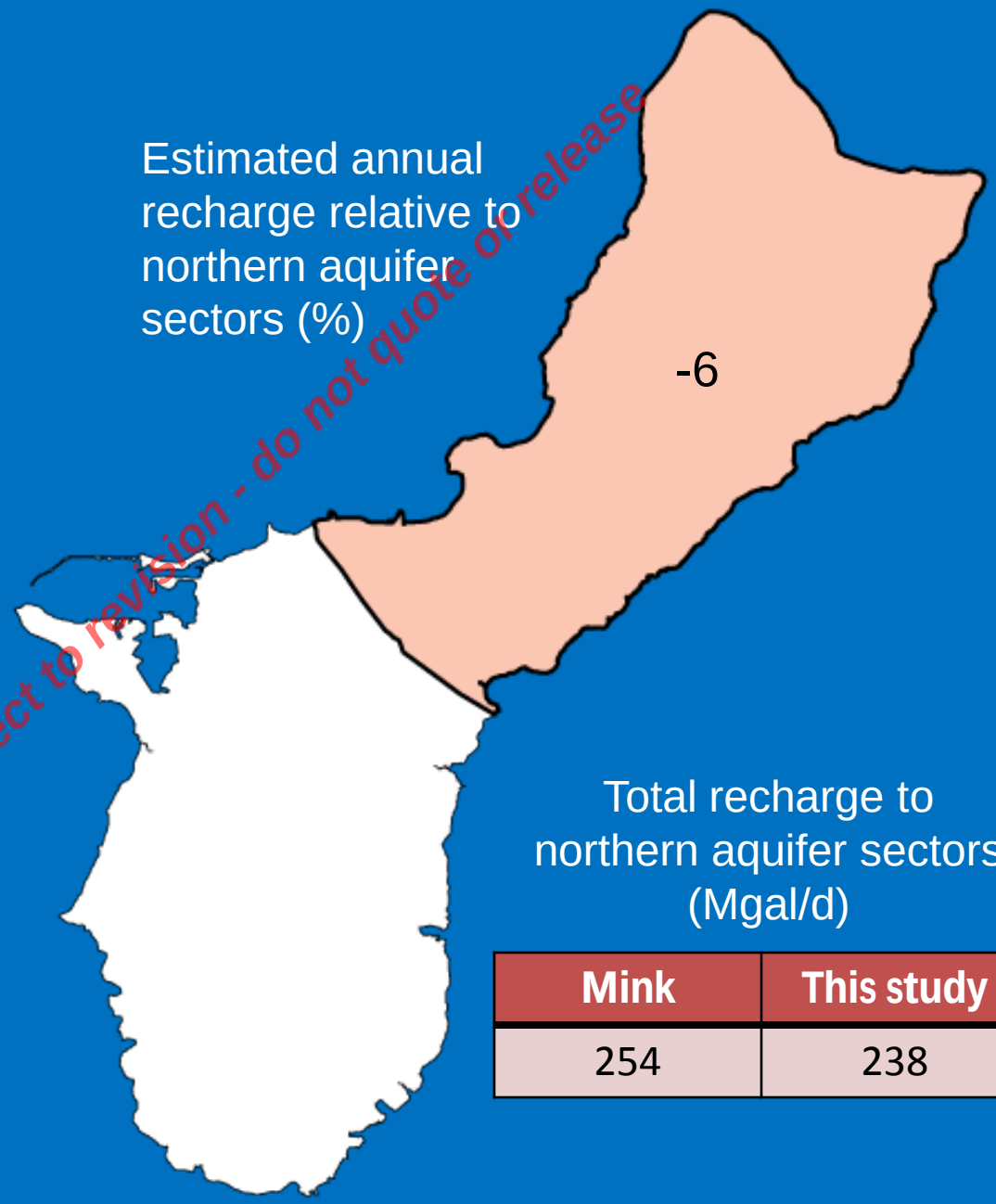
Comparison to Mink (1991)

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 (%)



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Total recharge to northern aquifer sectors (Mgal/d)

Mink	This study
254	238

Comparison to Jocson and others (2002)

Recharge computed as daily rainfall minus daily pan evaporation

Implicit assumptions:

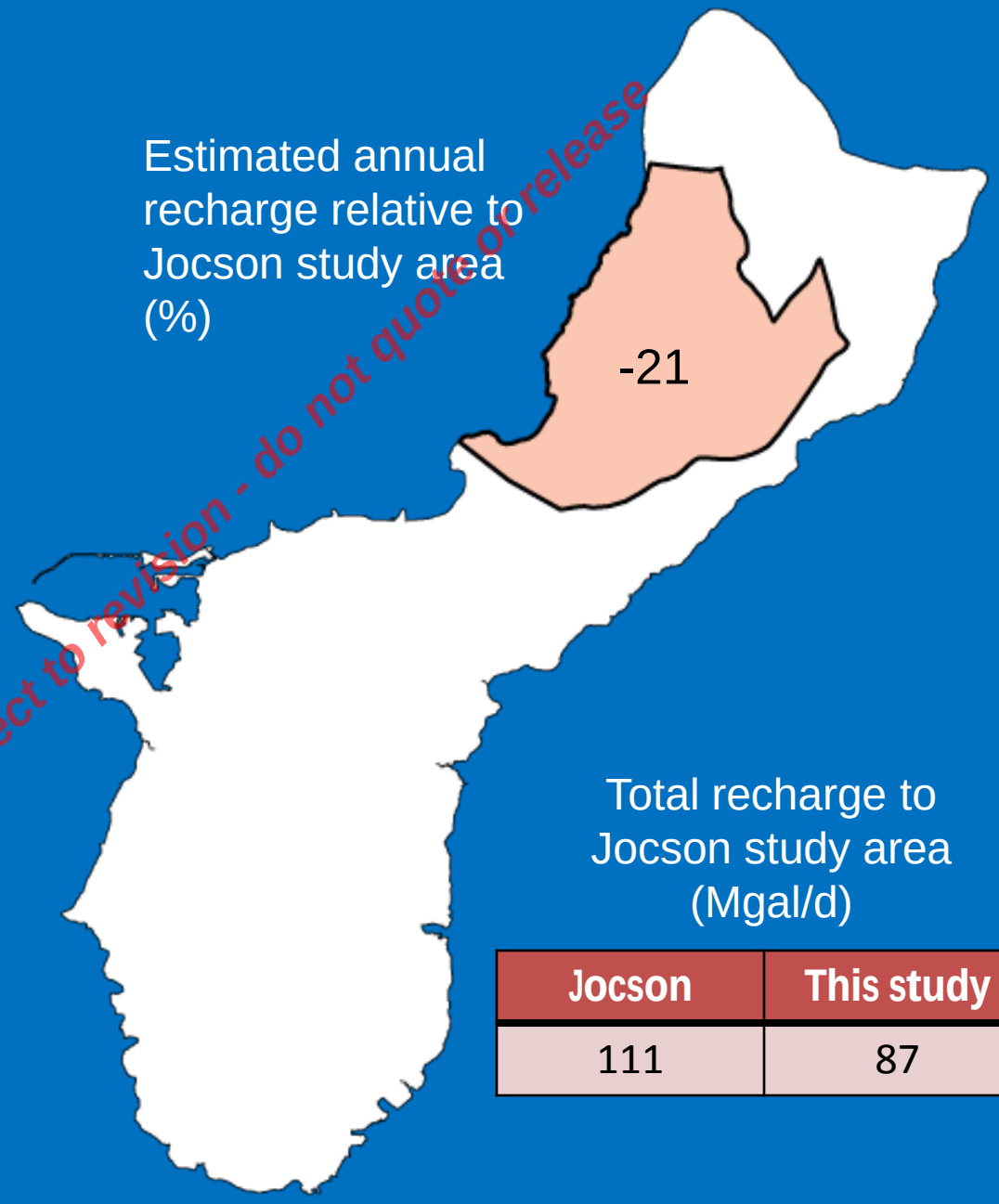
1) ET is zero on days with no rain

2) no moisture stored in soil for more than a day

Did not directly account for canopy evaporation

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

Estimated annual recharge relative to Jocson study area (%)



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Total recharge to Jocson study area (Mgal/d)

Jocson	This study
111	87

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

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

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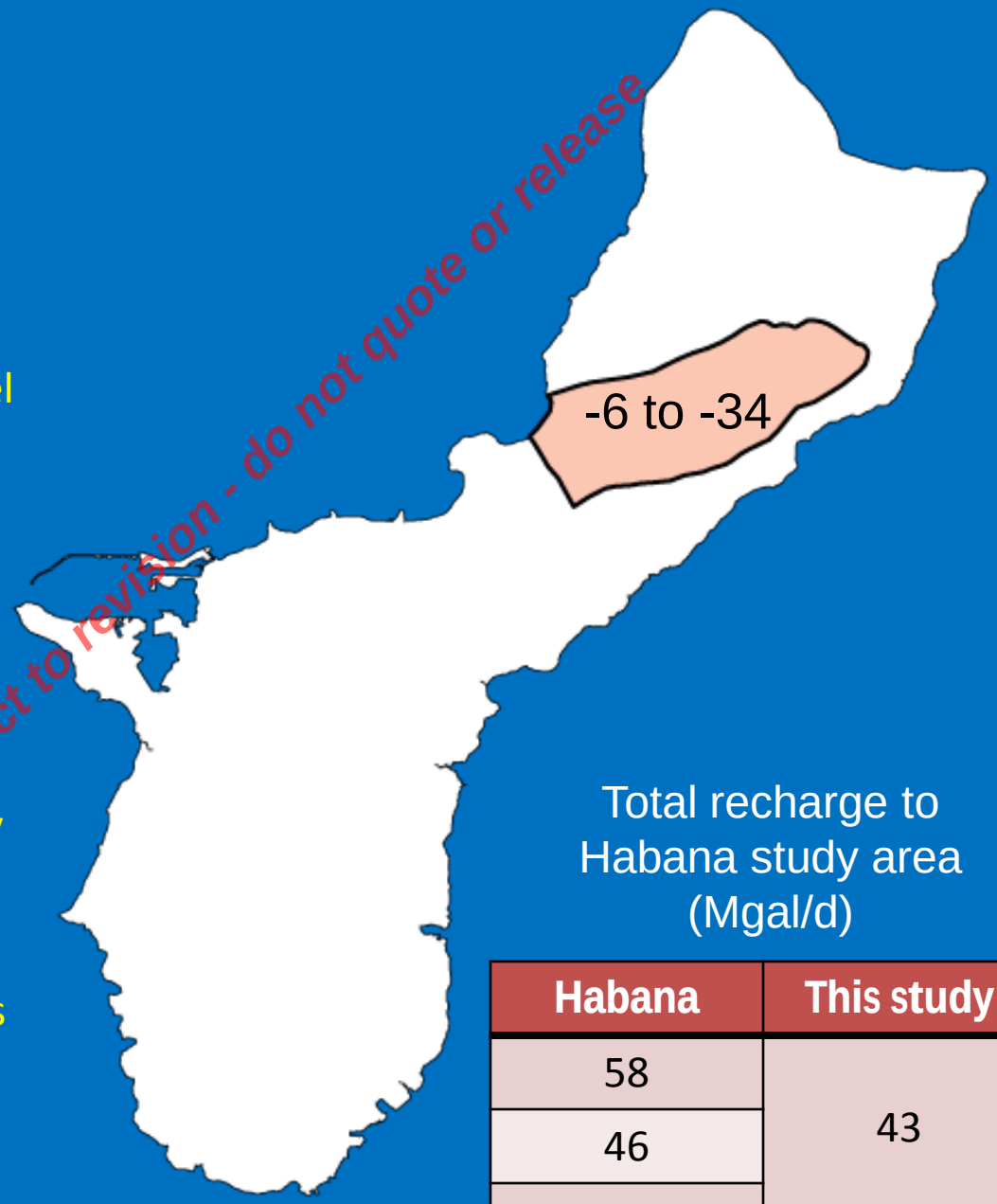

