# Mapping Hydromorphic Areas and Drainage Networks in Tropical Riparian Zones using Topographic Attributes

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**Abstract**

Riparian areas and channel networks are important landscape compartments, with key hydrological and ecologic functions. Hence, defining their spatial boundaries is an important step towards sustainable riparian management. In tropical countries, riparian areas are rarely mapped, although they represent a crucial component of local livelihoods and ecosystems. In this study, topographic attributes generated with a 30m SRTM DEM were used to delineate wet areas and stream networks of two small catchments in Central Brazil. The topographic attributes were the local slope, the slope curvature, and the Topographic Wetness Index-TWI, respectively. Threshold values of the selected topographic attributes were calibrated in the Santa Maria catchment, comparing the synthetic wet areas and drainage networks with corresponding reference (map) features, and validated in the nearby Santa Maria basin. Drainage network and wet area delineation accuracies were estimated with multi-criteria and confusion matrix methods. The drainage network delineation accuracy was 67.2% and 70.7%, and wet area prediction accuracy was 72.7% and 73.8%, for the Santa Maria and

Gama catchments, respectively. The delineation errors resulted from model incompleteness, DEM grid size and vertical inaccuracy, and from cartographic misrepresentation of the reference maps. The method performed equal or better than other studies in the literature, and could be used for preliminary mapping of riparian areas of tropical catchments.

**Keywords:** modelling, drainage network, riparian areas, delineation, catchment, GIS.

## 1. INTRODUCTION

Riparian zones play a fundamental role in the regulation of stream water quality, reducing sediment and nutrient loading (Laudon et al., 2016) through increased deposition and nutrient uptake (Tomer et al., 2009). Riparian areas also fulfil important ecologic functions in catchments (Johnson et al., 1999).

In the Cerrado biome in Central Brazil, gallery forests and grassy wetlands occur in riparian zones of valley bottoms, along stream channels (Skorupa et al., 2013), and are associated with the seasonal fluctuation of the water table (Eiten, 1972). Low-lying grasslands occur over hydric soils, and gallery forests cover well drained and hydromorphic soils (Oliveira Filho et al., 1989), forming the wet areas of river basins.

In tropical countries, data on riparian processes, functions, and values are scarce, even though riparian areas provide a crucial component of local livelihoods (Johnston et al., 2013). Therefore, defining the spatial boundaries between well drained/upslope and poorly drained/valley bottom areas is an important step towards riparian management (Acevedo et al., 2017). However, due to the high spatial variability of the soils and groundwater levels, soil and vegetation mapping in riparian zones is challenging (Skorupa et al., 2013), particularly when the original gallery forest was removed (Laudon et al., 2016).

Since shallow water tables in landscape bottoms are associated with hydric soils (Güntner et al., 2004; Laudon et al., 2016), gallery forests (Lenza et al., 2015; Oliveira Filho et al., 1989), and stream heads (Dunne, 1980; Hastings & Kampf, 2014), and because soil wetness is a function of hillslope convergence (O'Loughlin, 1986), different topographic attributes that predict soil wetness can be used to map riparian zones (Moore et al., 1988), particularly in data-scarce locations, such as the tropics (Moore et al., 1991).

Most studies dealing with riparian area and drainage delineation were carried in temperate regions. In an American catchment, Detty & McGuire (2010) found that the upslope area and the topographic wetness index-TWI (Beven & Kirkby, 1979) were correlated with shallow water table persistence. Burt & Butcher (1985) reported that the product of primary topographic attributes, such as upslope area, slope gradient, and slope curvature, were good predictors of soil wetness and water table depth. Buchanan et al. (2014) found that the TWI was significantly correlated with soil wetness in agricultural fields in the USA, particularly when high-resolution DEMs were used.

Güntner et al. (2004) used the upslope contributing area, the slope curvature, and the TWI to predict the distribution of wetlands in a landscape in Sweden, utilizing geobotanical and pedological criteria. They concluded that the upslope contributing area was the most important explanatory factor in the prediction of saturated areas. The TWI and a model-derived wetness index were utilized by Grabs et al. (2009) in the prediction of the spatial distribution of saturated areas in Sweden, with the latter resulting in a higher accuracy because of its dynamic nature.

