Hydrogeochemical zonation of groundwater in the Botany Sands aquifer, Sydney

Ian Acworth & Jerzy Jankowski

The groundwater quality in the Botany Sands aquifer has deteriorated in the last 50 years due to contamination associated with industrial developments, urbanisation and over-abstraction from the aquifer. This paper presents a conceptual hydrogeochemical model for the Botany Sands Aquifer based upon the analysis of newly acquired field data, supplemented by published data, and identifies three different zones in a hydrogeochemical cross-section along the Lakes Valley.

- A Northern Zone is characterised by groundwater with an average TDS of 136 mg/L and a chemical type Cl-HCO3-SO4-Ca-Na. This zone occurs in Centennial Park and Moore Park, extending south to Kingsford and Rosebery. The chemical composition of groundwater in this zone is the result of rain-water recharge mixed with storm-water run off from the surrounding urban areas.

- A Middle Zone is characterised by groundwater with an average TDS of 104 mg/L and a chemical type Cl-SO4-HCO3-Na-Ca arising from direct rain-water recharge through Holocene sand dunes in the Eastlakes and Pagewood areas. The middle zone groundwaters are characterised by the uniformity of their chemical composition.

- A Southern Zone is characterised by groundwater with an average TDS of 461 mg/L and a chemical type Cl-HCO3-SO4-Na-Ca. The chemical composition of groundwater in the Southern Zone is highly variable, occurring as the result of mixing between the Middle and Northern Zone waters flowing southwards, with significant additional point and diffuse sources of contamination from industrial processes. Identification of these zones allows the development of an improved model of the groundwater resource in the Botany area.

Introduction

The earliest detailed study of groundwater in the Botany Basin was undertaken by Sheil (1942) to determine its suitability as an emergency water supply for Sydney. His results indicated that the water in the Basin was generally soft and well suited to manufacturing purposes without prior treatment. However, there were many cases where bores only a few metres apart produced water having entirely different chemical characteristics, with several indications of leachate contamination from reclaimed land.

In subsequent work, Griffin (1963) compiled all the available information concerning the hydrogeology of the Botany Basin and, along with new hydrochemical data, demonstrated that water quality in the Botany Basin was extremely variable. Griffin (1963) identified very high salinities in the Botany-Banksmeadow area, which indicated possible saline intrusion of the aquifer; however, Cornell (1964) studied the bromide/chloride ratios for these groundwaters, concluding that saline intrusion had not occurred. Cornell (1964) concluded that the presence of chloride ions was the consequence of pollution. This view was shared by several other workers in the area, such as Nettleton & Hall (1964), Walis (1967), Hawke (1973), and Smart (1974).

A further detailed hydrogeochemical study was carried out by Johnson (1978, 1981a,b) who established the presence of several groundwater quality zones in the aquifer, concluding that many of the chemical characteristics identified in the groundwater had their origin in natural water-rock interactions.

New studies carried out by the UNSW Groundwater Centre (Butler, 1990; Hitchcock, 1991; Jankowski & Knight, 1991a,b; Jankowski & others, 1991; Evans, 1993; Dudgon, 1993; and Smolski, 1993), and by Kinhill Pty. Ltd. (Kinhill, 1990) have provided more detailed information concerning the chemical composition of groundwater and pollution in the Botany Sands Aquifer.

Site description

The Botany Basin is situated to the south of Sydney Centre...
and covers an area on both sides of Botany Bay (Fig. 1). The groundwater basin in the Botany Sands Aquifer lies to the north of Botany Bay and is an area of mixed residential and industrial activities. Industrial development has been extensive along the shores of the Bay giving way to residential and amenity development to the north. There are

![Figure 2. Hydrogeochemical zonation of groundwater.](image-url)

**Legend**

- Pezometer (sampling point)
- Open space
- Pond
- Main road
- Observed ground-water flow directions
- Hydrogeochemical zone
- Axis of Hawkesbury Sandstone Lakes Valley
- Hawkesbury Sandstone Outcrop

**Figure 2.** Hydrogeochemical zonation of groundwater.
large open space areas in the northern and central part of the aquifer associated with parks, golf courses and lakes.

Geology

The Botany Basin occupies an erosional depression formed in the Triassic Hawkesbury Sandstone. Erosion during the Tertiary created three deeply incised valleys in the sandstone (Griffin, 1963). During the Pleistocene and Holocene, these valleys were filled with unconsolidated sands, silts, clays and peats. These unconsolidated sediments form the Botany Sands Aquifer.

