RECHARGE ON NON-IRRIGATED LANDS

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Eastern Snake Plain Aquifer Model Enhancement Project Scenario
Document DDW-003

DESIGN DOCUMENT OVERVIEW

Design documents are a series of technical papers addressing specific design topics on the Eastern Snake Plain Aquifer Model Enhancement Project (ESPAM). Each design document will contain the following information: topic of the design document, how that topic fits into the whole project, which design alternatives were considered and which design alternative is proposed. In draft form, design documents are used to present proposed designs to reviewers. Reviewers are encouraged to submit suggested alternatives and comments to the design document. Reviewers include all members of the Eastern Snake Hydrologic Modeling (ESHM) Committee as well as selected experts outside of the committee. The design document author will consider all suggestions from reviewers, update the draft design document, and submit the design document to the Eastern Snake Plain Model Enhancement Project Model Upgrade Program Manager. The Program Manager will make a final decision regarding the technical design of the described component. The author will modify the design document and publish the document in its final form in .pdf format on the ESPAM web site.

The goal of a draft design document is to allow all of the technical groups which are interested in the design of the ESPAM Enhancement to voice opinions on the upgrade design. The final design document serves the purpose of documenting the final design decision. Once the final design document has been published for a specific topic, that topic will no longer be open for reviewer comment. Many of the topics addressed in design documents are subjective in nature. It is acknowledged that some design decisions will be controversial. The goal of the Program Manager and the modeling team is to deliver a well-documented, defensible model which is as technically representative of the physical system as possible, given the practical constraints of time, funding and manpower. Through the mechanism of design documents, complicated design decisions will be finalized and documented. Final model documentation will include all of the design documents, edited to ensure that the “as-built” condition is appropriately represented. This is the final as-built report on the calculation of recharge on non-irrigated lands.

INTRODUCTION

This Design Document discusses calculation of two spatially-distributed components of the aquifer water budget; recharge from precipitation on non-developed lands and spatially-distributed recharge and discharge from land uses that comprise a small fraction of the study area. These minor-use areas are dry farms, cities, and wetlands.

Precipitation on the plain is approximately 6,700,000 acre feet per year, with 80% of this falling on non-developed lands. It is estimated that precipitation on non-developed lands produces 700,000 acre feet of recharge per year (Garabedian 1992), which equals approximately 30% of the magnitude of irrigation recharge. It is the component of recharge to which Garabedian assigned the most uncertainty. The other land uses - dry farms, cities, and wetlands - represent minor components of the water budget, with a combined net effect of about 160,000 acre feet per year (calculated from data reported by Goodell 1988).

This design document presents the method used for calculating recharge from precipitation using GIS grid maps of monthly precipitation (Daly and Taylor 2001) and generalized soil maps (Garabedian 1992). This calculation was performed for all the areas of the plain not represented as dry farms, cities, or wetlands. These minor-area lands were represented as separate polygons to which a fixed net recharge rate was applied. The outcome was a single GIS grid map per stress period, covering the entire plain and representing recharge for non-irrigated land use. In calculating the water budget, the recharge tool (comprised of a GIS component and a Fortran component) considered maps of irrigated lands and applied either the irrigated-lands recharge calculation or the recharge depth from the GIS grid map to appropriate areas of each model cell. The irrigated-lands map is described in Design Document DDW-015 and the irrigated-lands recharge calculation is described in Design Documents DDW-001, DDW-002, DDW-021 and DDW-022.

METHOD FOR CALCULATING PRECIPITATION RECHARGE ON NON-DEVELOPED LANDS

Because of the magnitude of this recharge component, a flat rate of recharge for the entire calibration period was rejected. Because of spatial and temporal concentration due to topography and snowmelt, and because of the effects of preferred pathways, a percentage-of-precipitation approach was rejected (Gee 1988).

Calculation

The proposed calculation formula is suggested by Rich (1951). Rich studied basins which, unlike the Eastern Snake Plain, had a component of surface discharge. His relationship actually described total basin yield, but it is simplified here to represent recharge, since runoff that does occur on the plain collects in depressions where it also recharges the aquifer. The equation is:

$$\text{Recharge} = K * (\text{Precipitation})^N \qquad \text{(eq. 1)}$$

where K is an empirical slope parameter and N is an empirical exponent that introduces curvature into the relationship.

This formula is sensitive to length units and time period. For use in the model water budget, the calculation was applied to monthly precipitation values from PRISM

(Daly and Taylor 2001). The initial result was monthly GIS grid maps of recharge depth (feet), which were archived for future reference. These were aggregated by model stress period for inclusion in the model recharge calculations.

To represent the phenomena of reduced wintertime ET and temporal concentration of recharge from snowmelt (Gee 1988), November, December, January, and February precipitation amounts were accumulated, and applied entirely in February. This is a modification to Rich's approach.[1]

Recharge must never exceed precipitation. However, a more restrictive test is that the slope of the precipitation - recharge relationship should never exceed one (Rich 1951). This represents the level of precipitation where all storage, evapotranspiration, and abstraction mechanisms are satisfied, and any additional precipitation contributes 100% to yield or recharge. This can be tested by setting the first derivative equal to one, and solving for transition precipitation (that is, the point where slope equals one):

$$N * K * (\text{Precipitation})^{(N-1)} = 1 \qquad \text{(eq. 2)}$$

$$\text{Transitional Precipitation} = (1/ (N * K))^{(1/(N-1))} \qquad \text{(eq. 3)}$$

From this test, the transition point (the maximum precipitation for which the exponential relationship is appropriate) can be identified. When precipitation exceeds this transitional value, a linear relationship is used. This is also a modification of Rich's approach.[2] Figure 1 illustrates the general results of this calculation. The dark arrow points to the transition from an exponential to linear relationship.

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[1] Rich considered only yearly totals of rainfall and yield.

[2] Rich's annual curves never approached a slope of one within his range of anticipated precipitation.