In the prediction of saturated areas using soil information coupled with terrain data, Ali et al. (2014) concluded that wetness indices worked well only when wet areas covered more than 30% of the catchment. In Taiwan, Chang & Lee (2008) found that the TWI was well correlated with runoff generating areas. Using the TWI together with the slope gradient and the slope curvature, Qin et al. (2011) predicted the spatial distribution of soil types and their properties at fine scales.

Reviewing the application of primary and secondary topographic attributes in riparian vegetation mapping, Franklin (1995) concluded that they are useful for interpolating vegetation-environment correlations within a region. Kopecký & Čížková (2010) found an important correlation between soil moisture, predicted by the TWI, and vegetation composition. The latter also concluded that the choice of the flow routing algorithm had a considerable effect on the index performance.

In eastern Brazil, Silva et al. (2019) used the slope, the valley bottom flatness, and the TWI to map the soils of a riparian area, and concluded that mapping accuracy depended on the soil drainage conditions. In the Brazilian savanna, Skorupa et al. (2013) found that the use of gallery forests as a proxy for hydric soils overestimated the distribution of the latter, since that type of vegetation also occurred on well-drained soils. This finding was corroborated by Marimon et al. (2010), who concluded that gallery forests of Cerrado catchments were found over both well and poorly drained soils, and that local slope and the distance from the stream were useful attributes in riparian soil mapping.

Stream heads, on the other hand, are the boundaries between hillslopes and river channels (Roth & La Barbera, 1997), and commonly occur at topographic convergences (hollows) where enough runoff accumulates and exceeds an erosion threshold (Julian et al., 2012). In steep terrains, land-sliding and seepage erosion are the dominant factors controlling channel initiation (Montgomery & Dietrich, 1992), whereas in gentle slopes the main driving process is overland flow (Gallon & Lindberg, 2014).

The ability to determine the location in the landscape where channels initiate is important for understanding hydrologic and geomorphologic processes, and for managing headwater streams (Henkle et al., 2011). However, because of the dense canopy of the gallery forests, the conventional photogrammetric mapping of stream heads and the corresponding drainage network is a subjective task, often resulting inaccurate hydrographic representations (Jaeger et al., 2007).

Mapping channel heads in Oregon (USA), Montgomery and Dietrich (1992) confirmed the hypothesis that the channelization threshold is a distance just shorter than the hillslope length. In an earlier study, the same authors concluded that the location of channel heads on steep slopes is controlled by the subsurface flow-induced instability of the colluvial fill (Montgomery & Dietrich, 1989).

Roth & La Barbera (1997) found that channel initiation in the landscape can be predicted by the square root of the contributing area times the slope gradient. Julian et al., (2012) reported that local slope, local plan curvature, and average profile curvature were good predictors of channel heads, but the predictive effectiveness depended on the type of catchment.

Hastings & Kampf (2014) concluded that channel heads could be mapped using TWI threshold values. According to those authors, successful drainage network mapping should strike a reasonable balance between channel density, head-ward extent, and positional accuracy. Quinn et al. (1995) reported that the TWI threshold value for channel initiation (TWI $\geq$ 12) was dependent on the DEM grid size.

Kim & Lee (2004) integrated the TWI channel initiation threshold with a spatially distributed flow-apportioning algorithm, to delineate channel networks in Korea, and obtained reasonable results. McMaster (2002) used a critical support area to define channel initiation and drainage position, and concluded that the DEM routing method (D8 or D$\infty$) did not matter in steeper slopes, provided that the pixel size was smaller than the hillslope length. Ruhoff et al. (2011) utilized the TWI and different flow direction algorithms in six catchments in southern Brazil, and concluded that the single direction D8 algorithm concentrated runoff along the main channel, whereas the D$\infty$ method dispersed it.

