SUBSURFACE FLOW PATTERNS IN A RIPARIAN BUFFER SYSTEM

D. D. Bosch, R. K. Hubbard, L. T. West, R. R. Lowrance

ABSTRACT. Matric potential was measured in a grass and forest riparian buffer system adjacent to a cropped field in the Georgia Coastal Plain. The soil in the adjacent cropped field is a Tifton loamy sand, containing an argillic subsurface horizon with plinthite at approximately 1 m which has been shown to restrict vertical infiltration and induce lateral flow. Two years of matric potential data and measurements of soil hydraulic characteristics were examined to evaluate and quantify unsaturated water flow in the riparian buffer. The lowest soil matric potential occurred at the grass/forest interface, and the greatest surface infiltration occurred within 10 m downslope of the same interface. The area of low matric potential was likely due to water uptake by trees. Water flowed laterally through the unsaturated soil into the riparian area from the upland field, apparently induced by low vertical conductivity in the subsurface and driven by the high water demand of the forest. Keywords. Matric potential, Soil water, Unsaturated flow, Groundwater response.

Nonpoint source pollution is one of the greatest forms of contamination threatening our nation’s waters. Agriculture accounts for up to two-thirds of the nonpoint pollution sources identified in many states (Long, 1991). The primary emphasis of research in this area has been on the development of best management practices (BMPs) which limit contaminant migration. Although BMPs provide solutions for many problems, during high intensity and high volume rainfall events, surface runoff, erosion, and deep percolation can still lead to adverse environmental impacts, even with BMPs in place. For this reason, buffers which can slow and sometimes prevent movement of the contaminants from the agricultural watershed have recently received renewed interest. Examples include sediment detention basins, wetlands, and riparian buffer systems. While these buffers have been demonstrated to provide significant benefits for filtering and breakdown of agricultural pollutants, little is known about the mechanisms and processes through which these benefits are obtained.

Riparian vegetation is known to have beneficial effects on streambank stability, stream biological diversity, and stream water temperatures (Karr and Schlosser, 1978). Riparian forests consisting of mature trees (30 to 75 years old) are known to be effective in reducing nonpoint pollution from agricultural fields (Lowrance et al., 1985). Several studies at different sites in the Gulf-Atlantic Coastal Plain physiographic province have shown reductions in surface runoff and subsurface flow are markedly reduced after passage through a riparian forest (Jacobs and Gilliam, 1985; Lowrance et al., 1983, 1984; Peterjohn and Correll, 1984). Other studies in a variety of settings have shown the importance of near-stream zones (Pionke et al., 1988; Rhodes et al., 1985; Schnabel, 1986).

Limited field data on using riparian forests to control agricultural nonpoint pollution have been integrated into draft specifications for riparian buffer system design and management (Welsch, 1991). These draft specifications provide for a riparian buffer system of three zones (fig. 1). Zone 1 is a narrow band of permanent trees (5 to 10 m wide) immediately adjacent to the stream channel to provide streambank stabilization, organic debris input to streams, and shading of streams. Zone 2 is a forest management zone (20 to 50 m wide) where maximum biomass production is stressed, within limits placed by economic goals. Zone 2 may be harvested on appropriate rotations (20 to 60 years). Zone 3 is a grass buffer strip

Figure 1—A representative three-zone buffer system for a second order stream in the coastal plain (adapted from Welsch, 1991).

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(5 to 10 m wide) to enhance deposition of coarse sediment and spreading of overland flow. With these guidelines as a starting point, additional data are now needed to establish specific recommendations with a strong scientific basis on zone lengths and management.

The Gulf-Atlantic Coastal Plain physiographic region extends from Virginia to east Texas and comprises about 70% of the land area of the southeastern United States. This region contains major groundwater aquifers which have extensive recharge areas near the inner margin of the region. In addition, the almost year-round production of vegetables and row crops has led to extensive and sustained use of fertilizers and pesticides in most production systems. Summer rainfall events are poorly distributed over space and frequently occur as short duration and high intensity convective thunderstorms. The average annual rainfall in this area is approximately 1200 mm. The summer thunderstorms promote runoff and erosion which may carry soluble and sorbed phases of applied agricultural chemicals to lower landscape positions or surface waters. Soils in the area are generally low in organic carbon, dominated by low-activity clays, and usually have a low capacity to adsorb applied agrochemicals.