Total recharge to Habana study area (Mgal/d)

Habana	This study
58	43
46	
48	

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Recharge scenarios

Scenario	Rainfall	Land cover
Baseline	1961 – 2005	2004
Future land cover	1961 – 2005	After military buildup
Drought	1969 – 1973	2004
Future land cover and drought	1969 – 1973	After military buildup

- 1969 – 1973 had the lowest 5-year rainfall average since 1961

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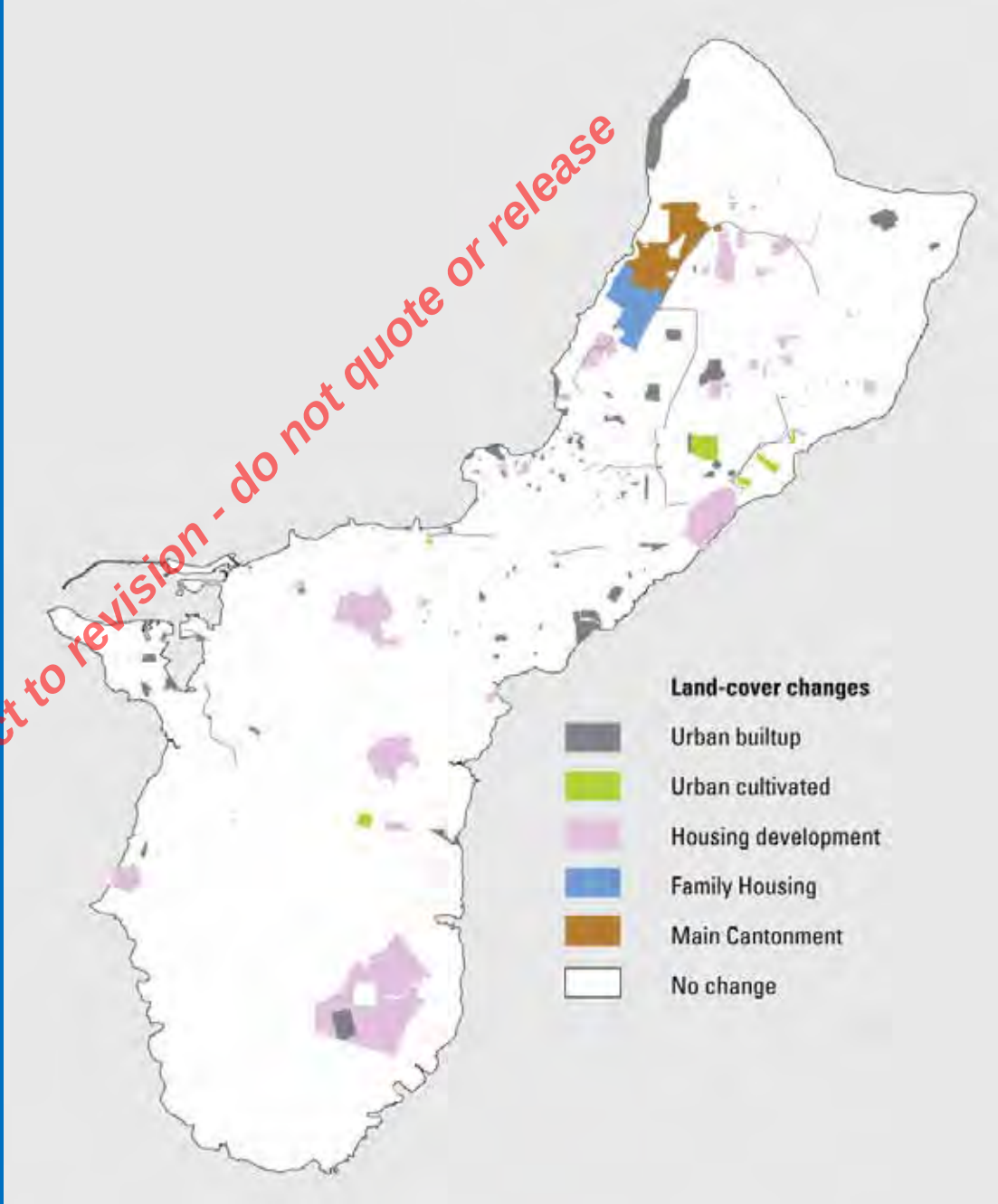
Future land-cover changes

Includes potential land-cover changes incurred by:

- proposed military buildup
- normal background growth

Sources:

- Final EIS (2010)
- GWA Water Resource Master Plan (2007)
- Database of approved development projects from Guam Bureau of Statistics and Plans (Victor Torres)



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Comparison to baseline recharge

Percent difference from baseline recharge

Scenario	Entire island	Northern aquifer sectors
Future land cover	+1%	+1%
Drought	-34%	-31%
Future land cover and drought	-32%	-30%

baseline recharge is long-term average recharge

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Drought scenario

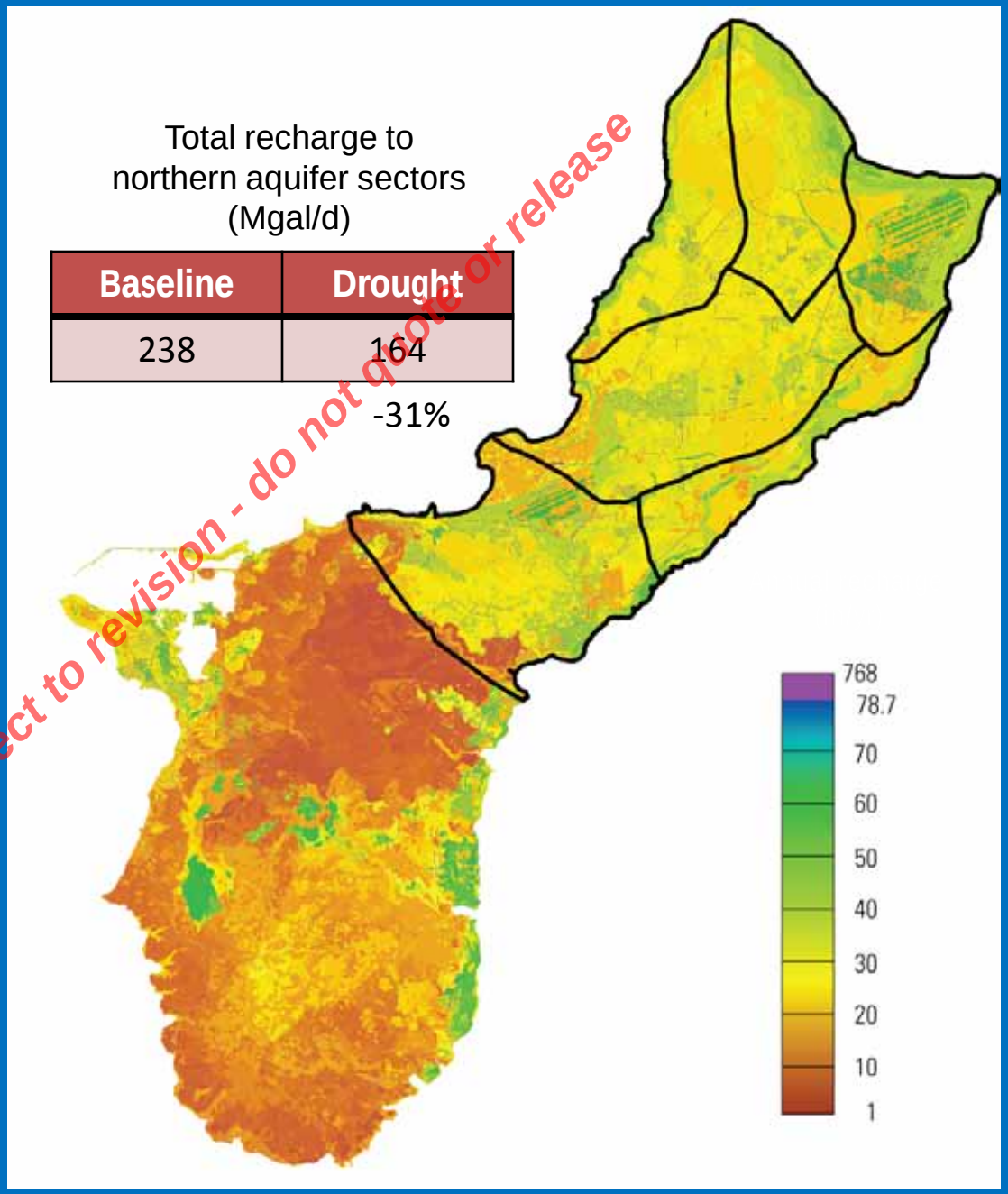
Annual rainfall is 20 percent less than mean annual rainfall