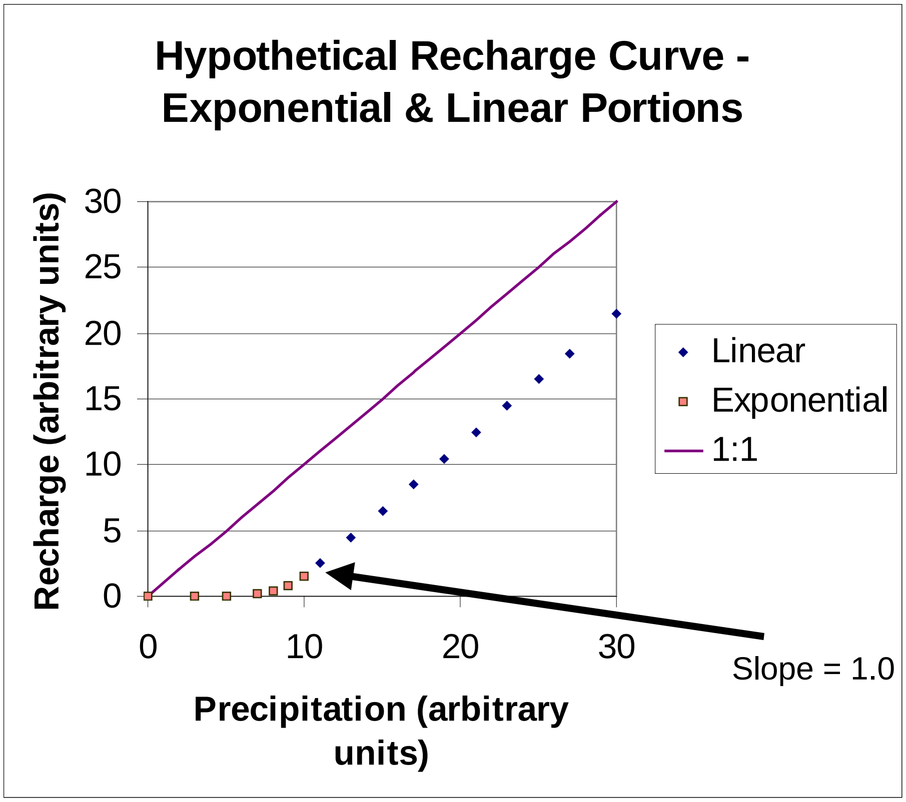

Figure 1. Hypothetical Recharge Curve

The vertical offset from the extended recharge curve to the 1:1 line represents the total possible abstractions during the period. This is approximately equivalent to the potential increase in soil moisture storage during the period, plus the potential evapotranspiration. (The final fate of leaf interception is evaporation or transpiration, the final fate of depression storage is evaporation or infiltration, and the final fate of runoff on the plain is infiltration or evapotranspiration in the depressions and playas to which it drains.) For long calculation periods, potential evapotranspiration dominates this abstraction. Rich used a one-year calculation period. Over a fifteen-year data set, the slope of the recharge curve did not approach one even when annual precipitation exceeded twice the normal rate (Rich 1951). Rich found that well-watered shrubs in lysimeters evapotranspired about 50 inches per year in an area of Arizona where normal precipitation ranges from 16 to 34 inches. Stearns and Bryan (1925) measured similar evapotranspiration from a lysimeter in wetlands at Mud Lake, Idaho, where normal precipitation is under 12 inches. These values provide an indication of the potential maximum abstraction for long calculation periods.

For shorter calculation periods, change in soil moisture storage dominates the potential abstractions. The part of the soil profile from which water can be lost to evapotranspiration is the region of interest; any water below this region is assumed to eventually contribute to aquifer recharge. The entire root zone is subject to transpiration, when plants are actively growing. Range-land plants can have extremely deep root systems (USDA 1955), so the entire soil profile above rock or gravel can be the effective root zone.

The Eastern Snake Plain has significant areas of lava rock cover where vegetation is sparse and ET low. In these areas, the early precipitation in a storm event is still stored in the upper rock layers where it is subject to later evaporation. An estimate of this potential storage comes from estimates of direct soil evaporation in agricultural settings. A sandy soil can store 1/4 to 1/2 inch of water subject to direct evaporation (Allen et al 1998) in the upper part of the soil profile. Lava rock may be similar. An additional abstraction on rocky lands could be the direct evaporation of rain stored in surface depressions. A rough estimate of this is depression-storage loss is 0.3 inch per storm event.

Rough calculations for the study area provide three general maximum abstractions for a one-month calculation period:

Lava Rock	Storage Subject to Evaporation	0.5 inches[3]
	Depression Storage	
	3 storms @ 0.3 inches	1.2 inches
	Total	1.7 inches
		(0.14 feet)
Thin Soil	Storage Subject to Evapotranspiration	
	2 ft @ 1.5 inches/foot	3.0 inches
	Potential ET	
	30 days @ 0.3 inches/day	9.0 inches
	Total	12.0 inches
		(1.0 foot)

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[3] Value for sand proposed by Allen et al (1998).

Thick Soil	Storage Subject to Evapotranspiration	
	8 feet @ 2.0 inches/foot	16.0 inches
	Potential ET	
	30 days @ 0.3 inches/day	9.0 inches
	Total	25.0 inches (2.05 feet)

These values represent the expected offset from the linear portion of the recharge curve and the 1:1 line, for a one-month calculation period.

The degree of curvature of the exponential part of the curve relates to preferential recharge pathways and spatial concentration of runoff. If much of the precipitation runs into depressions where percolation is concentrated, or if there are cracks or other preferred pathways, even small precipitation events will result in some recharge. This corresponds to a small value of N, represented by the “small exponent” curve in Figure 2. The “large exponent” curve in Figure 2 corresponds to a smooth-surfaced homogeneous soil with little spatial concentration and few preferred pathways.

