Overview of Chapter B: Additional Regional Investigations of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells

By Sandra M. Eberts, Leon J. Kauffman, Laura M. Bexfield, and Richard J. Lindgren

Section 1 of

Hydrogeologic Settings and Groundwater-Flow Simulations for Regional Investigations of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Investigations Begun in 2004

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Contents

Figures

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Abstract

A study of the Transport of Anthropogenic and Natural Contaminants to public-supply wells (TANC study) was begun in 2001 as part of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program. The study was designed to shed light on factors that affect the vulnerability of groundwater and, more specifically, water from public-supply wells to contamination to provide a context for the NAWQA Program's earlier finding of mixtures of contaminants at low concentrations in groundwater near the water table in urban areas across the Nation. The TANC study has included investigations at both the regional (tens to thousands of square kilometers) and local (generally less than 25 square kilometers) scales. At the regional scale, the approach to investigation involves refining conceptual models of groundwater flow in hydrologically distinct settings and then constructing or updating a groundwater-flow model with particle tracking for each setting to help quantify regional water budgets, public-supply well contributing areas (areas contributing recharge to wells and zones of contribution for wells), and traveltimes from recharge areas to selected wells. A great deal of information about each contributing area is captured from the model output, including values for 170 variables that describe physical and (or) geochemical characteristics of the contributing areas. The information is subsequently stored in a relational database. Retrospective water-quality data from monitoring, domestic, and many of the public-supply wells, as well as data from newly collected samples at selected public-supply wells, also are stored in the database and are used with the model output to help discern the more important factors affecting vulnerability in many, if not most, settings. The study began with investigations in seven regional areas, and it benefits from being conducted as part of the NAWQA Program, in which consistent methods are used so that meaningful comparisons can be made. The hydrogeologic settings and regional-scale groundwater-flow models from the initial seven regional areas are documented in Chapter A of this U.S. Geological Survey Professional Paper. Also documented in Chapter A are the methods used to collect and compile the water-quality data, determine contributing areas of the public-supply wells, and characterize the oxidation-reduction (redox) conditions in each setting. A data dictionary for the database that was designed to enable joint storage and access to water-quality data and groundwater-flow model particle-tracking output is included as Appendix 1 of Chapter A. This chapter, Chapter B, documents modifications to the study methods and presents descriptions of two regional areas that were added to the TANC study in 2004.

Introduction

Because subsurface processes and management practices differ among aquifers and public-water systems, public drinking-water-supply wells in different parts of the Nation are not equally vulnerable to contamination—even where similar contaminant sources exist. The U.S. Geological Survey's National Water-Quality Assessment Program study of the Transport of Anthropogenic and Natural Contaminants (TANC) to public-supply wells was initiated to identify why such differences exist, determine if there are similarities between different aquifer systems, examine the effects of land use, and provide a context for many of the NAWQA Program's groundwater-quality observations (Hamilton and others, 2004). By providing a general understanding of the response of wells in different systems to differing management practices, TANC study results should benefit those involved in locating wells, managing resources, and protecting groundwater quality (Eberts and others, 2005).

The TANC study investigations began in 2001 using retrospective data, a limited amount of newly collected water-quality data, and groundwater-flow models with particle tracking to evaluate factors that affect aquifer and public-supply well vulnerability to contamination at a regional scale in seven regional areas, hereafter termed "regional study areas" or simply "study areas." *Chapter A* of this U.S. Geological Survey Professional Paper presents the hydrogeologic settings—including redox and pH conditions—of the initial seven study areas and documents the accompanying regional-scale groundwater-flow models (Paschke, 2007). Chapter A also documents study methods and the data dictionary for a relational database that was designed to store the water-quality data and public-supply well contributing area characteristics derived from the flow models and particle tracking. Since 2001, the TANC study has incorporated some additional study areas to complement the settings that were initially investigated, and minor changes have been made to the study methods.

Purpose and Scope

The purpose of this report is to document the changes made to the study methods and to present the hydrogeologic settings and regional groundwater-flow models for the two areas in which work began in 2004. This report, Chapter B, is organized into four sections: an introductory section, two study-unit specific sections with information similar to what is presented in Chapter A for the initial study areas, and an Appendix (Appendix 1 of Chapter B), which documents changes to the particle-tracking program, MODPATH (Pollock, 1994) that were necessary to accomplish the work presented herein. The combined chapters (A and B), along with the accompanying database, provide a foundation for comparative analysis of the susceptibility (characterized by the ease with which water enters and moves through an aquifer) and vulnerability (a combination of susceptibility and contaminant input, mobility, and contaminant persistence) of public-supply wells in a variety of settings. Results of these analyses are not the subject of this report, but will be reported separately.