Argillic horizons are common in soils in this region. In general, an argillic horizon is a B horizon that has at least 1.2 times as much clay as some overlying horizon (Soil Survey Staff, 1990) and is formed by immigration of clay. Argillic horizons in the Atlantic Coastal Plain often contain plinthite, a sesquioxide rich, humus poor, highly weathered mixture of clay with quartz and other diluents (Soil Survey Staff, 1990). Plinthite normally occurs in lower B horizons (0.5 to 1.5 m). Plinthite formation is related to periodic saturation of soil horizons and reduction, solubilization, and movement of iron to oxidized zones (Daugherty and Arnold, 1982). More than 3.5 million ha of soils with plinthite have been mapped in the Coastal Plain.

Argillic horizons form subsoil layers which restrict vertical infiltration and promote lateral flow. Lateral flow above argillic horizons is believed to be a significant mode of agrochemical transport into riparian areas (Hubbard and Sheridan, 1983). A study on a 0.34-ha field in the Georgia Coastal Plain indicated as much as 79% of the total runoff losses (surface and shallow subsurface) can occur as lateral subsurface flow above these argillic horizons (Hubbard and Sheridan, 1983). In addition, 94% of the total nitrate-nitrogen losses occurred in the shallow subsurface flow (Hubbard and Sheridan, 1983). This combination of climate, soil properties, shallow groundwater, and extensive application of agrochemicals, makes this region susceptible to contamination of surface and groundwater resources.

A cooperative study between the USDA-Agricultural Research Service and the University of Georgia was begun in 1991 to establish a better understanding of the mechanisms associated with water flow and chemical transport in riparian areas. As part of this study, objectives were outlined to determine hydraulic gradients and flow patterns in the riparian system. The specific objectives of this study were to:

- Determine seasonal and spatial patterns in water flow pathways through riparian systems.
- Determine dominant water flow pathways through a typical Coastal Plain riparian system.
- Examine the effects of forest management on water flow in the riparian zone.

**METHODS**

A site at the University of Georgia Coastal Plain Experiment Station Gibbs Farm near Tifton, Georgia, was selected for this research (fig. 2). The riparian forest study site contains an Alapaha loamy sand soil (Arenic Plinthic Paleaquults; fine-loamy, siliceous, thermic) on a 2% slope, downslope from a tilled field with a Tifton loamy sand soil (Plinthic Kandiudults; fine-loamy, siliceous, thermic) (Perkins et al., 1986). The upland field contains a restrictive subsurface argillic horizon from 0.5 to 1.8 m of the soil surface which directs subsurface flow into the study area. The Tifton soil contains 7 to 14% plinthite from 0.8 to 1.4 m, evidence of a perched water table in this zone during the wetter periods of the year. Over the year, the water table varies from 0 to 3 m below the ground surface. The riparian forest trees are primarily slash pine (Pinus elliottii Engelm.) and long leaf pine (Pinus palustris Mill.). The 5 m nearest the stream channel supports hardwoods including yellow poplar (Liriodendron tulipifera L.) and black gum (Nyssa sylvatica Marsh.). The forest provides a buffer zone which averages 70 m in length from the field to the stream, along an intermittent second-order stream channel.

Monitoring wells and tensiometers were installed at the site in late 1991 and early 1992. Figure 2 shows surface contours of the study area, tensiometer and center well locations, and plot identifications. Three plots were established within the study site, each containing the three defined zones. Zone 3 begins at the base of the field and is

![Figure 2–Surface contours, plot boundaries, and location of the tensiometers and central wells in the study area.](image-url)
made up of a 10-m-long strip of common bermudagrass and bahiagrass mixture. The buffer strip is interplanted with abruzzi rye during winter to provide both biomass production and nutrient uptake. The forest portion of the buffer consists of an approximately 40-m-wide zone 2 and a 10-m-wide zone 1 (fig. 2). As recommended by the Forest Service (Welsch, 1991), zone 2 is used for forest management.