All parameters except rainfall kept the same as baseline

Total recharge to northern aquifer sectors (Mgal/d)

Baseline	Drought
238	164

-31%



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Chloride mass-balance method

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

Equation variable	Definition
C_p	Chloride concentration of rain infiltrating into the ground
P	Annual rainfall
R	Annual runoff
C_{gw}	Chloride concentration of groundwater

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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

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Chloride mass-balance recharge results

Recharge, as a percent of annual rainfall

Bulk-deposition station	Chloride mass-balance method	Water-budget model
Jinapsan	26%	55%
Y-15	25%	50%
Beng Bing	40%	50%
Airport	36%	54%
Almagosa	20%	30%

Runoff assumed to be zero at all stations except for Almagosa

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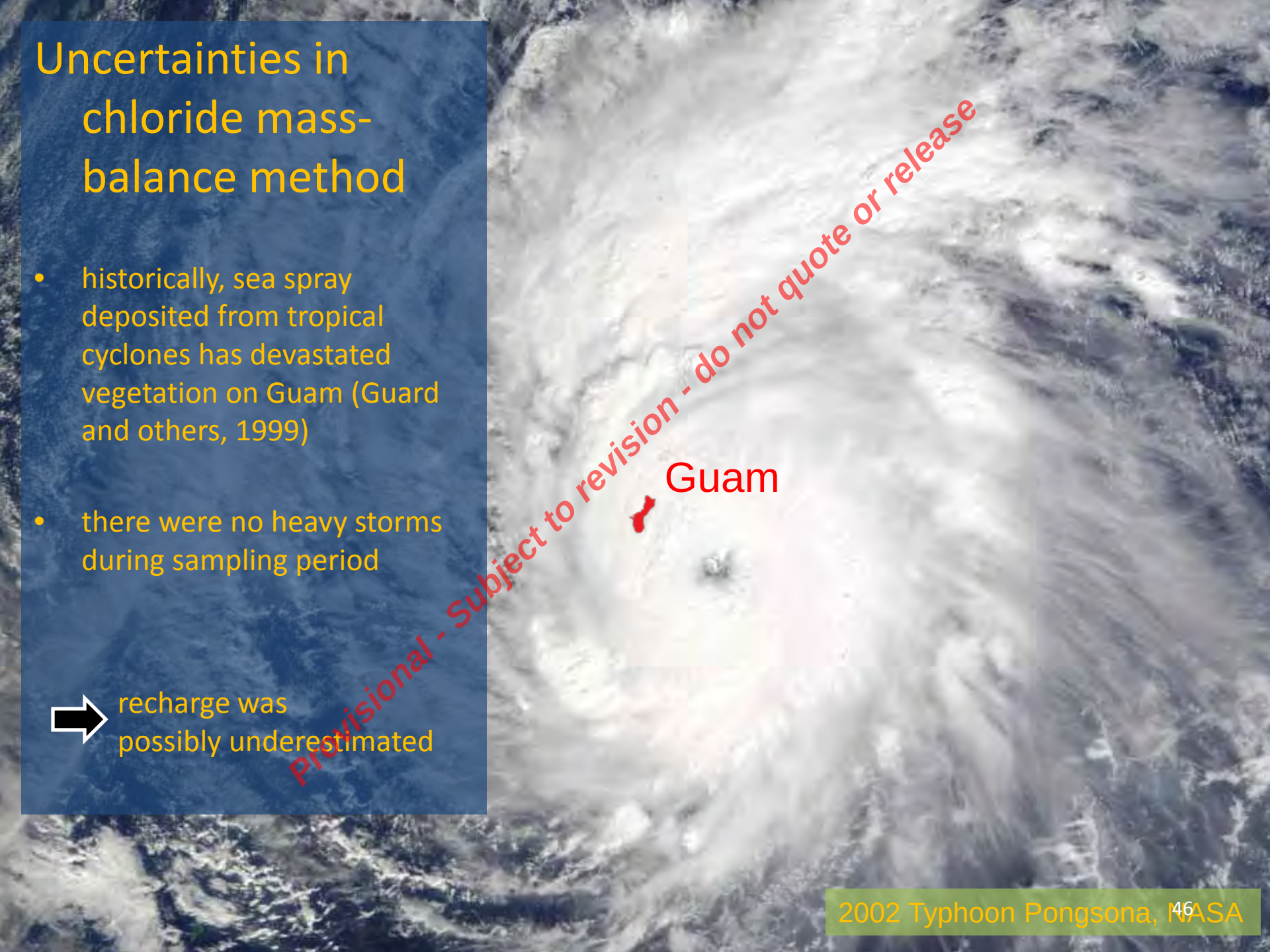
Uncertainties in chloride mass-balance method

- 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



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2002 Typhoon Pongsona, NASA

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

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Water-Level Data Consistency

- Accurate water-level data is needed to determine spatial changes
- Errors can be 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

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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:

GWA 2 1,000 ft S/N 48410

Correction table for measurements since 04/18/11

From (feet)	To (feet)	Add to Depth to Water (feet)
0.00	24.88	0.00
24.89	74.64	-0.01
74.65	124.40	-0.02
124.41	174.17	-0.03
174.18	223.93	-0.04
223.94	273.69	-0.05
273.70	323.46	-0.06
323.47	373.22	-0.07
373.23	422.99	-0.08
423.00	460.13	-0.09
460.14	472.75	-0.09
472.76	550.00	-0.10

Values in blue are extrapolations beyond deepest test measurement (460.13 ft)

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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

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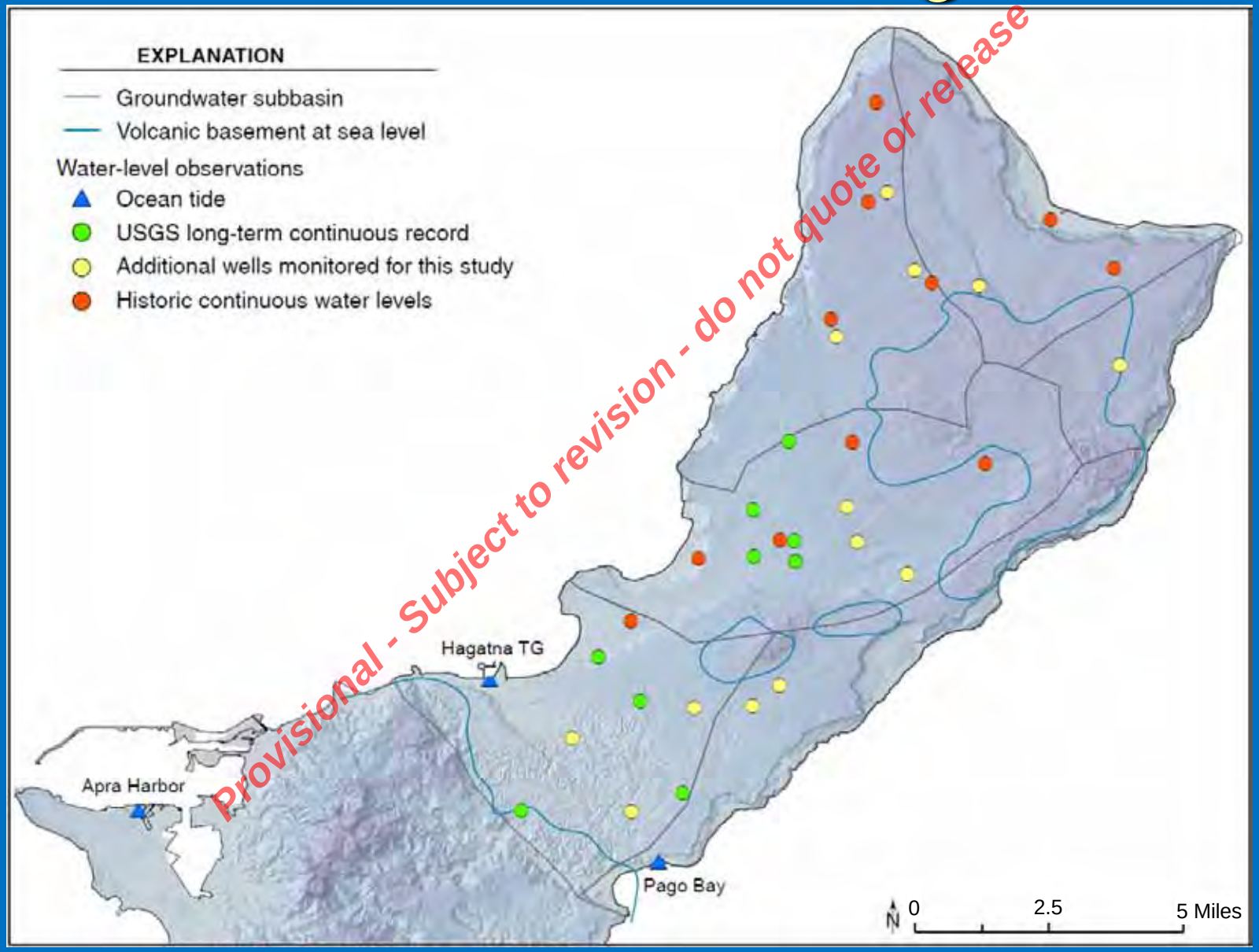
by Kolja Rotzoll, John Jenson, Steve Gingerich, and Aly El-Kadi