Study Area Locations

The seven TANC study areas in which investigations began in 2001 are located in five different principal aquifers as identified by the U.S. Geological Survey (Miller, 1999) (fig. 1.1). These study areas and principal aquifers, which are described in Sections 2 thru 8 of Chapter A, are:

A2—Salt Lake Valley, Utah, in the Basin and Range basin-fill aquifers,

A3—Eagle Valley and Spanish Springs Valley, Nevada, in the Basin and Range basin-fill aquifers,

A4—San Joaquin Valley, California, in the Central Valley aquifer system,

A5—Northern Tampa Bay, Florida, in the Floridan aquifer system,

A6—Pomperaug River Basin, Connecticut, in the glacial aquifer system,

A7—Great Miami River Basin, Ohio, in the glacial aquifer system, and

A8—Eastern High Plains, Nebraska, in the High Plains aquifer.

The two study areas and associated principal aquifers that were added to the TANC study in 2004 (fig. 1.1) are:

B2—Middle Rio Grande Basin, New Mexico, in the Rio Grande aquifer system, and

B3—South-Central Texas, Texas, in the Edwards-Trinity aquifer system.

A succinct hydrogeologic description of these two study areas and the associated principal aquifers follow. Additional details for each of these two study areas are provided in Sections 2 and 3 of this chapter, Chapter B.

Rio Grande Aquifer System

The Rio Grande aquifer system is the principal aquifer in southern Colorado, central New Mexico, and western Texas (fig. 1.1) and extends approximately 181,000 square kilometers (km^2). The aquifer system consists of a network of hydraulically interconnected aquifers in basin-fill deposits located along the Rio Grande Valley and nearby valleys (Robson and Banta, 1995). Several alluvial basins of the Rio Grande aquifer system share major characteristics with the Basin and Range basin-fill aquifers of the Southwestern United States (described in *Section 1 of Chapter A*). Much of the streamflow in the northern part of the Rio Grande is from snowmelt runoff in the mountains. In the southern part of the river system, streamflow is from upstream flow, groundwater discharge, and runoff from summer thunderstorms. The arid climate of the Rio Grande Valley provides insufficient precipitation for the growth of most commercial crops; average annual precipitation at the City of Albuquerque is about 22 centimeters (cm) (Western Regional Climate Center, 2006). As a result, irrigated agriculture accounts for a substantial amount of water use within the valley (Robson and Banta, 1995).

The Middle Rio Grande Basin—a large alluvial basin of the Rio Grande aquifer system in central New Mexico—exhibits the same large thickness (hundreds to thousands of meters) of unconsolidated alluvium bounded by bedrock mountain ranges that is typical of the Basin and Range principal aquifer system. The primary mechanisms of groundwater recharge and discharge in the Middle Rio Grande Basin also are similar to those of typical Basin and Range basin-fill aquifers, with the possible exception of a substantial quantity of seepage from the dominant surface-water feature of the basin—the Rio Grande. Chemical characteristics of groundwater in the Middle Rio Grande Basin are representative of the water chemistry in Basin and Range basin-fill aquifers that are connected to adjacent basins. Concentrations of dissolved solids in groundwater within the basin range from less than 200 milligrams per liter to more than 5,000 milligrams per liter (Plummer and others, 2004).

The Middle Rio Grande regional study area is located in the northern half of the Middle Rio Grande Basin. The study area covers about 4,500 km^2, including the Albuquerque metropolitan area. The basin-fill aquifer of the Middle Rio Grande