To evaluate the effects of forest management, three treatments were designed. In November 1992, after collecting data for a period of six months with no treatment in order to establish a baseline, zone 2 of plot B was clear cut and zone 2 of plot C was thinned. As a control, plot A was left untreated. Plot B was reforested by planting improved slash pine at a rate of 1,560 trees ha$^{-1}$ based on Georgia Forestry Commission (GFC) recommendations (Georgia Forestry Commission, 1993). Plot C was thinned according to GFC recommendations, with the standing biomass removed from all size classes to a target basal area of about 25 m$^2$ ha$^{-1}$. All woody debris greater than 60 mm diameter was removed, while other debris generated from the harvest treatments was left in the respective plots and distributed within the sites by hand.

Measurements of subsurface water and solute movement were made using fully penetrating wells and a network of tensiometers installed in the spring of 1992 (fig. 2). A gridded network of wells extending from the field/grass interface to the stream was established using a tractor-mounted auger. The wells in each plot were installed in three parallel transects, 10 m apart, with wells in each transect 5 m apart for the 20 m of the buffer system nearest the field and 10 m apart for the remainder. Data collected from the center transect of wells were used for this study (fig. 2). Water depth readings were made every two weeks.

A network of tensiometers in transects perpendicular to the stream were used to monitor unsaturated flow above the water table (fig. 2). Starting from the field to the stream, the first four tensiometer stations were spaced 5 m apart, at every 0.3 m depth interval down to 1.5 m. The remaining five stations were spaced 10 m apart and installed at 0.3, 0.6, and 0.9 m depths. A coarser grid was used near the stream because the water table there was closer to the soil surface and soil moisture changes were expected to be smaller. The tensiometers were constructed using a 100 kPa porous ceramic cup (Soil Moisture Corp., P. O. Box 30025, Santa Barbara, CA 93105. General description: porous ceramic cups, round bottom tapered neck cups, part no. 655X01-B1M1.), 13 mm I.D. schedule 80 PVC piping, and 16 mm O.D. clear acrylic tubing. Each tensiometer was glued using epoxy adhesive and fitted with a septum stopper (Soil Measurement Systems, 7266 N. Oracle Road, Suite 170, Tucson, AZ 85704).

Soil matric potential readings in zones 1 and 2 were taken approximately twice weekly using a data logging tensiometer (Soil Measurement Systems, 7266 N. Oracle Road, Suite 170, Tucson, AZ 85704). Tensiometers in the grass buffer, zone 3, were equipped with Sensym pressure transducers (Sensym, Inc., 1512 Ridgeway Drive, Suite 203, Box 136, Mt. Airy, MD 21771. General description: precision compensated pressure sensors, 0-100 kPa, model no. SCX 15DN.) and monitored with a Campbell CR10 recorder (Campbell Scientific Inc., P. O. Box 551, Logan, UT 84321). Transducer voltage measurements were made every 10 min and converted into soil matric potential using linear calibration data for each transducer. Tensiometers were filled as required during data collection.

Hydraulic and moisture characteristics were evaluated from samples collected in the spring of 1992. Samples collected at five sites, along a transect bisecting plot B were characterized based upon soil morphology. The samples were visually classified at the site based upon color and texture, and saved for particle size analysis.

Saturated hydraulic conductivity, soil-water release, and bulk density measurements were made on 24 soil cores collected at the site. These cores were collected in two depth intervals, from 0.02 to 0.10 m and from 0.15 to 0.23 m, in a transect from the grass buffer to the stream. Four cores from each depth interval were collected from six sites along a transect from the field edge to the stream through plot A. Two of the sites were in the grass buffer, 5 m from the field edge. The remaining sites were 25, 35, 45, and 60 m from the field edge. An impact-type soil sampler was used to collect the samples in 0.08-m-diameter $\times$ 0.08-m-long metal rings. Saturated hydraulic conductivities were determined on presaturated cores (overnight soaking) using the constant head method (Klute and Dirksen, 1986). Soil moisture retention measurements were made at 0.4, 6.0, 30.0, 100, and 1500 kPa using tempe cells (Klute, 1986; Reginato and van Bavel, 1962). Following soil moisture retention measurements, the cores were oven dried for 24 h at 105°C and weighed to determine bulk density.