Considering that topographic attributes were used to map wet areas and drainage networks, particularly in temperate basins, and recognizing that tropical watersheds may require specific mapping strategies, the objective of this study was to use appropriate topographic attributes and thresholds to delineate wet areas and drainage networks of two small catchments in the Brazilian Cerrado, and to assess their mapping accuracy with unbiased methods.

## 2. MATERIALS AND METHODS

### 2.1 Study Catchments

Two small and hydrologic similar catchments of the Brazilian Cerrado biome, in central Brazil, were studied: The Santa Maria and the Gama river basins, situated 20 km apart (Figure 1). The former was used to calibrate the threshold values of the selected topographic attributes, and the latter was used to validate them. Table 1 presents the hydrologic characteristics of both catchments.

[Insert Figure 1]

[Insert Table 1]

Detailed (1:10,000) and semi-detailed (1:50,000) digital maps of hydrography, soils, and land-use were available for the Santa Maria (Figure 2) and Gama (Figure 3) basins, allowing the correlation of the selected topographic attributes with mapped (reference) features. However, since these reference maps were produced using aerial photogrammetry, they are subject to cartographic errors and misrepresentations (Jeager et al., 2007), and consequently were not taken as ground truth.

[Insert Figure 2]

[Insert Figure 3]

Both catchments have gentle slopes, well drained (Oxisols) and poorly drained (Entisols) soils, and are covered with different gradations of savanna vegetation (Unesco, 2002). In the upslope areas, open savanna vegetation occurs over well-drained soils. In valley bottoms, gallery forests cover poorly and well-drained soils, and grassy marshes occur over hydric soils. There are two types of valley bottoms in the catchments studied: *V-type* bottoms, where gallery forests predominate, and *U-type* bottoms, where marshy flats are dominant. Figure 4 shows these features in both catchments.

[Insert Figure 4]

**2.2. Topographic Attributes**

Considering the objective of the study, the selection of topographic attributes favoured the aspects of simplicity and data availability, requiring only the 30m-DEM as input. After a thorough search in the literature, the chosen attributes for the wet area delineation were the local slope and the slope curvature. The Topographic Wetness Index-TWI was selected for the delineation the drainage networks.

In the case of the local slope, flatter areas are associated with hydric soils (Marimon et al., 2010). In the case of slope curvature, negative values are associated with areas of flow accumulation (Moore et al., 1991).

The topographic wetness index-WTI, on the other hand, is an integrated indicator of concentrated flow paths (Beven & Kirkby, 1979; O'Loughlin, 1986), and more suitable for drainage delineation. The TWI is given by (Beven & Kirby, 1979):

$$\mathrm{TWI} = \ln\left(\alpha / \tan\beta\right) \tag{1}$$

where: α = the upslope contributing area per unit contour length (m), reflecting the tendency of the site to receive upslope water, and β = the local slope gradient (radians), indicating the tendency of the site to drain/retain water. In equation 1, soil transmissivity was assumed to be constant throughout the catchment (Schneiderman et al., 2007). When the slope β in equation 1 was smaller than 0.001, a constant value of 0.001 was added, to avoid a division by zero (O'Neill et al., 1997).

Considering that the D∞ flow routing algorithm tends to disperse water in gentle slopes, creating a feathering effect in the synthetic drainage network (Hastings & Kampf, 2014), the D8 flow direction routine (Jenson & Domingue, 1988), which concentrates runoff along a channel (Ruhoff et al., 2011), was selected for the TWI computation.

The DEM used in the calculation of the topographic attributes was the 1-arc-second, 30m SRTM-Topodata (Valeriano et al., 2009). All spatial calculations of the three topographic attributes, including their intermediary coverages (flow direction, filling, and flow accumulation), were performed with the *ArcGIS 10.6.1® Spatial Analyst* software.