Distribution of Monitoring Wells



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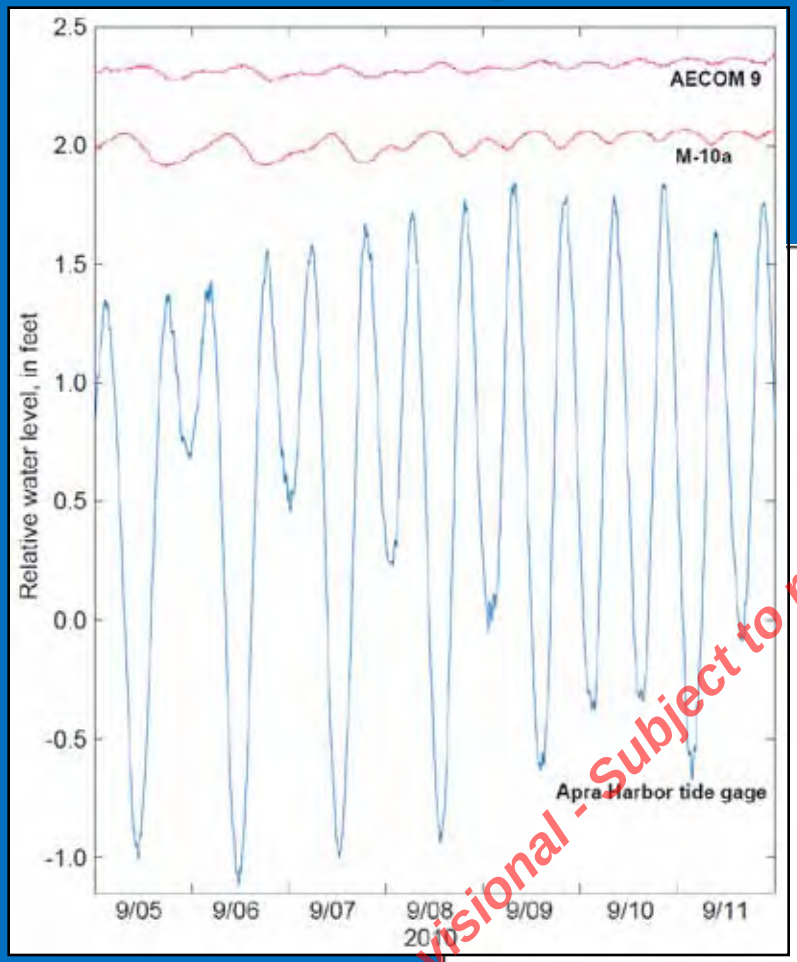
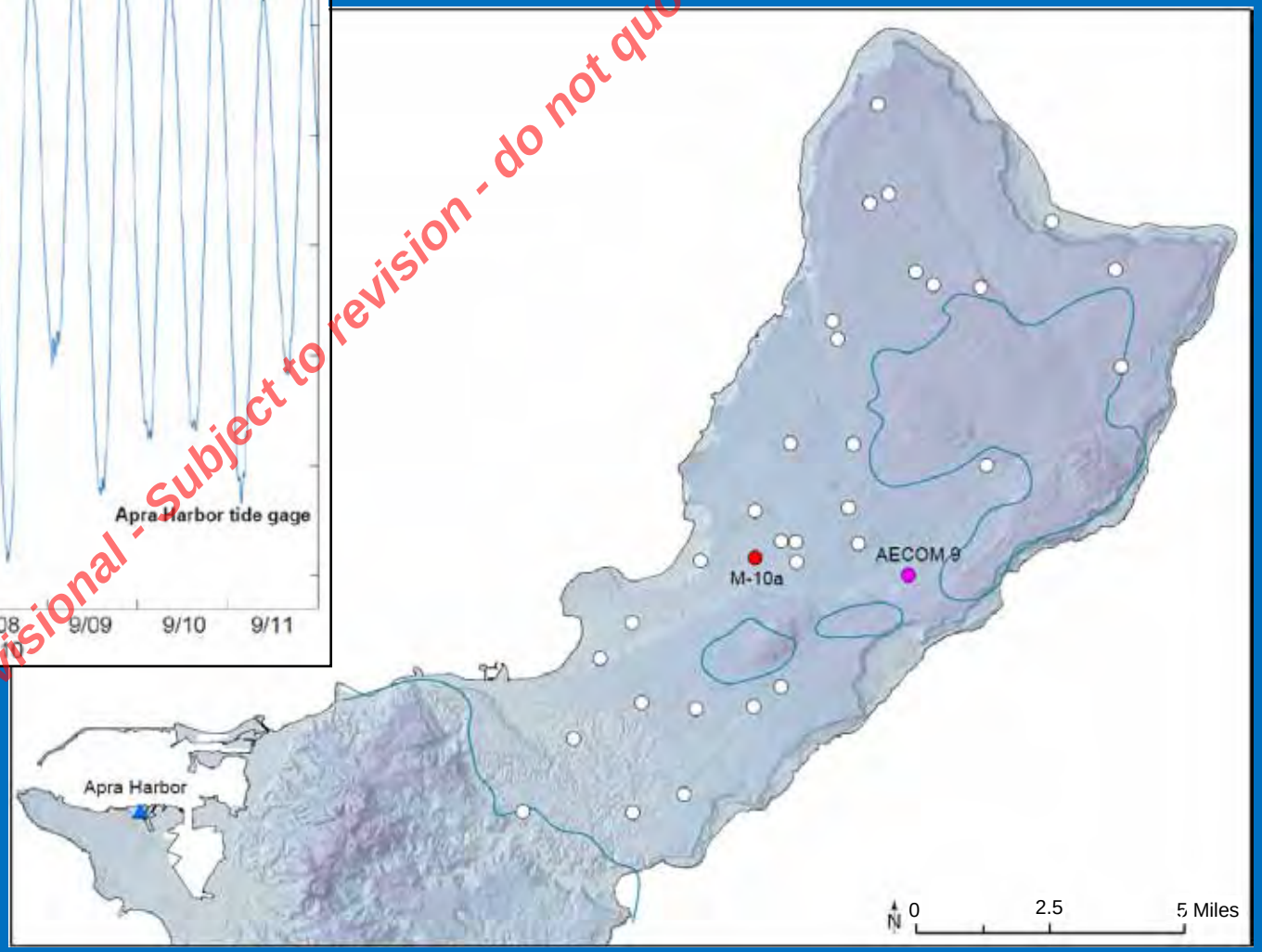
Tidal Response in Monitoring Wells



With increasing distance from the coast:

- amplitude decays exponentially
- time lag increases linearly



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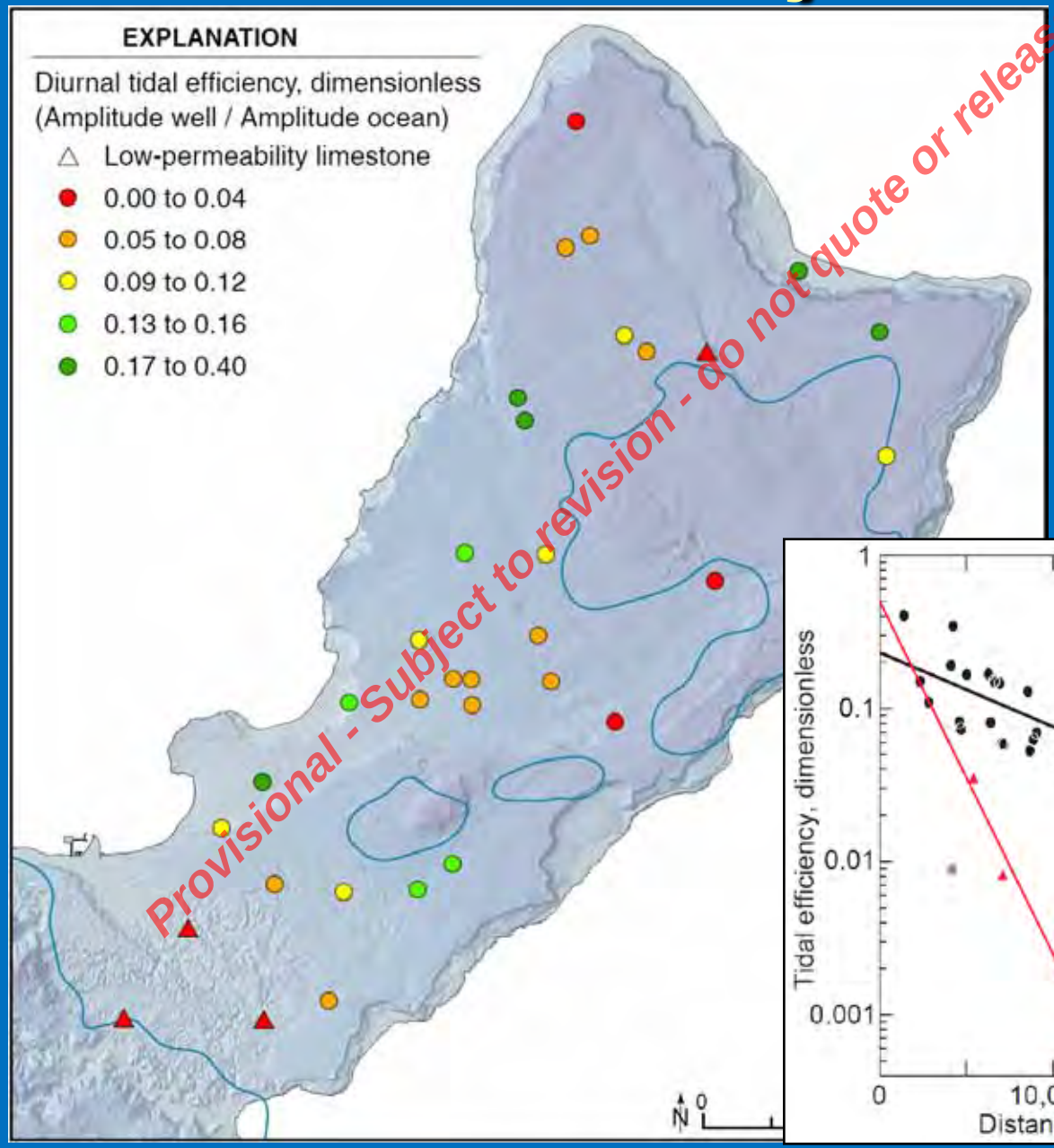
Tidal Efficiency