The Lakes Valley is one of these incised valleys, rising in the north of Centennial Park and running southwards to enter the Bay at Banksmeadow (Fig. 2). The present drainage (Lachlan Ponds) follows the tertiary drainage (Lakes Valley) as far as Eastlakes, where it has been deflected westwards by the growth of prominent northerly striking Holocene sand dunes.

The sediments have been subdivided into four Units (Roy, 1980). A basal Unit composed of fluvial sand with minor gravel grades upwards into marine sand with estuarine shells and overlain by estuarine muds. This Unit reaches depths of 30 m in the Lakes Valley, substantially filling the valley. The second Unit contains beds of peat, has a higher clay content than the basal Unit, and ranges in thickness from 5 to 15 m. This Unit overlaps the Lakes Valley, with deposition on the adjacent sandstone plateau, and is truncated by an erosional unconformity. The third Unit consists of a widespread aeolian sand with discontinuous peat and clay beds and reaches a maximum depth of 30 m. The top of this Unit may be marked by the development of a weak soil, which has produced cementation by organic material to form a horizon known locally as the 'Waterloo Rock' horizon. A fourth Unit is represented by Holocene aeolian sands.

The analysis of 50 sediment samples taken from the Botany Sands Aquifer (Yu & others, 1993) confirms that the aquifer consists predominantly of quartz sand with minor components of silty/peaty sand and sandy peat/clay. These minor components form discontinuous lenses embedded in the sands.

Hydrogeology

The unconsolidated Quaternary deposits form the Botany Sands Aquifer. Units 1 and 2 contain some groundwater supplies; however, the aeolian sands represented by Units 3 and 4 constitute the main aquifer.

The Botany Sands Aquifer covers an area of about 18 300 hectares and has an average water-bearing thickness of approximately 15 m. The facies within this aquifer consist of deposits with fluvial, estuarine, terrestrial, swamp, and aeolian origins, but predominantly consist of fine-grained and uniform quartzose sands with interspersed layers of peat and clay. The aquifer is mainly unconfined, but in some parts of the aquifer, the Waterloo Rock horizon or the peat and clay layers may act to confine groundwater at depth.

There are two sources of recharge to the aquifer. The first is direct rainfall recharge and is of major importance in the open areas, particularly under the areas of sand dunes developed as golf courses and parks. Indirect recharge also occurs in urban and industrial areas underlain by the Botany Sands where run-off from impermeable surfaces (roofs and covered areas) is directed into recharge pits.

The second major source of recharge is from rain falling within the catchment, but on the surrounding impermeable sandstone rim. This water is collected in the northern part of the catchment by the network of storm-water drains which discharge into the top of the Lachlan Pond system in Centennial Park (Dudgeon, 1993).

The main sources of discharge from the aquifer are the Lachlan Ponds and Botany Bay. The Lachlan Ponds provide the major sites for locally and regionally discharging groundwaters (Butler, 1990; Knight & others, 1990; Jankowski & Knight, 1991a) from the shallow aquifers; however, deeper groundwater discharges into Botany Bay.

The regional groundwater flow direction is generally from the recharge zone located in Centennial Park and Moore Park towards Botany Bay. Recent investigations in Centennial Park (Dudgeon, 1993) indicated that the average regional hydraulic gradient is approximately 1:200. Local flow systems exist in the central part of the Lakes Valley where local recharge onto the sand dunes creates flow towards the Lachlan Ponds. Hydraulic gradients in these local systems can exceed 1:140 (Evans, 1993).

Recent studies (Jankowski & Knight, 1991b; Yu & others, 1993; Evans, 1993; Dudgeon, 1993) indicated that the hydraulic conductivity can vary between 1 m/day and 40 m/day, both locally and across the Basin.

Groundwater zonation and chemistry

The chemical composition of groundwater from the Botany Sands Aquifer has been obtained for 85 samples from data presented by Johnson (1981a) and Niewegowski (1988), and has been supplemented by 52 additional analyses recently undertaken by the UNSW Groundwater Centre. The average chemistry of rain water (Table 1) has been determined at three locations, based upon data presented by Johnson (1981a); the chemical composition of samples taken from the storm-water drains (Table 2) are illustrated by three samples analysed by the UNSW Groundwater Centre.

The vast majority of groundwater chemical analyses (>97%) are from shallow (<10 m deep) piezometers. The shallow aquifer can be sub-divided into three zones, based upon the spatial distribution of the chemical composition data. The statistics derived from the chemical analyses of groundwater in each zone are presented in Table 3.

Table 1. Average chemical composition of rain water, Botany Basin.