**2.3. Drainage Network Delineation**

Different simulated drainage networks were obtained with the TWI in the Santa Maria (calibration) basin, testing different channel initiation threshold values (Hastings & Kampf, 2014; Kim & Lee, 2004). The synthetic stream networks were compared to the reference (map) hydrography. Following the recommendation of Quin et al. (1995), the calibrated (optimal) TWI threshold in Santa Maria catchment was obtained by the balance of two mapping criteria: i) the drainage network accuracy; and ii) the channel initiation accuracy, namely:

$$TWI_o = \frac{\left(B_p / T_p\right) + \left(O_1 / T_1\right)}{2} \quad (2)$$

where: $TWI_o$ = optimal threshold value; $B_p$ = number of TWI pixels falling inside a 150-m buffer, built around the reference drainage network (Russell et al., 1997); $T_p$ = the total number of pixels of the TWI drainage network in the basin; $O_1$ = number of first order streams of the reference map identified by TWI pixels; and $T_1$ = total number of first order streams of the reference drainage network.

The left term in the numerator of equation 2 represents the drainage delineation accuracy, and the right term indicates the channel initiation accuracy. The calibrated TWI threshold in the

Santa Maria catchment, obtained by the maximization of equation 2, was subsequently applied to the TWI in the Gama basin, to validate the methodology. Finally, the TWI prediction accuracy of both basins were compared with the accuracies of other drainage delineation studies, in the literature.

### 2.4. Wet Area Delineation

Following the recommendation of Marimon et al. (2010), the reference wet areas of both catchments were obtained by merging the features of ‘gallery forests’ and ‘grassy marshes’ of their corresponding land-use maps. Considering that wet areas in the landscape are associated with flats and hollows (Marimon et al., 2010; Skorupa et al., 2013) (see Figure 4), the combination of local slope and slope curvature was used to delineate them (Burt & Butcher, 1985; McMaster, 2002; Rinderer et al., 2014), with appropriate thresholds:

$$S_c \leq k_1 \quad \text{and} \quad S_l \leq k_2 \tag{3}$$

where: $S_c$ = slope curvature; $S_l$ = local slope, both obtained with the GIS, using the 30m DEM; and $k_1$ and $k_2$ are calibrated threshold values. In equation 3, the constant $k_1$ is negative, since convergent landscape features, such as hollows and concave slopes, were sought. The value of $k_2$, on the other hand, is small and positive, to assess valley flats.

The local slope and slope curvature maps of the Santa Maria and Gama catchments are shown in Figures 5 and 6, respectively. To assess the accuracy of the wet areas delineated by equation 3, 10 linear transects (Ågren et al., 2014) were randomly laid across riparian areas of both catchments (Figure 5).

[Insert Figure 5]

[Insert Figure 6]

Subsequently, the 10 gridded transects shown in Figure 5 were intersected with the predicted and reference wet areas of both basins, and a confusion matrix was obtained. The wet area prediction accuracy ($A_c$) was given by (Ågren et al., 2014):



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$$A_c = \frac{(T ¿¿ p + T_n)}{(T ¿¿ p + T_n + F_p + F_n) ¿} ¿ \qquad (4)$$

where: $T_p$ = number of true positive pixels in the transects; $T_n$ = number of true negative pixels; $F_p$ = number of false positive pixels; and $F_n$ = number of false negative pixels. A 'true positive' pixel was obtained when a predicted wet area in the transect lines correctly intersected a reference wet area. Conversely, a 'true negative' pixel occurred when a dry area was correctly predicted. A 'false-positive' (Type I error) was obtained when a predicted wet area in the transect was actually dry. Finally, a 'false-negative' (Type II error) occurred when a predicted dry area was actually wet.

In the calibration phase, carried in the Santa Maria catchment, the thresholds $k_1$ and $k_2$ which maximized equation 4 were obtained by trial and error. The calibrated values of $k_1$ and $k_2$ were then applied to the validation (Gama) catchment, and its prediction accuracy was calculated using equation 4. Finally, the wet area delineation accuracy of both basins was compared with those of similar studies in the literature.

## 3. RESULTS

### 3.1. Drainage Network Delineation

The calibrated value of TWI in the Santa Maria basin was 15, balancing stream initiation and channel delineation accuracies. Quinn et al. (1995) found a TWI threshold of 12 for a perennial drainage network in England. Moore et al. (1988) found that ephemeral gullies heads in an Australian catchment occurred when TWI $\geq$ 7.