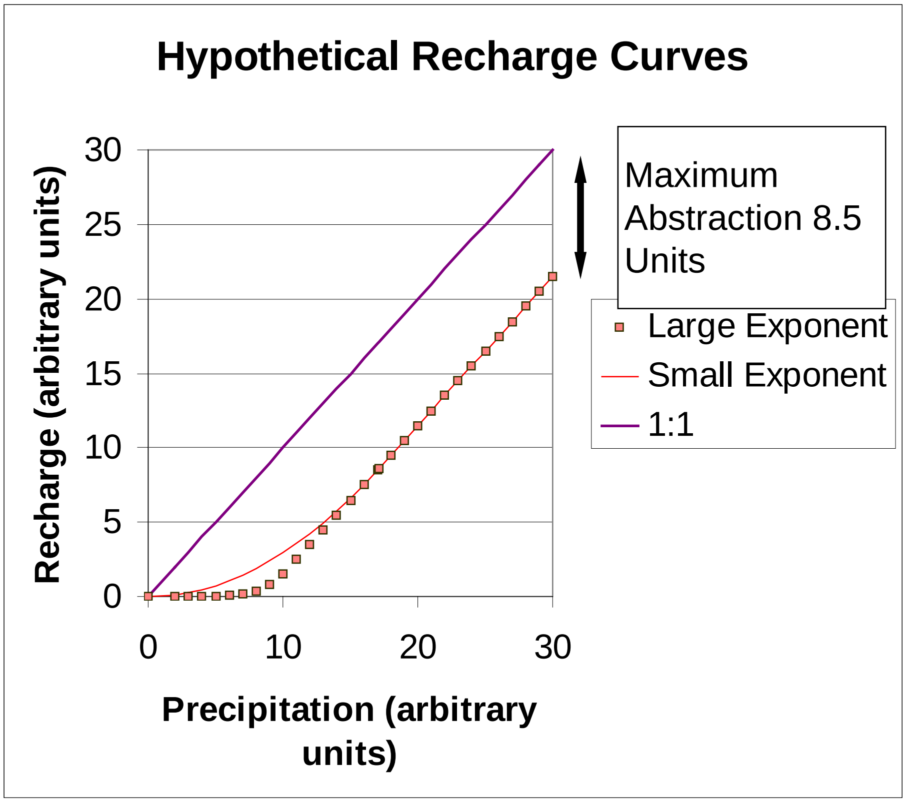

Figure 2. Hypothetical Recharge Curves and Maximum Abstraction

Figure 3 shows that by coordinated adjustment of the exponent and coefficient, the maximum abstraction and the degree of curvature can be manipulated independently. Adjusting exponent N changes both the degree of curvature and the maximum abstraction. After setting exponent N to obtain the desired curvature, factor K is adjusted to achieve the desired transition to a linear relationship. This transition defines the maximum abstraction.

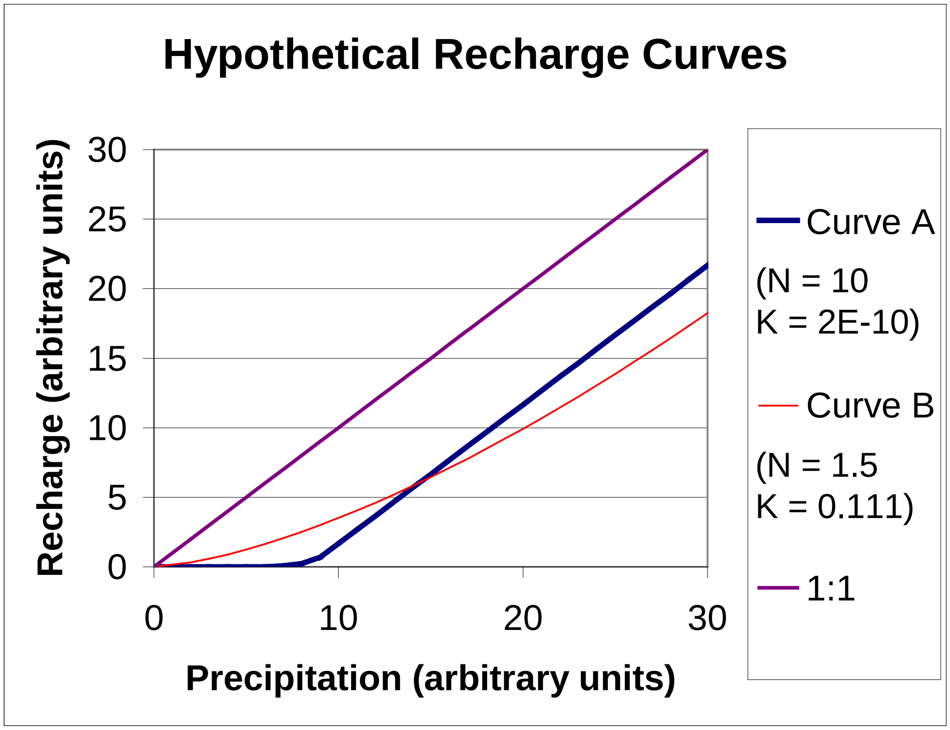

Figure 3. Comparison of Hypothetical Recharge Curves

Application to Model

Parameters can be adjusted to shape the calculated recharge curves. However, knowing the actual recharge from precipitation on non-irrigated arid lands is very difficult (Gee 1988). Attempts to use a water balance to determine the non-irrigated recharge are frustrated by the fact that another large component of recharge - tributary basin underflow - is also poorly defined. Parameters K and N were initially calibrated to match previous results, acknowledging that these values include significant uncertainty, but that improving on them is beyond the resources of the current project. It was not practical to complete initial plans to refine knowledge of non-irrigated recharge using parameter estimation (Wylie 2004).

Even though resolution of gross amounts is not improved over previous efforts, temporal and spatial distribution of recharge are improved because of the availability of monthly PRISM precipitation data (Daly and Taylor 2001) and GIS analysis tools.