Some information about horizontal saturated hydraulic conductivity is available from an associated study being conducted in the tilled field upslope from the riparian site (Hubbard, 1994). Core samples were collected from a soil pit in the field and tested for saturated hydraulic conductivity. Four cores were collected horizontally from the pit wall. The midpoints of the horizontal cores were 0.25, 0.40, 0.55, and 0.84 m. Due to the presence of plinthite, some of these samples did not fit tightly to the core walls.

**RESULTS**

**SITE CHARACTERISTICS**

The results of the soil morphology analysis are illustrated in figure 3. The surface soil in the riparian area is primarily a loamy sand, except the stream-side where there is a heavy organic layer at the surface. The surface soil is underlain by mixed sandy clay loam, sandy clay, and sandy loam horizons. The presence of finer textured layers may indicate a resistance to vertical infiltration. Up to 10% plinthite was found in the samples collected nearest the field edge, at approximately 0.5 m depth, indicating perched water. Interestingly, the sandy clay and sandy clay loam horizons appear to be a continuous feature from the field to the stream, at varying depths. This forms a subsurface water restricting layer which slopes toward the stream, but not at as great a slope as the soil surface. This may cause seeps where perched water would resaturate if the depth of saturation is greater than the depth between the surface and the restrictive layer. In addition, since the
densities, lower saturated hydraulic conductivities, and lower soil-water holding capacities than did cores collected within the woods. For the cores collected horizontally from the soil-pit, the saturated hydraulic conductivity in the top two cores averaged 25.0 mm/h, while the average was 7.0 mm/h for the bottom two cores.

**Seasonal and Spatial Patterns**

Daily matric potential values were plotted with the daily precipitation for each of the sites over the period of record. An example of these plots is shown in figure 4. The matric potential data clearly show seasonal differences. The soil was close to saturation from November through April, particularly at the deeper depths and lower landscape positions. As the data from the 0.3 m depths indicate (fig. 4a), the upper soil area was quite responsive to rainfall, frequently saturated, and dried out rapidly. While the 1.5-m tensiometers respond slowly to rainfall (fig. 4b), 0.9-m tensiometers respond rapidly. This appears to be due to restrictive soil horizons below the 0.9-m tensiometer (fig. 3).

Data from the tensiometers and well sites in each transect were combined to evaluate matric potential and hydraulic head patterns across the landscape. Cross-sectional contour plots were obtained using the SURFER (Golden Software, Inc., P. O. Box 281, Golden, CO 80402) computer software package (fig. 5). (Computer generated contour plots were compared to observed data and judged to be accurate.) The ground and water table surfaces were incorporated into the plots and are shown as the top and bottom boundaries. The water table was determined from

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**Figure 3**—Soil characteristics of samples collected at five sites, along a transect bisecting plot B.

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**Table 1. Physical properties of soil samples collected at the Gibbs Farm riparian research site along a transect from the field edge to the stream through plot A***

<table>
<thead>
<tr>
<th>Core Depth Interval (m)</th>
<th>Transect Position (m)</th>
<th>Soil-Water Retention (m³/m³)</th>
<th>Matric Suction (kPa)</th>
<th>Bulk Density (kg/m³)</th>
<th>Saturated Hydraulic Conductivity (mm/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02-0.10</td>
<td>5</td>
<td>0.36</td>
<td>0.32</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>0.02-0.10</td>
<td>5</td>
<td>0.30</td>
<td>0.27</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>0.02-0.10</td>
<td>25</td>
<td>0.41</td>
<td>0.29</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>0.02-0.10</td>
<td>35</td>
<td>0.45</td>
<td>0.26</td>
<td>0.16</td>
<td>0.13</td>
</tr>
<tr>
<td>0.02-0.10</td>
<td>45</td>
<td>0.41</td>
<td>0.28</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>0.02-0.10</td>
<td>60</td>
<td>0.45</td>
<td>0.28</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>0.15-0.23</td>
<td>5</td>
<td>0.27</td>
<td>0.23</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>0.15-0.23</td>
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<td>0.27</td>
<td>0.22</td>
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<td>0.11</td>
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<tr>
<td>0.15-0.23</td>
<td>25</td>
<td>0.35</td>
<td>0.23</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td>0.15-0.23</td>
<td>35</td>
<td>0.41</td>
<td>0.25</td>
<td>0.13</td>
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<td>0.15-0.23</td>
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<td>0.35</td>
<td>0.25</td>
<td>0.16</td>
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</tr>
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<td>0.15-0.23</td>
<td>60</td>
<td>0.36</td>
<td>0.27</td>
<td>0.18</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* Each value is the average of four cores.