<table>
<thead>
<tr>
<th>Location</th>
<th>N</th>
<th>EC μS/cm</th>
<th>TDS mg/L</th>
<th>pH</th>
<th>Ca mg/L</th>
<th>Mg mg/L</th>
<th>K mg/L</th>
<th>Na mg/L</th>
<th>Cl mg/L</th>
<th>SO₄ mg/L</th>
<th>HCO₃ mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banksmeadow</td>
<td>14</td>
<td>103.4</td>
<td>57.7</td>
<td>6.3</td>
<td>3.7</td>
<td>1.9</td>
<td>3.1</td>
<td>11.8</td>
<td>21.4</td>
<td>10.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Kensington</td>
<td>15</td>
<td>80.9</td>
<td>43.7</td>
<td>5.5</td>
<td>1.6</td>
<td>1.3</td>
<td>1.2</td>
<td>10.5</td>
<td>18.4</td>
<td>7.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Moore Park</td>
<td>14</td>
<td>45.2</td>
<td>26.4</td>
<td>5.9</td>
<td>1.3</td>
<td>0.7</td>
<td>0.8</td>
<td>5.7</td>
<td>9.3</td>
<td>4.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Table 2. Chemical analyses of storm water.

<table>
<thead>
<tr>
<th>Sample</th>
<th>EC</th>
<th>pH</th>
<th>Eh</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>CO3-</th>
<th>HCO3-</th>
<th>SO4-</th>
<th>Cl-</th>
<th>NO3-</th>
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<tbody>
<tr>
<td></td>
<td>µS/cm</td>
<td></td>
<td></td>
<td>mg/L</td>
<td></td>
<td>mg/L</td>
<td></td>
<td>mg/L</td>
<td>mg/L</td>
<td>mg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storm water draining into Centennial Park</td>
<td>603</td>
<td>9.13</td>
<td>+66</td>
<td>62.4</td>
<td>7.8</td>
<td>39.7</td>
<td>12.5</td>
<td>13.8</td>
<td>108.6</td>
<td>38.0</td>
<td>60.3</td>
<td>—</td>
</tr>
<tr>
<td>Storm water draining into Lachlan Ponds (Pond No 5)</td>
<td>286</td>
<td>7.17</td>
<td>—8</td>
<td>24.5</td>
<td>4.8</td>
<td>20.5</td>
<td>4.4</td>
<td>—</td>
<td>68.7</td>
<td>21.8</td>
<td>42.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Storm water draining into Lachlan Ponds (Pond No 6)</td>
<td>231</td>
<td>6.79</td>
<td>—10</td>
<td>15.9</td>
<td>6.2</td>
<td>16.5</td>
<td>5.4</td>
<td>—</td>
<td>35.4</td>
<td>23.4</td>
<td>36.9</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 2 shows the position of sampling points and the location of the hydrogeochemical zones.

**Northern Zone**

The average electrical conductivity (EC) and average TDS of groundwater in this zone is 213 µS/cm (σ = 56) and 136 mg/L (σ = 48), respectively. The concentrations of Ca²⁺ and Na²⁺ are high relative to Mg²⁺ and K⁺, while the anions have approximately similar concentrations.

Groundwater in this zone is derived from two sources. Dudgeon (1993) has demonstrated that groundwater levels respond within an hour of rain falling on the catchment. Rainfall provides an input of Cl⁻, Na⁺ and SO₄⁻ to the chemical composition of groundwater (Table 1). The second source is derived from urban storm-water drains, which discharge into the Lakes at many places in the catchment. The lakes are in direct hydraulic connection from the shallow aquifer in the Northern Zone.

Table 3. Statistical summary of chemical data from the Botany Sands aquifer.