The predicted and reference drainage networks of the calibration and validation catchments are presented in Figure 7. As expected, the synthetic drainage networks were concentrated flow paths, since the D8 single-direction routing algorithm was used (Ruhoff et al., 2011).

[Insert Figure 7]

Figure 7 indicates that there is a relatively good agreement between the simulated and reference channel networks, particularly in the Santa Maria catchment. Despite the small offsets observed in the Gama basin, there was a good overall drainage delineation accuracy in both catchments, namely 67.2% and 70.7% for the Santa Maria and Gama basins, respectively (Table 2).

[Insert Table 2]

### 3.2. Wet Area Delineation

The calibrated values of slope curvature ($S_c$) and local slope ($S_l$) in the Santa Maria basin were -0.05 and 0.01, respectively, and the simulated and reference wet areas of the Santa Maria and Gama catchments are presented in Figure 8. Table 3 shows the confusion matrix and overall wet area delineation accuracies for both catchments.

[Insert Figure 8]

[Insert Table 3]

According to Table 3, the overall wet area delineation accuracy in the Santa Maria and Gama catchments were 72.7% and 73.8%, respectively. The predicted wet areas in both catchments were concentrated in the valley bottoms, although scattered pixels occurred in well-drained upslope areas.

## 4. DISCUSSION

### 4.1. Drainage Network Delineation

According to Table 2, channel delineation (accuracies of 78.9% and 77.5%) was better predicted than channel initiation (accuracies of 44.4% and 63.9%), in the Santa Maria and Gama basins, respectively. Figure 7 also indicates that higher order channels were better delineated than first order streams.

Nevertheless, the overall drainage network prediction accuracies in Table 2 were higher than similar studies in the literature. Julian et al. (2012) found that stream mapping accuracy using ln(α) in the USA varied between 30% and 55%, depending on the geology. In Algeria, Dewitte et al. (2015) obtained a Spearman correlation of 0.5 between the predicted and observed gully heads, using the TWI.

The homogeneous geology and gentle topography of the Santa Maria and Gama catchments, with corresponding dendritic drainage patterns (Figures 2 and 3), may have contributed to the good drainage mapping accuracy. The discrepancies observed between predicted and reference drainage networks have resulted from a combination of model (TWI) error and cartographic misrepresentation of the reference maps (Kim & Lee, 2004). Additionally, the large DEM grid size (Capoane et al., 2015; Quinn et al., 1995) and DEM vertical error, the latter resulting from the SRTM radar inability to penetrate dense riparian vegetation (Orlandi et al., 2019), may have reduced the accuracies in Table 2.

Channel initiation was overestimated by the TWI with respect to the reference network because many simulated first order channels corresponded to temporary streams and ravines, which were not identified in the photogrammetry-based reference maps (Jaeger et al., 2017).

### 4.2. Wet Area Delineation

Although the overall wet area delineation accuracies of the Santa Maria and Gama catchments were acceptable (72.7% and 73.8%, respectively), wet areas were incorrectly assigned to the basins' upslope zones (Figures 2 and 3). This may have resulted from model error, large DEM grid size (Buchanan et al., 2014), and DEM vertical inaccuracy (Orlandi et al., 2019), affecting the overall mapping accuracy. Additionally, since the land-use feature 'gallery forest' was taken as a reference wet area, its occurrence over both well and poorly drained soils (Marimon et al., 2010) may have contributed to reduce the wet area delineation accuracy, as recognized by Skorupa et al. (2013).

In the literature, wet area mapping using topographic attributes gave mixed results. Ågren et al. (2014) obtained an accuracy of 85.2% in Sweden, using a combination of TWI and a depth-to-water index. Buchanan et al., (2014) reported a $R^2$ of 0.61 between the TWI and wet areas in the USA, and Russell et al. (1997) obtained a mapping accuracy of 73% in California. Considering that those studies used higher spatial resolution maps and secondary topographic attributes, the simplicity and robustness of the methods used in this study are encouraging, and allow their utilization in the mapping of drainage networks and wet areas of data-scarce tropical catchments.