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**Figure 4**—Matric potential values at (a) 0.3 and (b) 1.5 m depth, 5 m from the field/grass interface along transect A and daily precipitation over the period of record.
measurements made at approximately the same date the matric potential measurements were made. Spatial patterns and wetting effects are illustrated by a comparison of the matric potentials before and after rainfall (fig. 5). Prior to rainfall very low matric potentials can be observed throughout the profile. After rainfall the matric potential in the 0 to 1.0 m depth was substantially increased, indicating infiltration to this depth.

Prior to rainfall, an area of very low matric potential can be observed 15 m down the transect at 0 to 1.0 m of depth (fig. 5a). This was observed in other cross-sectional plots for similar climatic conditions. This position coincides with the interface between the grass buffer (zone 3) and the forest (zone 2) and illustrates the effect of the forest’s water demand. Further into the forest and down the profile, the lower position in the landscape causes a wetter soil condition.

DOMINANT WATER FLOW PATHWAYS

After rainfall, an area of saturation appears near the soil surface between 20 and 30 m down the transect (fig. 5b). This appears to be the position in the landscape at which runoff from the upland area infiltrates. Physical property data (table 1) indicate saturated hydraulic conductivity is greatest 25 m from the field boundary. More rapid infiltration through the surface layer is expected at this landscape position.

Hydraulic heads between the land surface and the water table were calculated by summing the matric and gravitational potentials. Water table elevations were used to determine the hydraulic head along the water table. Similar to the matric potential cross-sectional plots, hydraulic head plots were made to examine hydraulic gradients down the landscape. Prior to rainfall the gradients near the surface are larger (fig. 6a). The greatest gradient before rainfall occurs near the observed pocket of low matric potential, at the grass/forest interface at approximately 0.5 m depth. This indicates a significant water sink at this point. In contrast, after rainfall the dominant gradient direction in the upper 1.0 m of the profile was vertical downward (fig. 6b). The portion of the profile below 1.0 m appears to be largely unaffected by this rainfall. However, near the area of saturation, 20 to 30 m down the transect, the flow direction was downslope and toward the water table. Thus, any overland or shallow subsurface flow which reaches this point could flow directly to the groundwater if this gradient persists. Under these conditions, any surface runoff containing contaminants could have significant environmental consequences.

Evidence exists that subsurface flow may be entering the riparian area from the upland. An area of higher matric potential exists at the field/grass interface, at depths of approximately 1.0 m (fig. 6a). This would coincide with the approximate depth of the most restrictive horizons in this soil (fig. 3). These patterns were repeated for the other transects and for additional days. This reflects the higher horizontal saturated hydraulic conductivity in the upper 0.4 m of the field. Water flows more readily through this zone, increasing the soil-water and matric potential. In the area below this, where the saturated hydraulic conductivity is lower, less water is flowing into the zone.

Flow patterns during the wetter season are illustrated by the cross-sectional plot of transect A on 21 April 1993 (fig. 7). In contrast to the July cross-sections of the matric potential (fig. 5), higher matric potential dominates the profile at this time of the year, with greater uniformity than in the summer period. From January through April, the area was primarily saturated. During this period, flow occurs in the shallow subsurface aquifer from the field to the stream bottom, driven by the gravitational component of the hydraulic head. Also during this period, the hydraulic gradients are lower (fig. 7b). This is in contrast to the
hydraulic gradients during the summer which indicate a flow system driven by areas of low matric potential created by the forest water demands (fig. 6a).

The low point in the water table was 40 m upslope from the stream during the drier months of the year (fig. 5). During the wetter season, from January through March, the low point was at the stream bottom (fig. 7). This indicates the riparian forest was fed from groundwater flowing along the stream bottom as well as groundwater entering from upslope during the summer months. Thus, contaminants traveling via saturated flow from the upland to the stream bottom would be significantly reduced.