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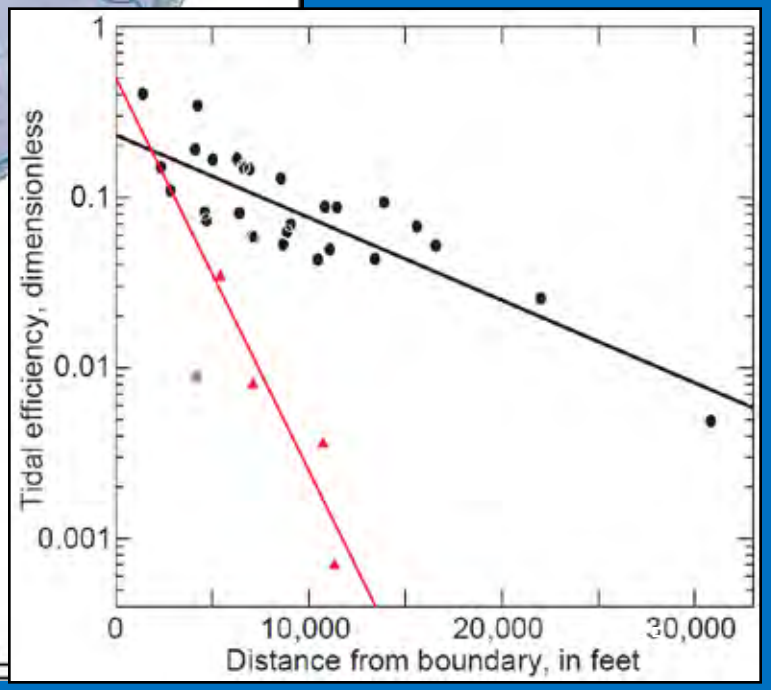
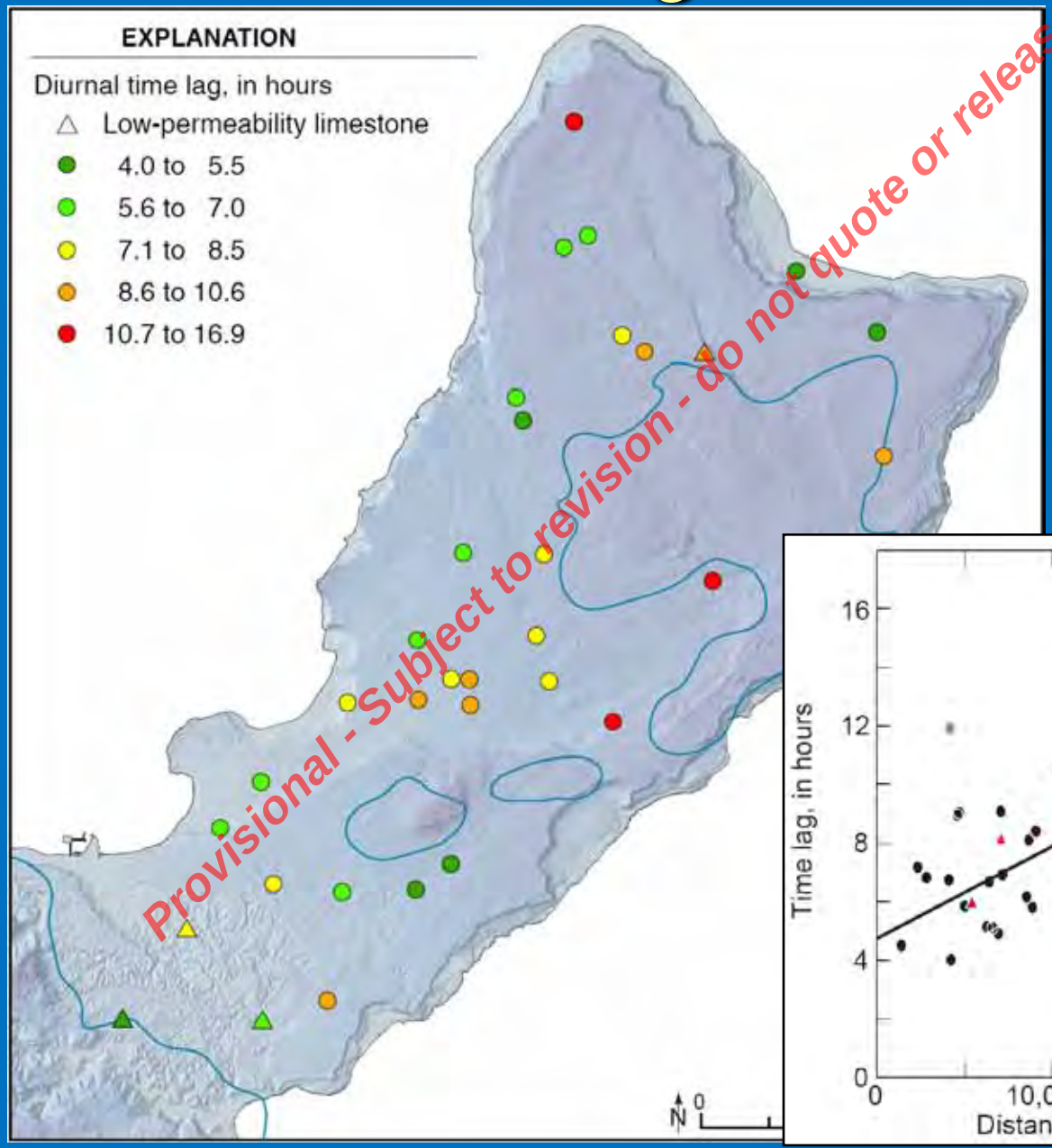
With increasing distance from the coast: amplitude decays exponentially



USGS
science for a changing world

Time Lag



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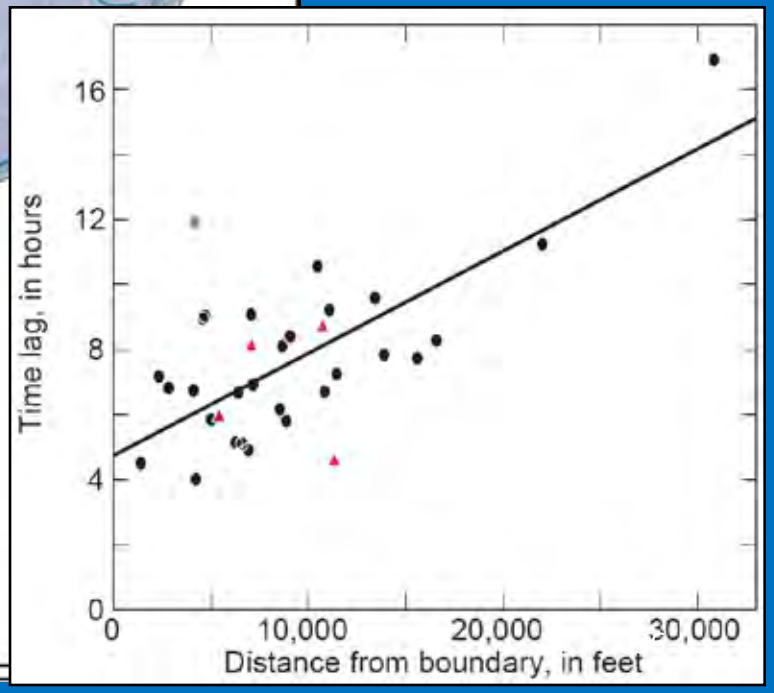
With increasing distance from the coast:

time lag increases linearly



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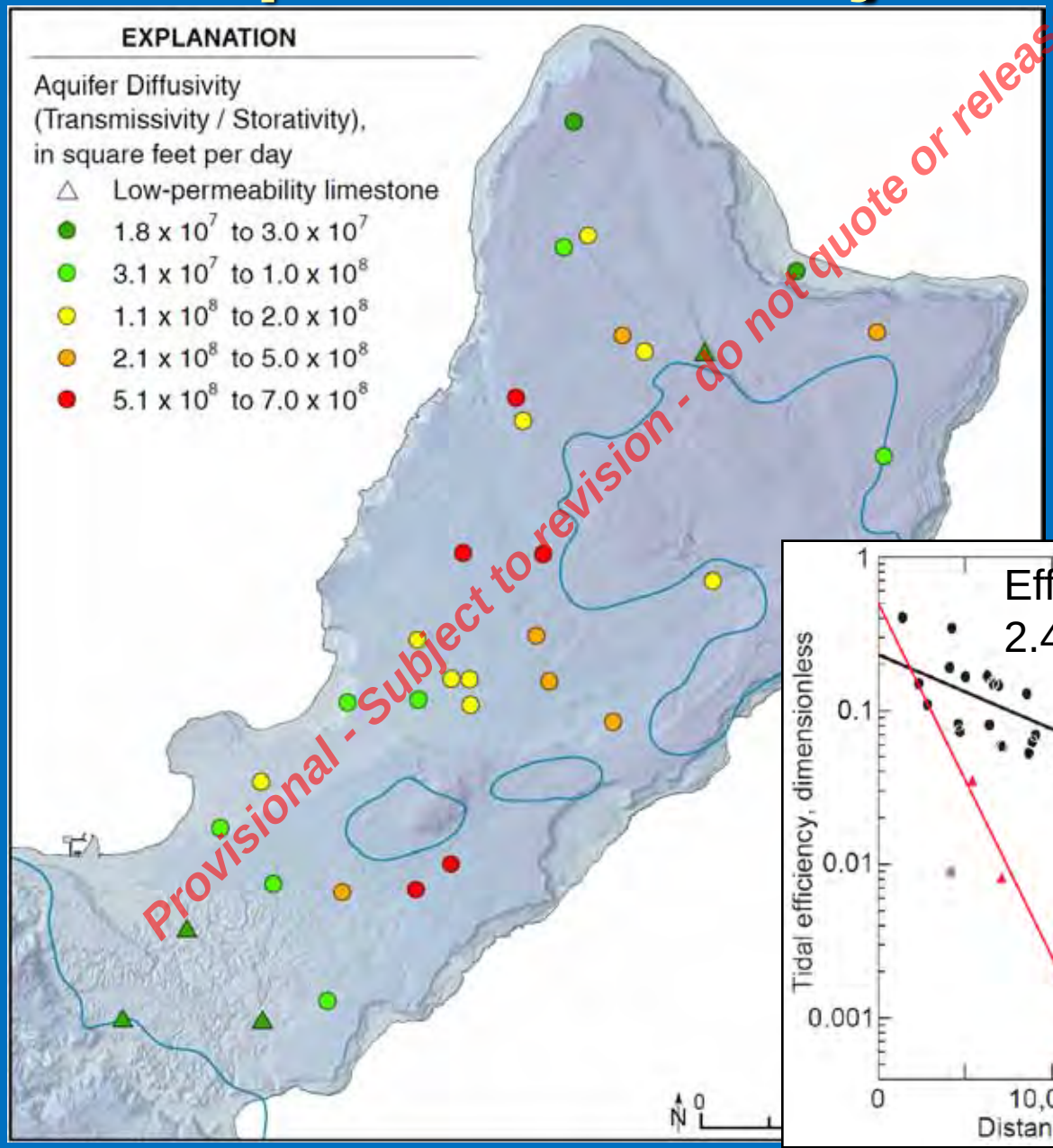
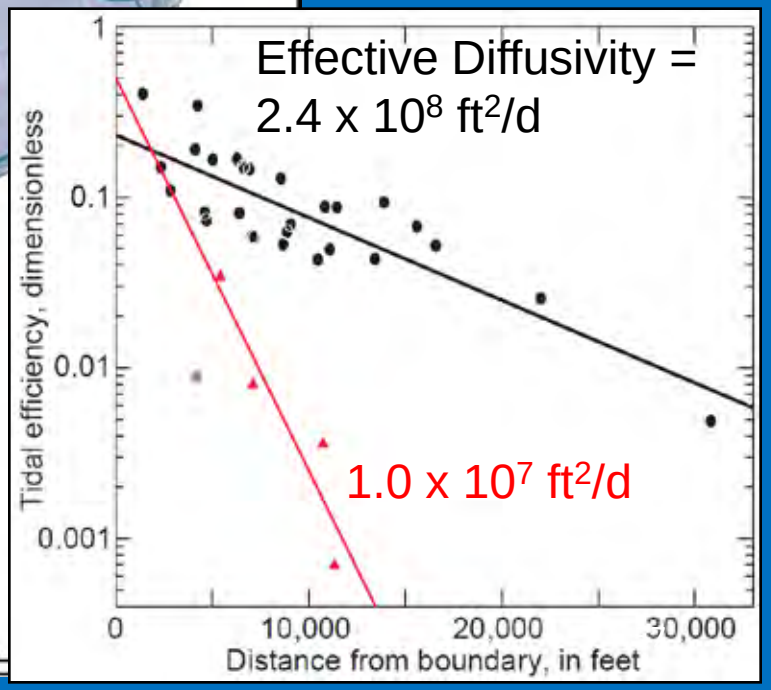
Aquifer Diffusivity