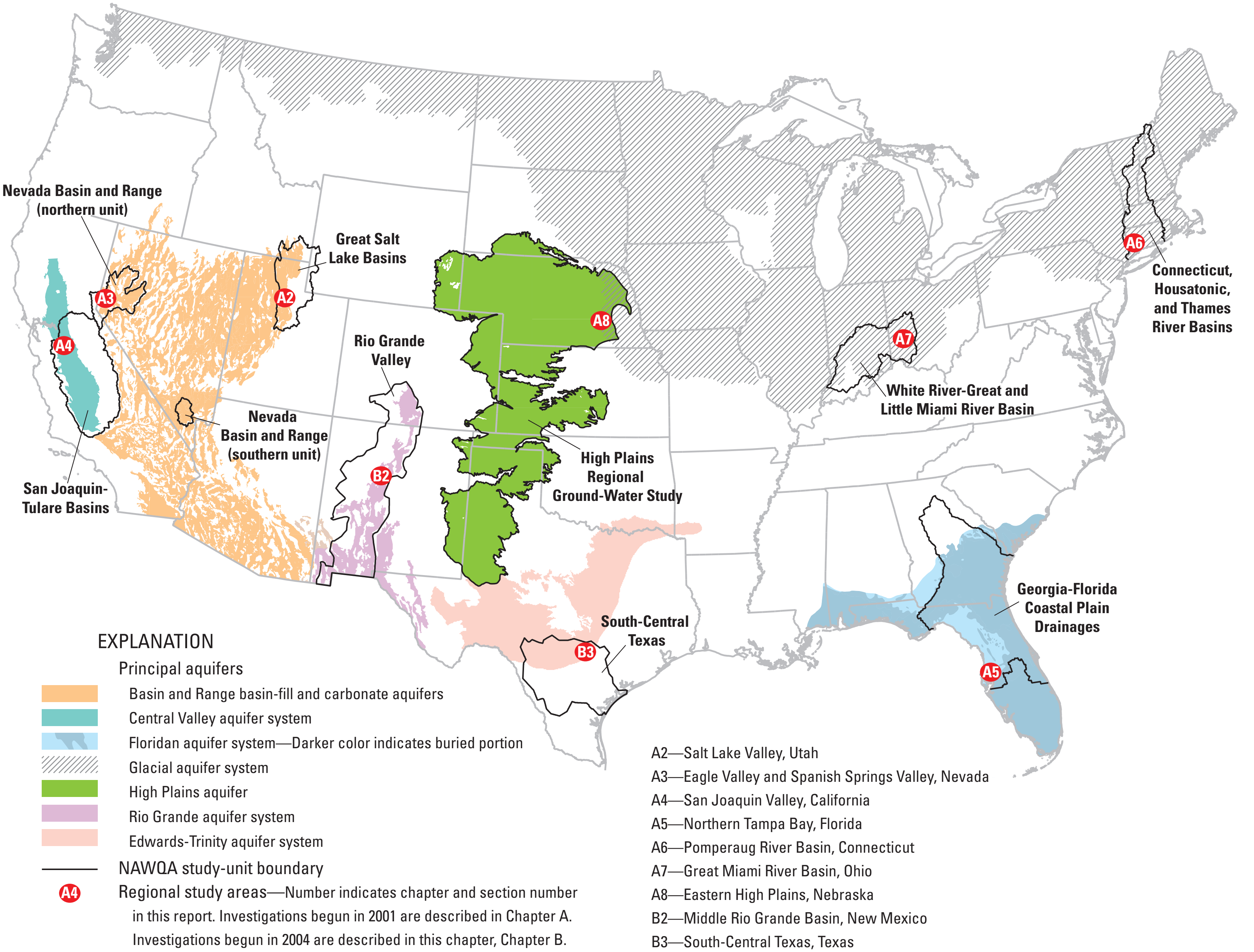

Figure 1.1. Locations of principal aquifers (Miller, 1999), National Water-Quality Assessment program study-unit boundaries, and study areas for regional investigations of the transport of anthropogenic and natural contaminants to public-supply wells begun in 2001 and 2004.

Basin and the regional study area is composed of the Tertiary to Quaternary Santa Fe Group and younger deposits, which together can reach a thickness of nearly 4,500 meters (m) and are commonly referred to as the Santa Fe Group aquifer system. The aquifer system is unconfined, with semiconfined conditions at depth. Although the depth to water is on the order of hundreds of meters throughout much of the study area, the generally shallow depth to water and intense agricultural and urban activity in the historic Rio Grande flood plain result in relatively high susceptibility and vulnerability of the aquifer to contamination in this area. Until surface-water diversions began in December 2008 to supply most water demand within the City of Albuquerque, the metropolitan area relied almost exclusively on groundwater for public supply. This change in water-supply strategy was a response to concerns about declining water levels in the aquifer (City of Albuquerque, 2003). Section 2 of this chapter presents the hydrogeologic setting, model setup, and modeling results for the Middle Rio Grande regional study area.