The K and N parameters are sensitive to the calculation period, but model calibration and contemplated model use require the ability to change stress-period length. This makes direct application of the algorithm within the recharge program extremely difficult. Unique pairs of K and N would have to be calibrated for each soil class, for each potential length of stress period, and the pairs for different stress period lengths would have to be compared during calibration to insure they represent consistent recharge regimes. Instead, the calculation of recharge on non-irrigated lands was performed outside of the recharge program month-by-month, and aggregated to match model stress periods. These aggregated values were delivered to the FORTRAN recharge program along with the area of non-irrigated land within the cell. The FORTRAN recharge program includes a check to preclude recharge on non-irrigated lands from exceeding precipitation. The recharge tools included a provision to independently adjust non-irrigated recharge on up to four classes of land, for parameter estimation purposes. This capability was not used, however.

Sample Calculations

To test this method, precipitation data for a small Arizona catchment (Rich 1951) were split 2/3 winter and 1/3 summer, then evenly distributed among winter and summer months. Yield was distributed 89% among winter months and 11% among summer months. This approximately matched the described temporal distribution of rainfall and yield. Parameters K and N were adjusted manually to match the yearly basin yield values, with an attempt to also match winter and summer totals. Figure 4 shows the results. For calculation of monthly values in millimeters, N was set to 1.95 and K was set to 0.0011. The maximum abstraction was 314 millimeters per period.

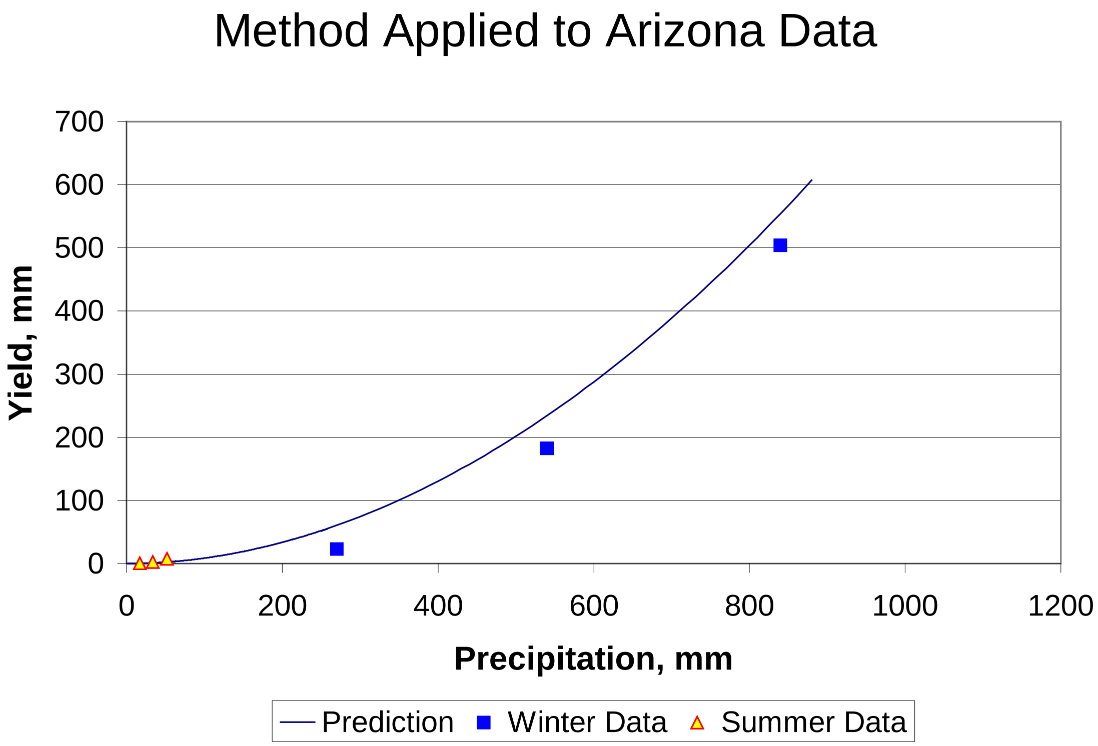

Figure 4. Method Applied to Arizona Data

In a second test, the calculation was applied to the study area using monthly values of PRISM (Daly and Taylor 2001) thirty-year average precipitation, by soil type according the Regional Aquifer System Analysis (RASA) generalized soil map (Garabedian 1992). Soil types outside Garabedian's boundary were assigned according to the STATSGO soil maps from Natural Resources Conservation Service (2001). Parameters N and K were adjusted manually to match the 700,000 acre feet of annual recharge reported by Garabedian,[4] with an attempt to also match his spatial distribution of recharge. At each iteration, resulting curves were inspected to see that the transition to a linear function occurred at high enough precipitation rates to allow the parameter estimation scaling adjustment described above. Figures 5, 6, and 7 show the resulting recharge curves for the three general soil types.

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[4] To obtain targets for calibrating N and K, total recharge was summed only on the lands for which Garabedian calculated non-irrigated-precipitation recharge. This allowed direct comparison with Garabedian's estimate of 700,000 acre feet per year.