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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

Wells commented_july 7 2010_0938 - Microsoft Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1		Agana (Hag		Yigo			Finegayan	Mang	Agafa Guma	Andersen			INACTIVE WELLS							
2				GWA			EARTH TECH	NAVY	AIR FORCE	USGS									Avg last 3 yrs - GWA	
3		Sub-Basin www database		WERI Tech Report	Latitude	Longitude	Land surface elevation	Well Depth	Solid Casing Length	Screen Length	Hole Diameter (inches)	Casing Diameter (inches)	Date Started Drilling	Date Completed Drilling	Test Pumping Rate (GPM)	Drawdown (ft)	Specific capacity (gpm/ft) pumping rate/drawdown	Depth to volcanic baseme	Chloride data	Water Level data (relative to MSL)
4				Production																
5		Agana	A01	A-1			67.66'	221.0'	70'	150'	11	8	13-Feb-65	20-Nov-65	210	103.49'	210/103.49'		36	18.91'
6		Agana	A02	A-2			118'	172'	110'	60'	11	8	19-Aug-65	8-Oct-65	210	23.23'	210/23.23'		33	106.1' ?
7		Agana	A03	A-3			127.45'	410'	???(390' ho	???	11	8	11-Apr-66	7-Jun-67	273	98'	273/98'		29	105.8'
8		Agana	A04	A-4			140.18'	300'	130'	170'	11	8	28-Jun-66	21-Mar-67	300		300/???		96	134'
9		Agana	A05	A-5			146.7'	332'	323'		11	8	3-Aug-66	18-Feb-69	100 ?	[illegible]	[illegible] ?	340'	33	322' (137.45'?)
10		Agana	A06	A-6			152'	306'	136'	170'/11	11	8	19-Jul-67	9-Sep-67	325				40	142'
11		Agana	A07	A-7			136'	186'	116'	70'	11	8	18-Apr-67	8-May-67	210	33			102	126'
12		Agana	A08	A-8			124'	305'	96'	205'	11	8	26-May-67	20-Jul-68	270				34	109'
13		Agana	A09	A-9			187.15'	240'	237'	70'	11	8	24-Mar-67	23sep??	83	1.2	83/1.2		228	180.5'
14		Agana	A10	A-10			191.01'	215'	171'	45'	11	8	10-May-67	???			???		372	184.5'
15				A-11			178'	375'	125'	205'	11	8	7-Jun-68	23-Jul-68	150	201'	150/201'		3	131'
16		Agana	A12	A-12			138'	390'	103'	225'	11	8	24-Jul-68	29-Aug-68	330		330/		37	108'
17		Agana	A13	A-13			130.8'	418'	205'	120'	11	8	24-Oct-68	10-Dec-68	200		10.5 GPM/FT @ 200 GPM /250GPM/2		512	123'
18		Agana	A14	A-14			208'	260'	220'	40'		8		05/21/73 (date	160		160 GPM/??		341	206'
19		Agana	A15	A-15			197.74'		210'	50'		8		06/13/73 (date	235		235 GPM/13.67'=17.19		168	194.5'
20				A-16																
21		Agana	A17	A-17			196'	235'	195'	40'		8		08/17/73 (date	180		180 GPM/		441	192.75'
22		Agana	A18	A-18			265.5' (205')	250'	227' (210')	40'		8	19-Sep-73	22-Sep-73	135		135 GPM/		391	172' (204')
23		Agana	A19	A-19				165'	135'	20'		8		08/17/73 (date drilled)			120		400	133.3'
24				A-20																
25		Agana	A21	A-21					255'(260' 19feb98 GWA Maint Rec)										413	180.9'
26				A-22																
27		Agana	A23	A-23										5/10/1983 (date	330		330 GPM/?		70	
28		Agana	A25	A-25			59.96'	70.56'	68'	40'		8		4/10/1994 (date	270		270 GPM/11.29'=23.91		89	50.11'
29		Agana	A26	A-26			156.5'	203.5'						05/05/83 (date	50		50 GPM/11.9'=4.20		84	148.5'
30				A-27			150.5'	197.5'												
31		Agana	A28	A-28			246'	242'						05/05/83 (date drilled)						199.6'
32		Agana	A29	A-29			58.93' (54.4')	105'	60'	40'	15	10	18-May-88	19-May-88	275		275gpm/8.59'=32.01gpm/ft		18-11	52.33'

UOG:
A-6 Well Info Layne Internattional

Sheet1 Sheet2

Cell O10 commented by UOG

80%

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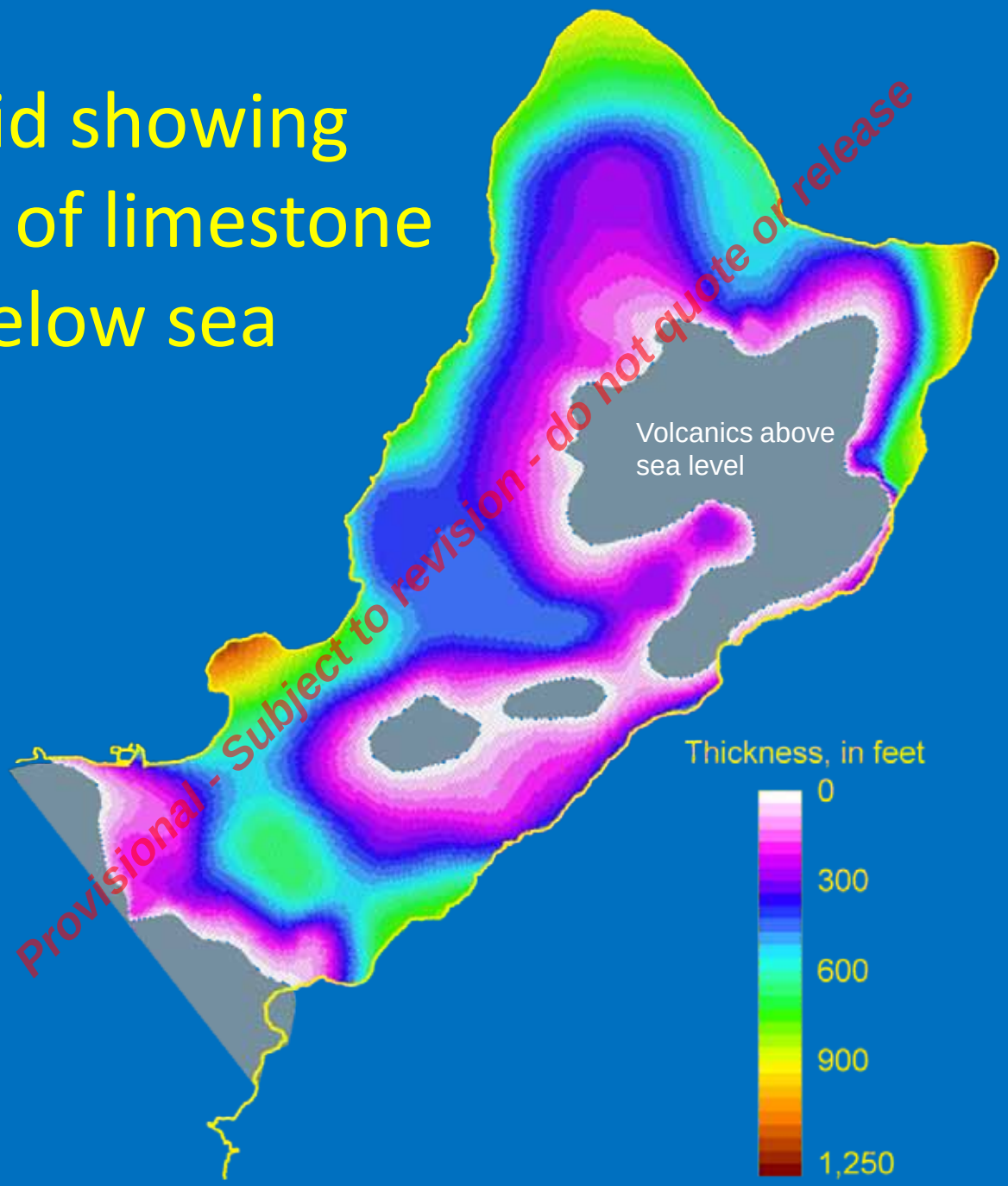
Model grid showing thickness of limestone aquifer below sea level