**TREATMENT EFFECTS**

Matric potential and hydraulic head spatial patterns across the plots were examined by combining all of the data from each of the transects for a single depth. Horizontal cross-section contour plots for representative depths were obtained using the SURFER program. The lowest matric potentials were observed at the field/grass interface (fig. 8a). A zone of saturation extends from the stream up through a large portion of zone 2. In figure 8b, the matric potential contours at 0.3 m on 22 July 1993, illustrate the effects of rainfall at the 0.3 m depth. While the zone of saturation remains approximately the same, the matric potentials in the grass and grass/forest interface are substantially increased. Similar results were observed at 0.6 m. Examination of the matric potentials at 0.6 m indicates a large portion of plots B and C became saturated below the 0.6 m depth following the 21 July rainfall event. This would indicate substantial infiltration in these plots, due to surface runoff or shallow subsurface lateral flow. Examination of the site topography contours indicates surface runoff into this area was likely (fig. 2).

The effects of the treatments were examined using the matric potential data. Some evidence exists which indicates the matric potentials in zone 2 of plot B, the clear cut area, are higher than in the other plots (fig. 8). This indicates a lower water demand in this area, which agrees with the anticipated effects of removing the mature forest. Comparison of matric potential data from 1992 to 1993 data collected in plot B indicate the removal of the forest reduced the demand for water within the root-zone at the grass/forest interface. However, spatial variability due to soil and elevation differences make it difficult to conclusively detect treatment effects over the entire site.

Comparison of hydraulic head data for 20 and 22 July 1993 shows the horizontal gradient was substantially reduced following rainfall (fig. 9). In addition, the flow direction was reversed from toward the grass to toward the stream bottom. This is indicated by the reversal of the position of the highest total potentials and the hydraulic gradient. The effect of the precipitation on the vertical
gradient is illustrated in Figure 10. The hydraulic gradient between the 0.3- and 0.6-m readings was calculated as the negative of the difference between the hydraulic head at the two points divided by the distance between the points. On 20 July 1993 the dominant flow direction was toward the surface, with the largest gradients observed along the field/grass and grass/forest interfaces. Following the rainfall event, flow was downward, with the greatest gradients observed between plots A and B.

The hydraulic head contours for the 0.3 and 0.6 m depths on 20 July 1993 indicate a significant horizontal component to the unsaturated flow patterns in the grass buffer and the first 10 m of zone 2. Following rainfall events the horizontal gradient was substantially reduced and the vertical gradient dominates.

CONCLUSIONS
Analysis of matric potentials and hydraulic gradients indicates there was water flowing laterally into the riparian buffer from the upland field. This water was moving in the unsaturated soil, above and within the argillic horizons of the soil. This unsaturated flow was taking place during the drier times of the year and was driven by the high water demand of the riparian forest. During the wetter times of the year, saturated flow takes place near the soil surface with flow from the field to the stream bottom driven by gravity.

A very low matric potential was observed at 0.5 to 1.0 m depth at the grass/forest interface. This area of low matric potential appears to be due to high water demands of the forest. Because of the higher position in the landscape,
water demands of the forest are not met by the surficial aquifer. This water demand creates hydraulic gradients moving water toward this area from the stream bottom as well as the upland. The water demand of the forest appears to be great enough to shift the gradient of the saturated flow from toward the stream bottom to toward the grass/forest interface.

Results indicate the greatest surface infiltration occurs within 10 to 20 m downslope of the grass/forest interface. At this point, surface runoff infiltrates into the upper surface of the forest soil. Infiltration was particularly high in the lower portions of plots B and C, driven by the gradients of the land surface. After rainfall events, this was the area where deep percolation occurred.

During the period of study, the pedon in the riparian area was largely saturated from January through March. During this time, the flow patterns in the shallow aquifer are from the field edge to the stream bottom, driven by the difference in gravitational head. During the spring and summer months, evapotranspiration of the forest creates large water sinks in the shallow subsurface and large gradients. These gradients largely control flow patterns during this part of the year. Examination of water table elevations throughout the period of record indicate the water demand of the forest shifts the direction of the shallow subsurface aquifer flow. During periods of high evapotranspiration the direction of flow was from the bottomland to the riparian buffer, reversed from the winter months.

The effects of the different treatments on water flow through the riparian area have been largely indistinguishable. Some evidence exists which indicates a lower water demand in the clear cut area. However, spatial variability in surface topography and matric potential data make it difficult to determine the specific causes for these differences. Additional data are necessary to fully understand these effects.

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