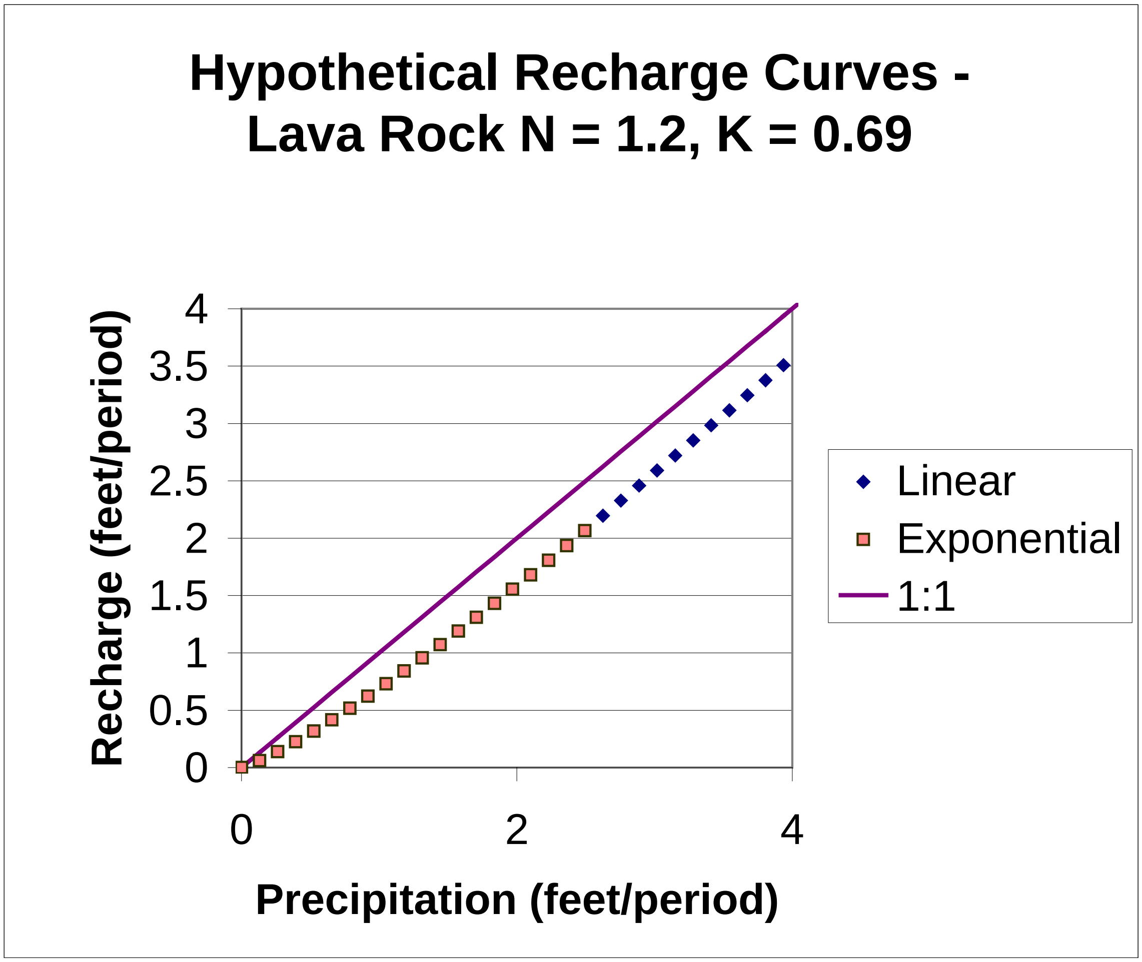

Figure 5. Recharge Curve Used for Lava Rock

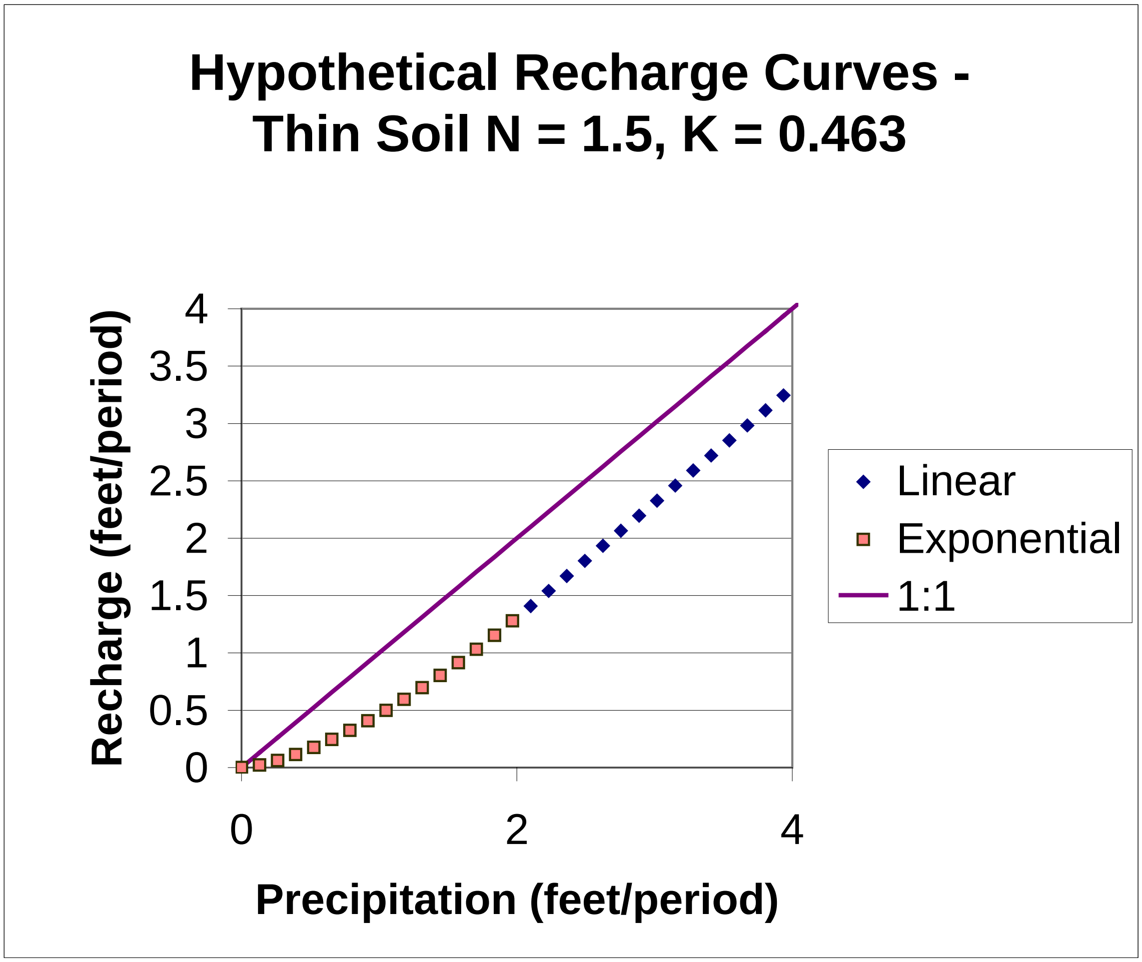

Figure 6. Recharge Curve Used for Thin Soil

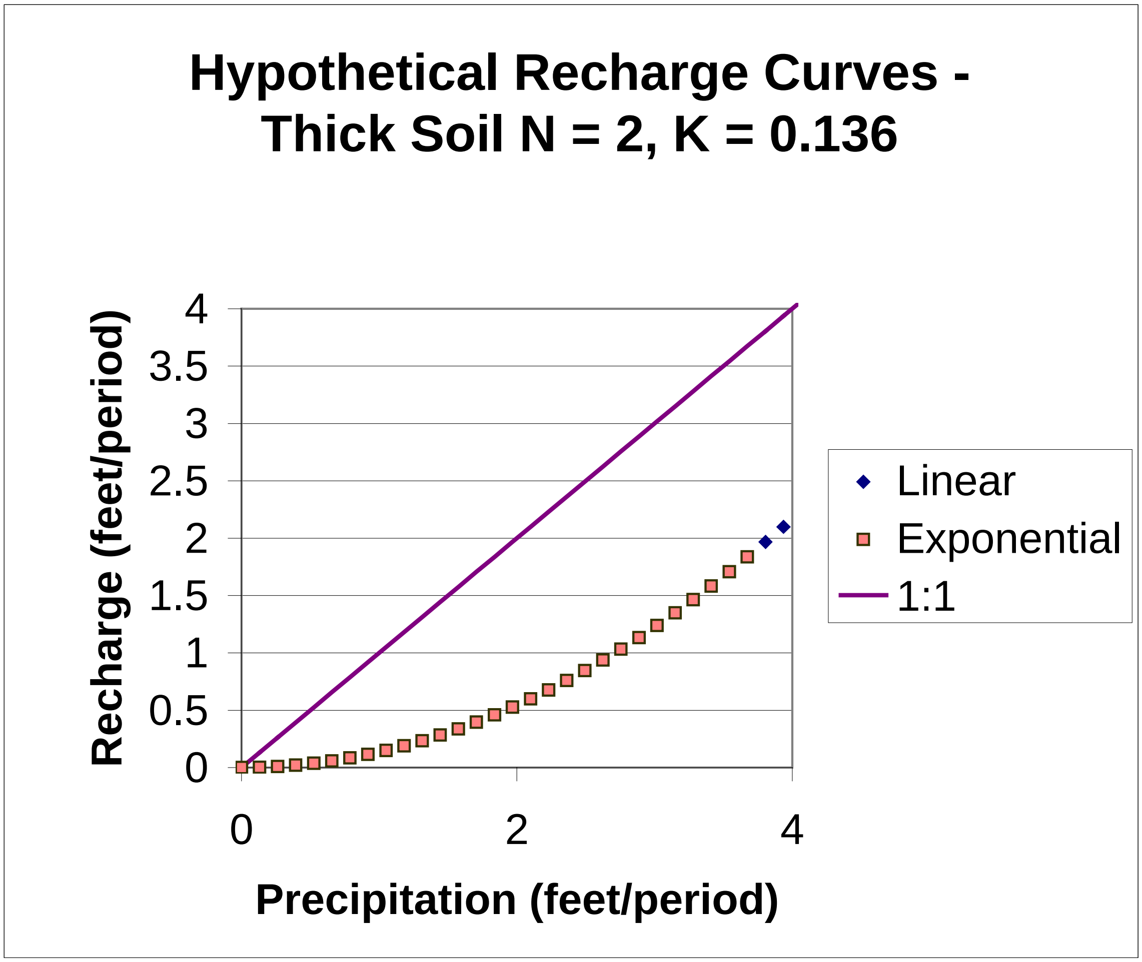

Figure 7. Recharge Curve Used for Thick Soil

Figure 8 shows the comparison with Garabedian's recharge contour map. The black lines are Garabedian's contours and the colored grid is the recharge calculated in this test.