Edwards-Trinity Aquifer System

The Edwards-Trinity aquifer system is in carbonate and clastic rocks of Cretaceous age in a 199,000-km^2 area that extends from southeastern Oklahoma to western and south-central Texas (fig. 1.1). The aquifer system consists of three complexly interrelated aquifers—the Edwards-Trinity, the Edwards, and the Trinity aquifers. The Edwards-Trinity and the Trinity aquifers are stratigraphically equivalent in part and are hydraulically connected in some places. The Edwards aquifer overlies the Trinity aquifer and the two aquifers are hydraulically connected where no confining unit separates them. The groundwater-flow systems and permeability of the three aquifers are sufficiently different, however, to allow them to be separately mapped and described (Ryder, 1996).

The Edwards aquifer is the most transmissive of all aquifers in Texas. The carbonate rocks in the aquifer are laterally and vertically heterogeneous. Groundwater flow and aquifer properties are appreciably affected by the presence of faults and karst dissolution features. Water in such features can travel many times faster than water in the primary porosity of the rock matrix. Average annual precipitation in the area underlain by the Edwards aquifer ranges from about 56 cm in the west to about 86 cm in the east (Ryder, 1996).

The Edwards aquifer is recharged predominantly through seepage losses from surface streams that flow onto the highly permeable, fractured and faulted carbonate rocks of the Edwards aquifer outcrop (recharge zone) in the Balcones fault zone (see fig. 3.2). Discharge from the aquifer is primarily from spring flow and withdrawals by wells. Six large springs issue from the confined part of the Edwards aquifer. Comal and San Marcos Springs are the largest springs, with flow rates of 10.8 and 7.7 cubic meters per second, respectively, in 2002 (Hamilton and others, 2003).

The groundwater chemistry of the Edwards aquifer is relatively homogeneous and typical of a well-buffered carbonate aquifer system, with calcium and bicarbonate being the dominant dissolved ions. The concentration of dissolved solids in the water typically ranges from 300 to 1,200 milligrams per liter (Ryder, 1996). Widespread occurrence of low concentrations (less than 1 microgram per liter) of some anthropogenically derived compounds (for example atrazine, deethylatrazine, simazine, prometon, chloroform, and tetrachloroethylene) indicates that the aquifer is vulnerable to the effects of anthropogenic activities (Bush and others, 2000; Fahlquist and Ardis, 2004).

The South-Central Texas regional study area is the San Antonio segment of the Edwards aquifer, which overlies the fractured karstic Edwards aquifer in south-central Texas. The study area includes part of the topographically rugged Edwards Plateau and the comparatively flat Gulf Coastal Plain, which are separated by the Balcones fault zone (see fig. 3.2), and the San Antonio metropolitan area. Groundwater accounts for nearly all of the water supply in the South-Central Texas regional study area, and the Edwards aquifer is the principal source. The Edwards aquifer in the study area is unconfined within and adjacent to where it crops out at or near the land surface (recharge zone). The water table is generally greater than 30 m below the streambeds in this area. The aquifer is confined downdip of the outcrop; however, the presence of karst features and the extensive and increasing development on the recharge zone make the Edwards aquifer vulnerable to contamination. Vulnerability to contamination and the dependence of more than 1.5 million people on the aquifer for public water supply combine to make the water quality of the Edwards aquifer and the streams that recharge it a critical issue for the future of the San Antonio region. Section 3 of this chapter presents the hydrogeologic setting, model setup, and modeling results for the South-Central Texas regional study area.

Methods Update

The TANC study regional-scale investigations that began in 2001 consisted of implementing the following six tasks, which are presented in more detail in *Section 1 of Chapter A.*

1. Compilation of retrospective water-quality, well construction, water-use, and geologic data.

2. Collection of groundwater samples from public-supply wells in each study area in association with the NAWQA Source Water-Quality Assessment (SWQA) project. Sampled wells had pumping rates within the upper quartile of pumping for their respective study area.

3. Development of a steady-state regional groundwater-flow model for each study area to represent conditions for 1997–2001.

4. Use of the regional groundwater-flow models and advective particle tracking to compute the extent of the steady-state area contributing recharge and zone of contribution

for supply wells across the range of pumping rates within each modeled area.