## 5. CONCLUSIONS

Topographic attributes were used to delineate drainage networks and wet areas in two small catchments of the Cerrado biome, in Central Brazil. The selected attributes were the TWI, and the local slope and the slope curvature, respectively. A 30-m SRTM DEM was used as input, and hydrographic and land-use maps were used as references. Calibrated threshold values were obtained for the three topographic attributes in the Santa Maria catchment, and subsequently validated in the Gama basin, using balanced multi-criteria methods.

The accuracies obtained for the simulated drainage networks (67.2% and 70.7%) and wet areas (72.7% and 73.8%) in the Santa Maria and Gama catchments, respectively, were equivalent or higher than those of similar studies in the literature, and the delineation errors were associated with DEM grid size, DEM vertical inaccuracy, and with reference map bias. Due to its simplicity and robustness, the method could be used in the mapping of drainage networks and wet areas of tropical catchments.


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Table 1. Main hydrologic characteristics of the Santa Maria and Gama catchments.

| **Catchment** | **A** ($km^2$) | $\mathbf{H_{min}}$ (m) | $\mathbf{H_{max}}$ (m) | **S** (%) | $\mathbf{D_d}$ ($km^{-1}$) | $\mathbf{C_r}$ | **O** | **P** (mm) | **Q** (mm) |
|---|---|---|---|---|---|---|---|---|---|
| **Santa Maria (C)** | 368.8 | 1,012 | 1,307 | 5.04 | 0.45 | 0.48 | 4 | 1,400 | 335 |
| **Gama (V)** | 144.7 | 1,012 | 1,263 | 6.73 | 0.58 | 0.44 | 4 | 1,460 | 326 |

A = basin area; $H_{min}$ = minimum altitude; $H_{max}$= maximum altitude; S = mean basin slope; $D_d$ = drainage density; $C_r$ = Miller's circularity ratio; O = Strahler's basin order; P = mean annual precipitation; Q = mean annual runoff; C = calibration catchment; V = validation catchment.

Table 2. Drainage network mapping accuracy of the Santa Maria (calibration) and Gama (validation) catchments, using the TWI.

| **Catchment** | **Network Delineation Accuracy (%)** | **Channel Initiation Accuracy (%)** | **Overall Accuracy (%)** |
|---|---|---|---|
| **Santa Maria** | 78.9 | 44.4 | 67.2 |
| **Gama** | 77.5 | 63.9 | 70.7 |

Table 3. Confusion matrices and overall wet area delineation accuracy of the Santa Maria and Gama catchments.

| **Catchment** | | **Santa Maria** | | | **Gama** | |
|---|---|---|---|---|---|---|
| | | ***Ref. Wet Area*** | | | ***Ref. Wet Area*** | |
| | | ***No*** | ***Yes*** | | ***No*** | ***Yes*** |
| ***Predicted Wet Area*** | ***No*** | 1406 | 83 | ***No*** | 911 | 80 |
| | ***Yes*** | 510 | 172 | ***Yes*** | 292 | 137 |
| **Accuracy** | | **72.7%** | | | **73.8%** | |

## FIGURE CAPTIONS

Figure 1. Location of the Santa Maria and Gama catchments, in Central Brazil.

Figure 2. Elevation, hydrography, soils, and vegetation of the Santa Maria catchment.

Figure 3. Elevation, hydrography, soils, and vegetation of the Gama catchment.

Figure 4. Typical topographic profiles of the Santa Maria (A & B) and Gama (C & D) catchments. A, C are U-type bottoms, and B, D are V-type valleys.

Figure 5. Local slope of the Santa Maria (left) and Gama (right) catchments, and the transects used to assess wet area delineation accuracy.

Figure 6. Slope curvatures of the Santa Maria (left) and Gama (right) catchments.

Figure 7. Predicted (TWI-based) and reference drainage networks of the Santa Maria (left) and Gama (right) catchments. The insets show both networks in higher detail.

Figure 8. Predicted and reference wet areas of the Santa Maria (left) and Gama (right) catchments. The insets show the predicted and reference wet areas in higher detail.