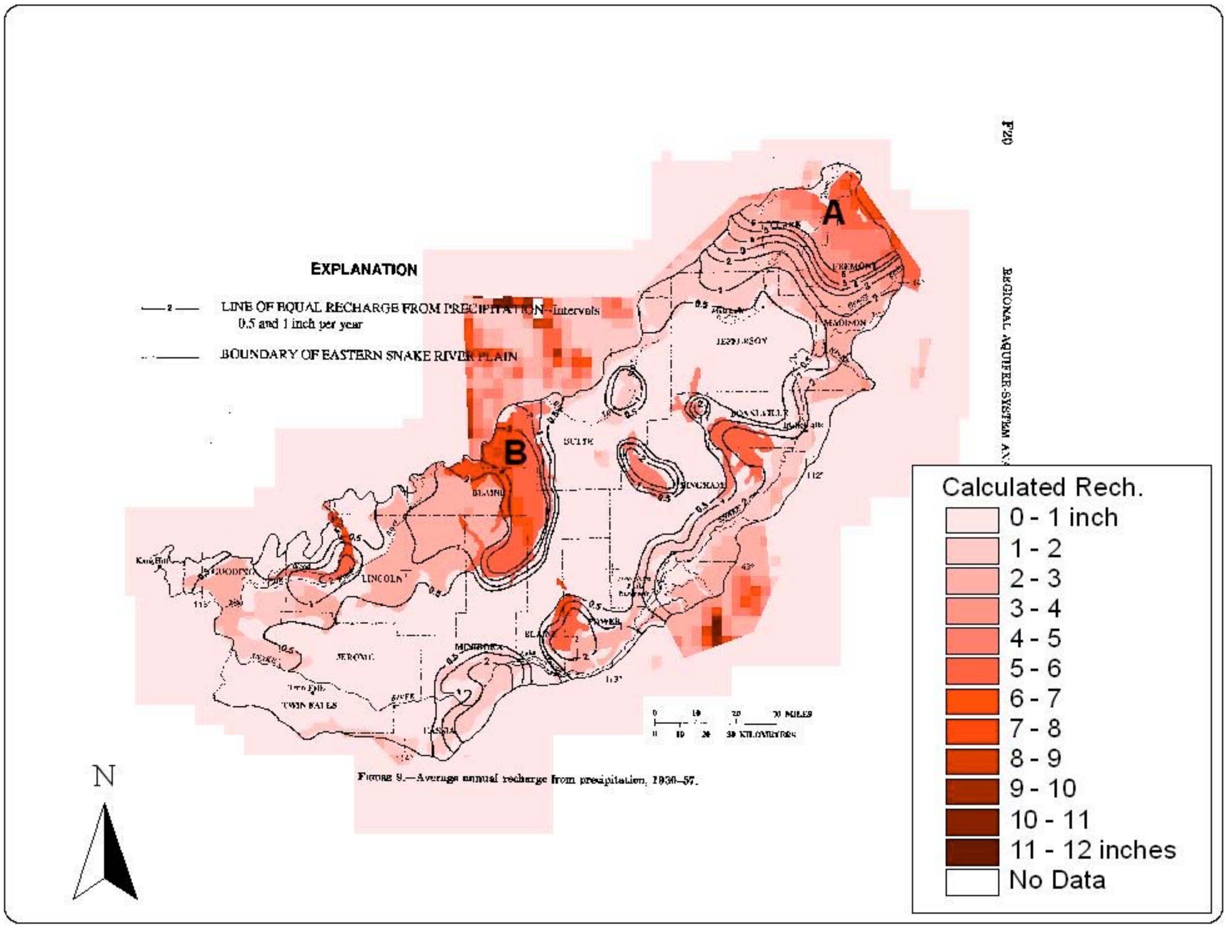

Figure 8. Comparison with Garabedian Recharge Map

The maximum abstraction indicated by the thick-soil parameters is 1.84 feet, agreeing reasonably with the rough calculation of two feet. The thin-soil maximum of 0.7 feet also agrees reasonably with the estimate of one foot. The lava rock parameters indicated maximum abstraction of 0.4 feet, which exceeds the approximation of 0.1 to 0.2 feet. Adjusting parameters to more closely match the expected maximum abstraction resulted in under-estimating Garabedian's values in area "A" (thin soil) and over-estimating in area "B" (lava rock) illustrated in Figure 9. The recharge parameters illustrated in Figures 5, 6, and 7 were retained through model calibration and are suggested for future use of the model.

The possibility of using GIS to accommodate more soil classes from other available data sets was considered. The RASA (Garabedian 1992) soils map was compiled from detailed National Resource Conservation Service maps, and the distribution of soil type and depth will not have changed significantly. Because of the lack of required knowledge to appropriately treat more than the three soil classes used in RASA, the RASA map was used. Additionally, using other available data would require devoting significant resources to compiling appropriate soil depths and water holding capacities from the raw data available. The raw data involve large numbers of soil groups with several soil classes in each group, and multiple soil layers per soil class.

OTHER RECHARGE AND DISCHARGE ELEMENTS

The recharge associated with dry farms and cities represents small geographic areas and small portions of the water budget, with small uncertainty relative to other budget elements. A single table of net recharge rates by land cover class was constructed from USGS data (Goodell 1988). Table values were applied to the appropriate cities, wetlands, or dryfarm polygons within the plain. The precipitation-based calculations described above were applied to all other non-irrigated areas of the plain. The minor-area polygons were based on the GIS data set SRBAS91LU (IDWR 1994), which appears to give a good delineation between wetlands and irrigated agriculture as well as adequate representation of dry farms and cities (see Design Document DDW-015).

Some wetlands are hydrologically connected to the Snake River. The evapotranspiration associated with these wetlands is part of the reach-gain calculations used as model targets in calibration. During use of the model, this evapotranspiration will be part of the reach gains predicted by the model. This class of wetlands was excluded from the non-irrigated lands data set. Non-excluded wetlands used a standard evapotranspiration rate calculated from Goodell's (1988) data, offset by PRISM precipitation. This implies that excess wetland evapotranspiration is supplied by the aquifer, corresponding to the observation that significant wetlands only exist where aquifer water levels are close to land surface.

The estimate of zero recharge on dry farms assumes that soil depth and farming practices are such that virtually all precipitation is stored in the root zone and evaporated or transpired. The depth of recharge for cities was calculated by applying Goodell's volume to the area of cities and industrial areas in the GIS data (IDWR 1994). The depth compared favorably with depths calculated from reported volumes for the cities of Idaho Falls and Pocatello (Aamold 2002). Table 1 summarizes the minor non-irrigated recharge depths used in model calibration:

Table 1. Recharge Classifications

Classification	Acres	Percent of Study Area	Recharge Rate
Dry Farm	95,000	1.3 %	zero
Excluded Water and Wetlands	80,000	1.1 %	zero
Water and Wetlands	65,000	0.9 %	Precipitation minus three feet/year
Cities and Industrial Areas	48,000	0.7 %	Negative 1.2 feet/year

CALCULATION OF NET RECHARGE

Design Document DDW-015 describes the determination of irrigated lands. Irrigated lands are represented by a single map of land cover that applies to the entire calibration period. The GIS and FORTRAN recharge tools apply the irrigated-lands recharge calculation to all irrigated lands, and the recharge depths from the GIS grid maps described above to all non-irrigated lands, within each model cell.

In testing model results, an anomaly with wetlands recharge was discovered. Many wetlands are adjacent to irrigated lands. In the GIS component of the recharge tool, the average non-irrigated-recharge depth is calculated for each model cell without regard to how much of the cell is irrigated. In the Fortran component, the average non-irrigated-recharge depth is applied to the non-irrigated lands, and a more complex recharge calculation is applied to the irrigated lands. Many cells containing wetlands also contain farmland. Typically the farmland is on thick soil, which has a very low non-irrigated recharge rate for most stress periods. The average for the cell includes this low value, and would produce a correct result if the entire cell were non-irrigated. Instead, the overall average is applied just to the wetlands, since the rest of the cell is treated with the irrigated-lands calculation. It turns out that this effect produced a significant bias in the non-irrigated-recharge calculation. It was corrected by manually calculating the bias for each model cell with both wetlands and irrigation, and applying an offsetting correction using individual wetlands points within the Fixed Point data set. No correction was applied to excluded wetlands.