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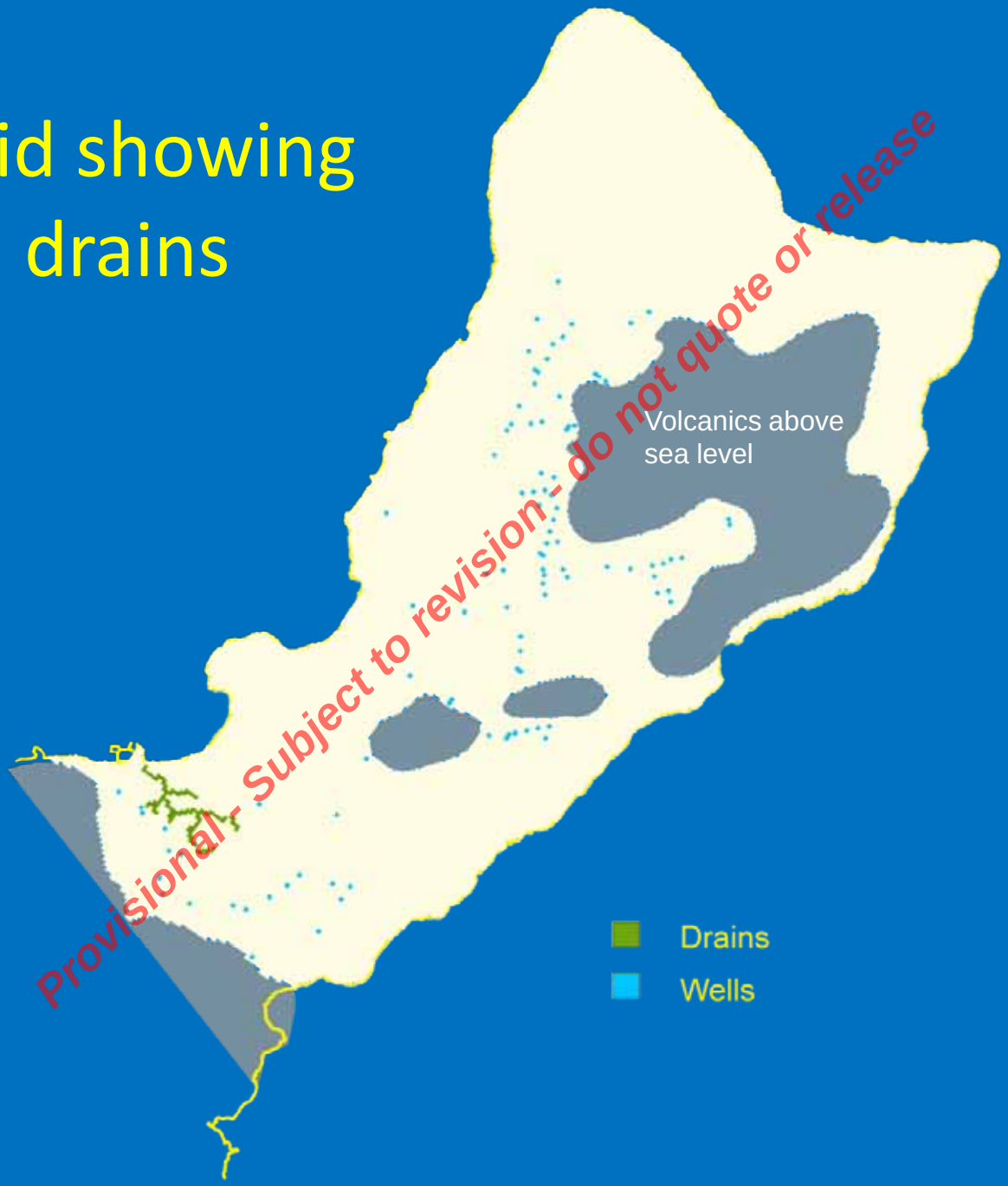
Model grid showing wells and drains



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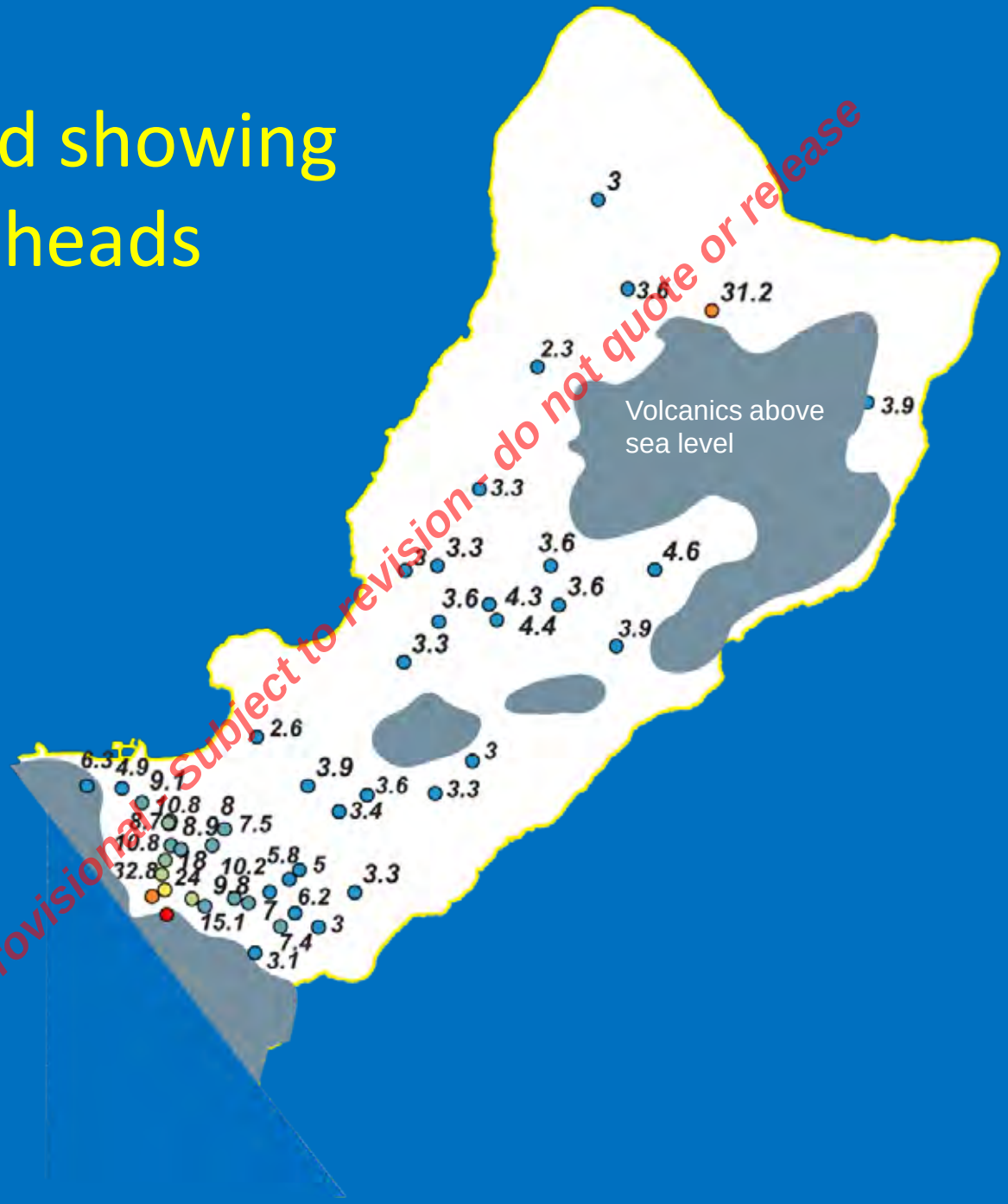
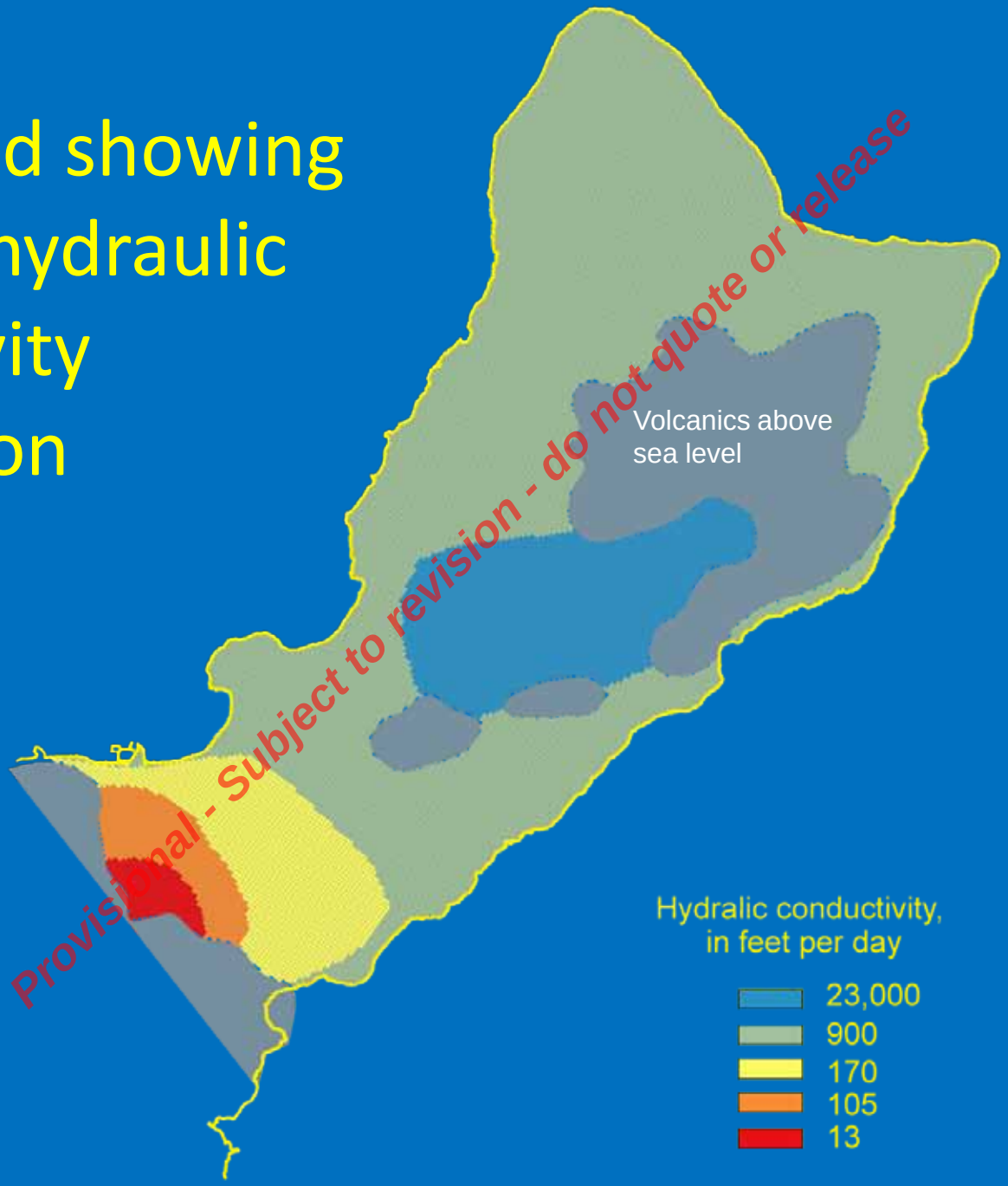
Model grid showing observed heads