5. Mapping of regional redox and pH conditions using the retrospective and newly collected SWQA water-quality data.

6. Development of a TANC database to store retrospective data and modeling results.

The investigations that began in 2004 implemented similar tasks with the following modifications. The collection of groundwater samples from public-supply wells was not constrained by the design of the NAWQA SWQA project, which was limited to high-production wells (Delzer and Hamilton, 2007). Rather, 15 public-supply wells from the upper quartile of pumping and 8 public-supply wells from each of the lower 3 quartiles of pumping were sampled for raw water quality in each of the 2 new study areas. The additional samples from the lower quartiles were included for the new study areas to allow for a more thorough description of the groundwater used as a drinking-water source than was possible for the initial seven study areas. Samples were analyzed for natural and anthropogenic constituents as described in Section 1 of Chapter A, with the addition of low-level analysis for halogenated volatile organic compounds (VOCs) at selected wells to serve as environmental tracers of groundwater age. Analytical methods for the age tracers are described in Busenberg and others (2006) and Shapiro and others (2004).

The areas contributing recharge and zones of contribution to supply wells in the Middle Rio Grande regional study area were simulated using a transient-state model, as opposed to a steady-state model. Consequently, the mapped areas for the Middle Rio Grande do not represent the extent of steady-state contributing areas. A modified approach was used because pumping during the past 50–60 years in the Middle Rio Grande aquifer system has changed groundwater-flow directions on a time scale that is much less than the total traveltime of most water reaching supply wells. Particles were tracked backward from each well to the areas of recharge. Then, to associate each particle with a clearly defined area and a specified volume of flow, a grid of particles was started in each cell that had been determined to be a source of water to the well and tracked forward until all particles reached a sink or until the end of the simulation time. The forward tracking was limited to particles with traveltimes less than 100 years; backward tracking alone was used for particles with longer traveltimes. The time step in which particles in a given cell were started in the forward simulation was based on the time step in which the particles began to contribute water to the well in the backwards simulation. The area associated with particles that terminated at the well during the time step representing June 2005 was mapped as the area contributing recharge to the well.

The grid-refinement approach that was used to help simulate contributing areas for wells that function as weak sinks within model cells also was adapted for use with the transient-state model of the Middle Rio Grande. A well will function as a weak sink when only some of the water entering the model cell in which it is located discharges to the well (see *Section 1 of Chapter A*). The solution to the weak sink problem is to create a highly discretized submodel (fine-grid model) for the weak sink cell so that all water entering the model cell discharges to the well. For the transient-state Middle Rio Grande model, boundary flows for the fine-grid models of the weak sink cells were set by transferring flows from each time step of the regional model to the fine-grid models cells. More specifically, regional model time steps corresponded to a stress period in the fine-grid models of the weak sink cells. Changes were made to the particle-tracking program, MODPATH (Pollock, 1994), to improve the efficiency of the weak sink program for the transient case and are documented in Appendix 1 of this chapter, Chapter B.

An additional complication arose because the MODFLOW Multi-Node-Well package (Halford and Hanson, 2002) was used in the Middle Rio Grande regional groundwater-flow model to allow for movement of water into and out of wells screened over multiple model layers based on simulated hydraulic heads. To account for this type of behavior in the fine-grid models of the weak sink cells while allowing particles to continue through a well in instances of downward leakage, the wells were simulated as follows: Well cells were defined as a stack of cells in a given row and column extending from the elevation of the top to the bottom of the screened interval of the well. The MODFLOW well package (Harbaugh, 2005) was used to set the desired pumping of the well in the top cell of the stack representing the well screen. The other cells representing the well cells were given a high vertical hydraulic conductivity (to simulate the ease of movement in the wellbore) and a reduced horizontal conductivity (to simulate the effects of well radius and formation damage near the well).

The areas contributing recharge and zones of contribution to supply wells in the South-Central Texas regional study area were estimated using a steady-state approach, similar to the initial seven study areas. However, two different models representing conditions during 2001–2003 were constructed, as opposed to a single steady-state model representing conditions during 1997–2001. Two models were constructed for this study area so that different conceptualizations of the groundwater-flow system in the South-Central Texas study area could be simulated. The first conceptualization was that of predominantly conduit flow in the aquifer. The second conceptualization was that of predominantly matrix (diffuse) flow through a network of numerous small fractures and openings. This approach was taken because the locations and interconnectedness of karst dissolution features in this study area were not known. Consequently, the simulated contributing areas for the study area were not estimated with certainty, but they provide insight into the general nature and patterns of contributing areas for public-supply wells in the area.

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