DESIGN DECISION

Net aquifer recharge and discharge from urban areas, dry farms, and wetlands were determined from a single table of recharge/discharge rates, by land use classification. Recharge from precipitation on other non-irrigated lands (rangeland, bare soil, and lava rock) was calculated according to the equation:

$$\text{Recharge} = K * (\text{Precipitation})^N \qquad \text{(eq. 1)}$$

with a transition to a linear relationship above a transition value where the recharge slope equals one. Parameters K and N were selected to match a monthly time step. Different parameters were calculated for the soil classes "Thick Soil," "Thin Soil," and "Lava Rock," and applied to the RASA map of soil classes (Garabedian, 1992). The preliminary values illustrated in Figures 4 through 6 were retained for model calibration and model use. Winter time (November through February) precipitation was summed, and the formula applied as if all the winter precipitation occurred in February. This compensates for lower winter-time evapotranspiration rates and temporal concentration of recharge from snow-melt events. When precipitation exceeds $(1/ (N * K))^{(1/(N-1))}$, a linear relationship is used.

The calculations were applied to monthly PRISM precipitation data, by soil type, producing a grid map of depth of recharge (in feet) for each wintertime period and each month March through October. Monthly grid maps (rasters) were summed for each stress period, resulting in a unique map for each stress period. In each model cell, the GIS recharge application calculated the average non-irrigated-recharge depth and calculated the irrigated area. It also delivered to the FORTRAN tool a wetlands correction, within the Fixed Points data file. The FORTRAN application performed the irrigated-lands calculation and applied the cell-average non-irrigated recharge depth to the non-irrigated lands within each cell. It also added the correction from the Fixed Point data set. Figure 9 illustrates the spatial distribution of recharge in one stress period, and the locations of the wetlands corrections in the Fixed Point data.

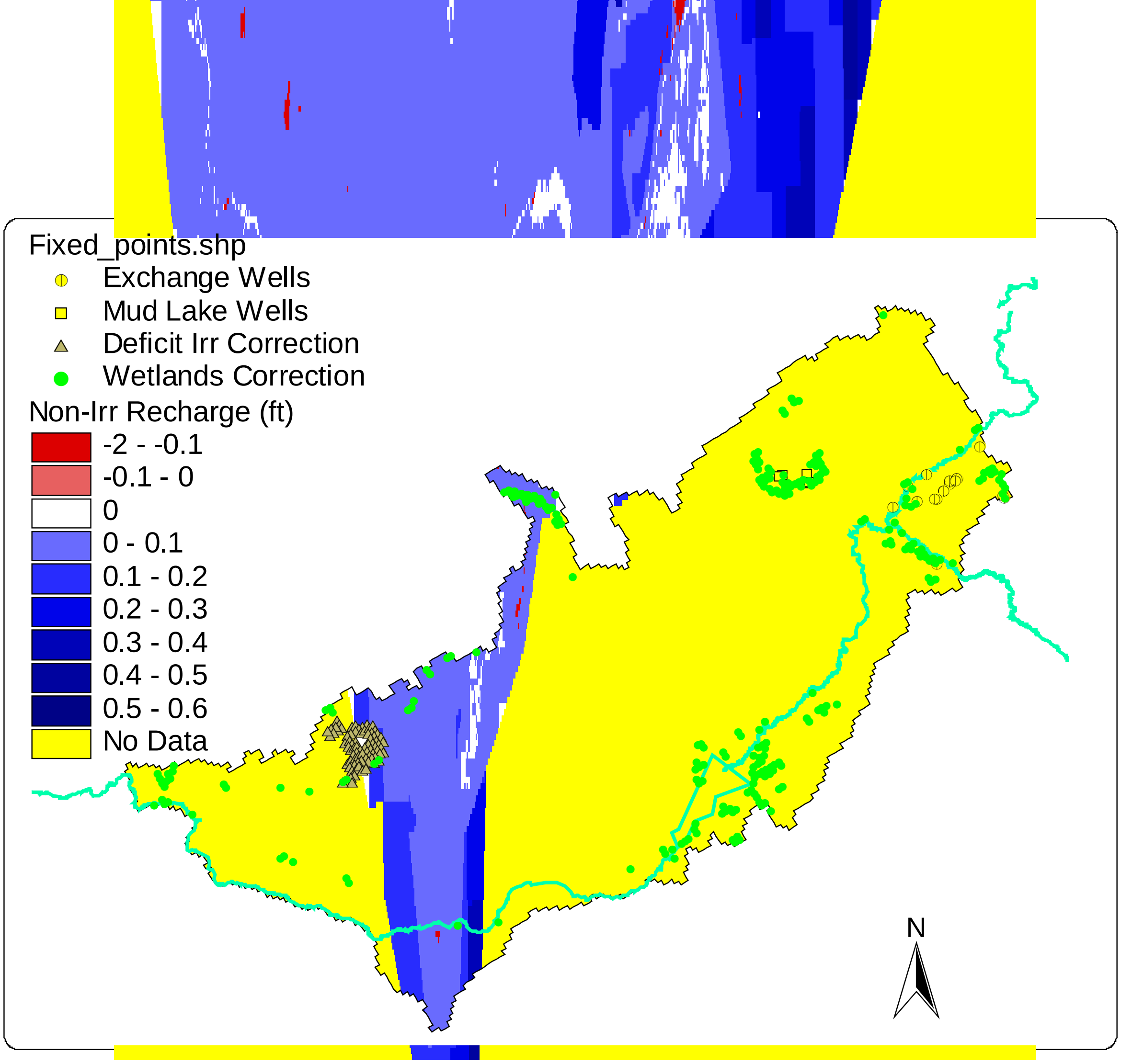

Figure 9. Typical spatial distribution of non-irrigated recharge, and location of wetlands correction points.

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