<table>
<thead>
<tr>
<th></th>
<th>EC</th>
<th>TDS</th>
<th>pH</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>HCO3-</th>
<th>SO4-</th>
<th>Cl-</th>
<th>NO3-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µS/cm</td>
<td>mg/L</td>
<td></td>
<td>mg/L</td>
<td></td>
<td>mg/L</td>
<td></td>
<td>mg/L</td>
<td>mg/L</td>
<td></td>
<td></td>
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<tr>
<td>Minimum</td>
<td>118.0</td>
<td>77.7</td>
<td>4.9</td>
<td>5.2</td>
<td>1.1</td>
<td>1.2</td>
<td>1.0</td>
<td>5.9</td>
<td>0.6</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>320.0</td>
<td>249.0</td>
<td>8.8</td>
<td>36.0</td>
<td>13.0</td>
<td>44.5</td>
<td>34.0</td>
<td>140.3</td>
<td>59.0</td>
<td>47.9</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>212.6</td>
<td>136.0</td>
<td>6.04</td>
<td>17.5</td>
<td>4.8</td>
<td>15.6</td>
<td>4.6</td>
<td>38.3</td>
<td>26.9</td>
<td>28.2</td>
<td></td>
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<tr>
<td>Standard Deviation</td>
<td>56.5</td>
<td>48.3</td>
<td>0.80</td>
<td>6.2</td>
<td>2.8</td>
<td>11.5</td>
<td>5.1</td>
<td>35.7</td>
<td>17.4</td>
<td>7.6</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>EC</th>
<th>TDS</th>
<th>pH</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>HCO3-</th>
<th>SO4-</th>
<th>Cl-</th>
<th>NO3-</th>
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<tbody>
<tr>
<td>Minimum</td>
<td>110.0</td>
<td>79.5</td>
<td>4.6</td>
<td>11.0</td>
<td>1.8</td>
<td>2.0</td>
<td>0.9</td>
<td>6.0</td>
<td>1.0</td>
<td>16.2</td>
<td></td>
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<tr>
<td>Maximum</td>
<td>230.0</td>
<td>145.5</td>
<td>8.9</td>
<td>30.8</td>
<td>7.5</td>
<td>16.9</td>
<td>7.0</td>
<td>76.0</td>
<td>54.8</td>
<td>46.0</td>
<td></td>
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<tr>
<td>Mean</td>
<td>159.1</td>
<td>103.8</td>
<td>5.65</td>
<td>17.1</td>
<td>3.4</td>
<td>8.0</td>
<td>3.7</td>
<td>21.9</td>
<td>21.2</td>
<td>28.4</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>26.5</td>
<td>17.7</td>
<td>0.74</td>
<td>4.2</td>
<td>1.3</td>
<td>4.3</td>
<td>1.3</td>
<td>19.0</td>
<td>11.2</td>
<td>5.5</td>
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</table>

Table 4. Representative chemical analyses from the Northern Zone.

<table>
<thead>
<tr>
<th>Sample</th>
<th>EC</th>
<th>pH</th>
<th>Eh</th>
<th>O₂</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>HCO3-</th>
<th>SO4-</th>
<th>Cl-</th>
<th>NO3-</th>
<th>NH₄</th>
<th>Fe</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µS/cm</td>
<td></td>
<td></td>
<td>mg/L</td>
<td>mg/L</td>
<td>mg/L</td>
<td>mg/L</td>
<td>mg/L</td>
<td>mg/L</td>
<td>mg/L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centennial Park</td>
<td>140</td>
<td>6.51</td>
<td>—147</td>
<td>14.8</td>
<td>3.3</td>
<td>6.3</td>
<td>3.1</td>
<td>49.2</td>
<td>0.6</td>
<td>10.3</td>
<td>&lt;0.01</td>
<td>0.28</td>
<td>0.30</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Centennial Park</td>
<td>118</td>
<td>6.39</td>
<td>+79</td>
<td>2.2</td>
<td>11.5</td>
<td>2.4</td>
<td>8.2</td>
<td>1.8</td>
<td>34.7</td>
<td>5.1</td>
<td>17.6</td>
<td>&lt;0.01</td>
<td>0.03</td>
<td>&lt;0.05</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Moore Park</td>
<td>470</td>
<td>4.50</td>
<td>+286</td>
<td>3.2</td>
<td>40.2</td>
<td>7.4</td>
<td>12.1</td>
<td>16.3</td>
<td>6.7</td>
<td>56.9</td>
<td>17.4</td>
<td>11.0</td>
<td>&lt;0.01</td>
<td>12.3</td>
<td>0.04</td>
</tr>
<tr>
<td>Rowland Park</td>
<td>263</td>
<td>6.59</td>
<td>+148</td>
<td>3.6</td>
<td>5.2</td>
<td>10.3</td>
<td>33.0</td>
<td>3.3</td>
<td>131.8</td>
<td>2.7</td>
<td>23.4</td>
<td>0.4</td>
<td>2.9</td>
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<td>0.8</td>
</tr>
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<td>Kingsford</td>
<td>235</td>
<td>6.50</td>
<td>+81</td>
<td>4.6</td>
<td>15.4</td>
<td>5.0</td>
<td>11.5</td>
<td>1.9</td>
<td>76.9</td>
<td>1.4</td>
<td>34.7</td>
<td>0.1</td>
<td>6.5</td>
<td>0.06</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Daceyville</td>
<td>275</td>
<td>7.19</td>
<td>+119</td>
<td>3.4</td>
<td>11.8</td>
<td>5.6</td>
<td>38.6</td>
<td>3.4</td>
<td>76.9</td>
<td>22.7</td>
<td>34.7</td>
<td>19.6</td>
<td>0.1</td>
<td>0.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>
The average chemical composition of groundwater in this zone is shown in Table 3. The very low standard deviation of all elements and the similarity to rainwater composition at Kensington, shown in Table 1, indicates a uniform body of groundwater dominated by rain-fall recharge. Representative chemical analyses for groundwater in this zone are shown in Table 5. The major elements in the Middle Zone are Na⁺ and Cl⁻ with appreciable SO₄²⁻ and HCO₃⁻. The pH is low (5.6) and similar to the average pH of rain water (5.5) measured in Kensington by Johnson (1981a).