Provisional: Subject to revision - do not quote or release

Model grid showing example hydraulic conductivity distribution



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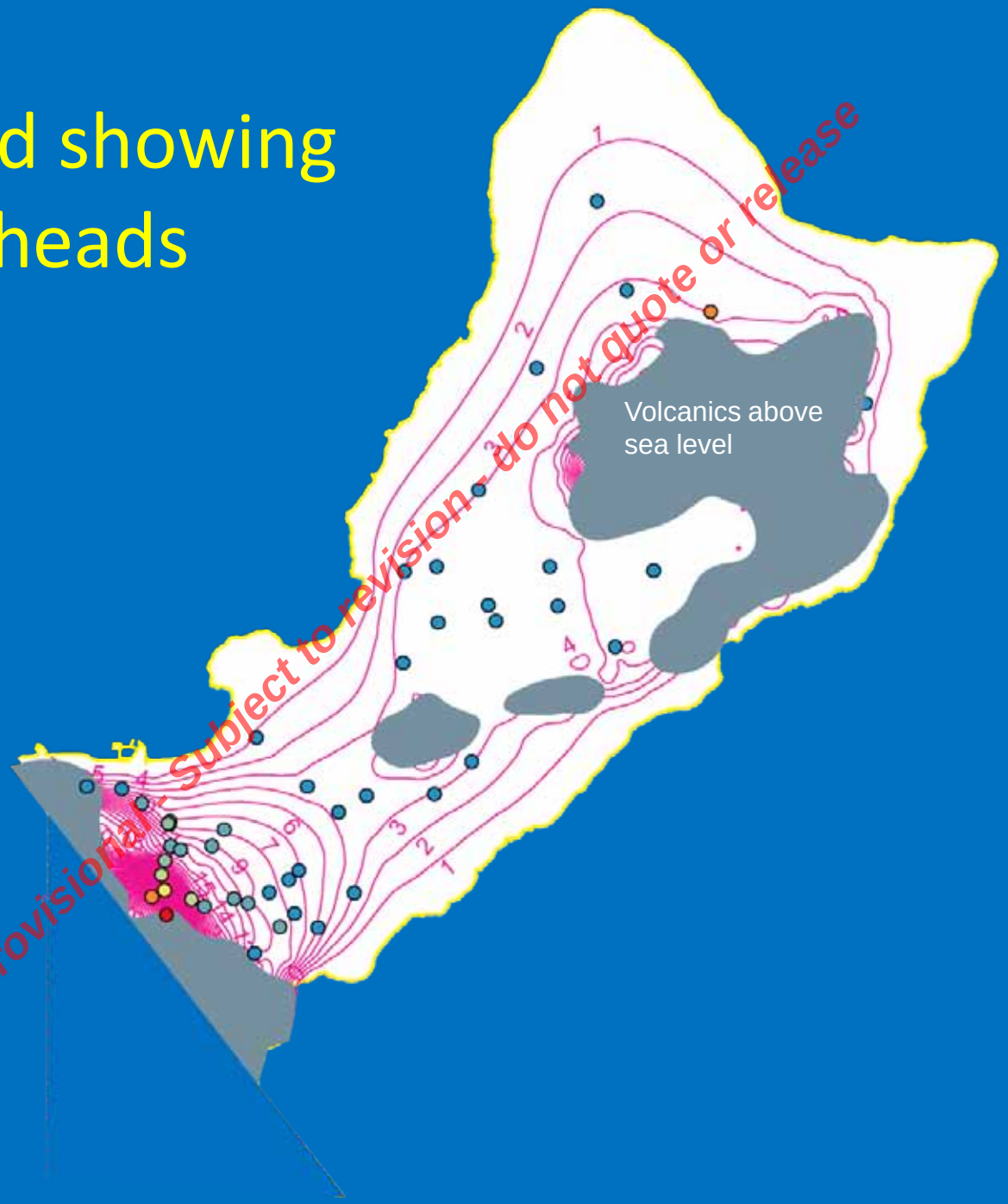
Model grid showing modeled heads



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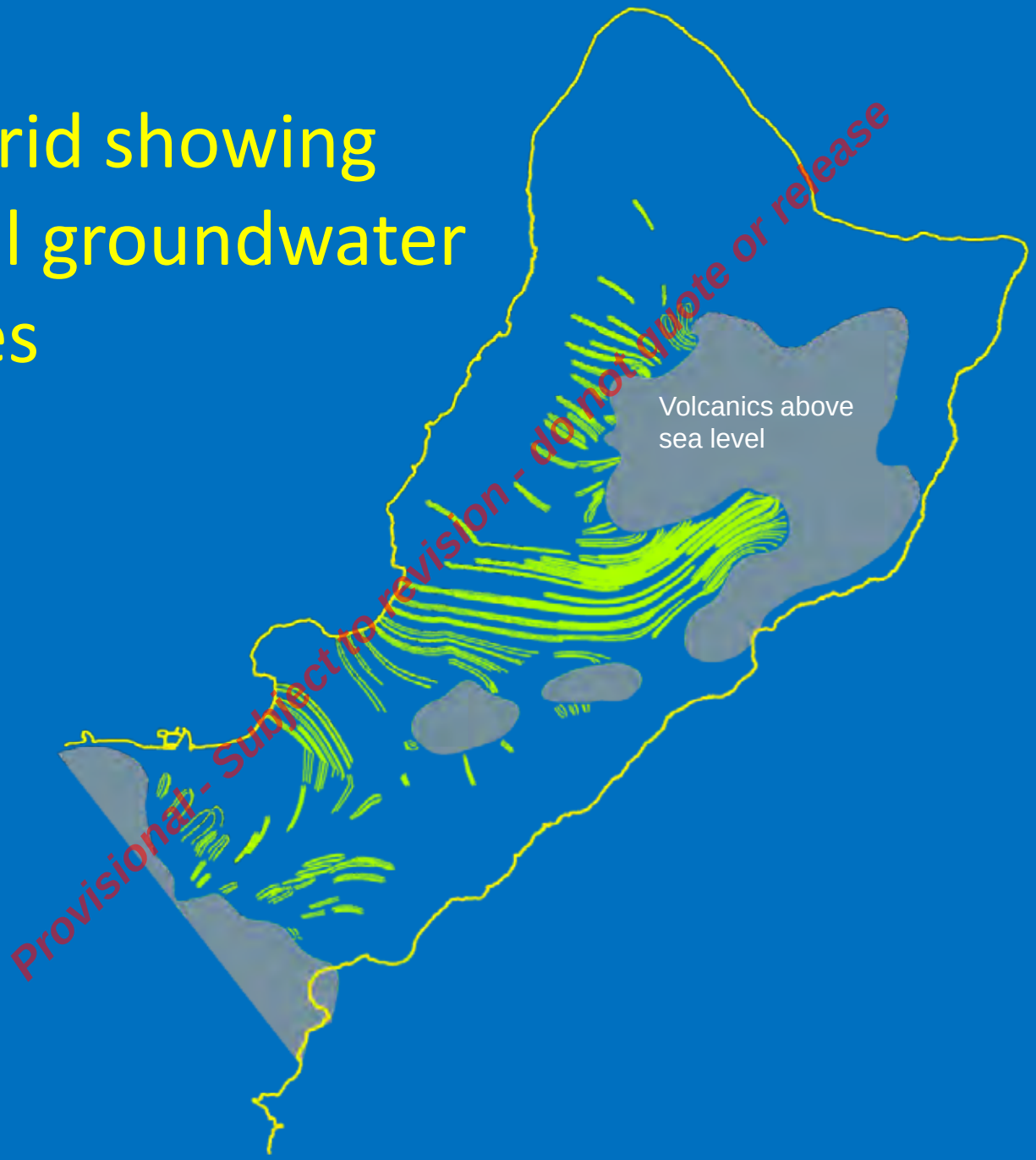
Model grid showing potential groundwater flow lines



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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

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