The chemical type of groundwater is Cl⁻-SO₄²⁻-HCO₃⁻-Na⁺-Ca. The concentration of K⁺ and Mg²⁺ are low and the concentration of Ca²⁺ and HCO₃⁻ are on average, lower than those in the Northern Zone.

**Southern Zone**

Groundwater from the southern part of the Lachlan Lakes Valley in the Banksmeadow and Botany suburbs has a completely different chemical composition from the Northern and Middle Zones. The average EC and TDS of these waters are 605 µS/cm (σ = 664) and 460 mg/L (σ = 486), respectively. There is also a wide range of chemical water types present in this zone. Representative chemical analyses for groundwaters in this zone are shown in Table 6.

The chemical composition of groundwater in the Southern Zone has been influenced by the mixing of groundwater flowing from the Northern and Middle Zones with locally polluted groundwater from existing point sources in the industrial suburbs of Botany and Banksmeadow. Leakage and overflow from the main sewage lines and storm-water drains also increases contamination in the area (Kinhill, 1990). Very fresh groundwater has been detected close to the Bay, possibly representing local discharge of rain-water dominated recharge from the open spaces at Mascot Airport.

The dominant anions are HCO₃⁻ and Cl⁻ and the dominant cations are Na⁺ and Ca²⁺. The concentrations of Mg²⁺, K⁺, and SO₄²⁻ are much higher than in either the Northern or Middle Zones. The average pH is slightly acidic at 5.8 (σ = 0.8) with the lowest value (4.2) occurring in this zone.

**Discussion and conclusions**

Three different hydrogeochemical zones have been defined in the Botany Sands Aquifer, which correspond to the chemical zonation of the Lachlan Ponds previously identified by earlier workers (Knight & others, 1990; Butler, 1990; Jankowski & Knight, 1991a) and confirm the close interaction of surface water and groundwater in this aquifer.

The presence of very fresh groundwater between two zones of more contaminated groundwater can be explained by the conceptual flow model shown in Figure 3. In the Northern Zone, urban run-off and storm water mix with rain water to recharge the aquifer in Centennial Park forming a Cl⁻-HCO₃⁻-SO₄²⁻-Ca-Na water type. This groundwater moves towards Botany Bay under the natural hydraulic gradient. Shallow groundwater discharges into the two northern ponds (Ponds No. 5 and No. 6) in the Lachlan Ponds system and dominates the chemical composition of these ponds during dry weather. Deep groundwater will pass beneath the ponds.

Rainfall recharge into the extensive sand dunes in the Middle Zone creates a lens of Cl⁻-SO₄²⁻-HCO₃⁻-Na⁺-Ca waters, which displace downwards the Northern Zone waters. Groundwater from this lens also discharges into the middle ponds (Ponds No. 3, No. 3A, No. 2, No. 1 and No. 1A) in the Lachlan Ponds system and improves the chemical quality of the pond waters, particularly in dry periods (Knight & others, 1991).

The Middle Zone fresh water lens penetrates at least as far south as East Botany before it loses its identity as the result
of contamination from numerous point and diffuse sources.

The Southern Zone represents a wide variety of groundwater chemical types. Inputs from the following sources have been identified:

- down-gradient flow of fresh Middle Zone water,
- additional rain-water recharge,
- down-gradient flow of deeper Northern Zone water,
- numerous point sources of contamination, and
- diffuse sources of contamination.

This wide variety of source waters is clearly shown in the large standard deviation of Southern Zone waters presented in Table 3. The chemical composition of the three southern ponds (Mill Pond, Engine Pond No. 1, and Engine Pond No. 2) also clearly demonstrate the high contamination from shallow discharging groundwaters in this zone (Knight & others, 1991). The conceptual model indicated by Figure 3 and described above has yet to be validated by sampling from the deeper aquifer as no reliable analyses exist for deep waters in the aquifer system. This work is under way.

Acknowledgements

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