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A Simple Empirical Stream Flow Prediction Model for Ungauged Watersheds

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Abstract. *Knowledge of streamflow is important for estimating groundwater recharge rates, forecasting floods, and designing hydropower structures and irrigation systems. However, many watersheds throughout the developing world remain ungauged. This fact demands a simple hydrological model that requires minimal but globally available data for estimating monthly streamflow. In this study, data from five watersheds in Honduras were used to develop an empirical monthly streamflow model using Moisture Adequacy Index (MAI), Leaf Area Index (LAI), and watershed characteristics such as soil infiltration rates, terrain slopes, and vegetation cover. The proposed model had an* R^2 *of 0.74 and was significant at the 95% confidence level. The model was verified with data from four other Honduran and one Bolivian watersheds. The streamflow model explained about 90% of the variability in the measured flow indicating that the model may be transferable to other ungauged watersheds.*

Keywords. Runoff; Geographic information systems; World water and climate atlas; Hydrology.

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Introduction

Knowledge of surface runoff or streamflow is desirable for planning and management of hydropower, municipal water supply, flood control, drainage and water for irrigating crops. However, many regions around the world do not monitor watersheds for streamflow at key locations. In these cases, hydrologic models, varying in complexity, are used to provide streamflow estimates. These models are deterministic, parametric, or stochastic in nature.

Hargreaves and Olsen (1999) used a simple linear model based on the Moisture Adequacy Index (MAI) to predict monthly streamflow. MAI is the ratio of the 75% probability of exceedance of precipitation (P75) to the grass reference evapotranspiration (ET_o). MAI is an index of the adequacy of precipitation in supplying vegetation moisture requirements. This index has been used for climate classification in Mediterranean countries (Le Houerou, 2004), in Bolivia (Hargreaves et al., 2001), and in some Asian countries (Hargreaves and Merkley, 1998). Kletti and Stefan (1997) correlated streamflow to precipitation, temperature, dew point and wind speed and unsuccessfully tried to relate the regression coefficients to watershed characteristics. However, the major drawback of their climate-based streamflow prediction method lied in the global transferability limitations. Generally, the statistical relationship established between climate data and streamflow are only valid for those watersheds for which they were developed, i.e., the coefficients are not transferable to other watersheds. Kothyari et al. (1991) successfully used vegetation cover factor, watershed area, rainfall, and temperature to calibrate a model to predict average annual runoff. The USDA-NRCS (1972) developed a method that primarily requires infiltration rates. The infiltration rate is based on land use, surface cover type, and soil texture and moisture content in the top one foot of soil at the time of a storm event. Perrone and Madramootoo (1998) improved the curve number method. They replaced the three antecedent moisture conditions used in the NRCS (Natural Resource Conservation Service) curve number method to estimate surface runoff volume with the antecedent precipitation index as an alternative indicator of soil moisture prediction in humid regions such as the Ottawa – St. Lawrence Lowlands.

Dostál et al. (2004) indicated that the formation of surface runoff is determined by the inability of the landscape to infiltrate and/or store rainfall and that runoff rate and volume are influenced by watershed characteristics such as area, terrain slope, vegetation cover, and soil properties. Hortness and Berenbrock (2001), using multiple power regression analysis, estimated monthly and annual streamflow for ungauged watersheds at different probability exceedance levels by relating measured streamflow to basin characteristics. These researchers included land cover derived from the Landsat 7 Thematic Mapper Plus data and topographic characteristics of watershed such as elevation and slopes from a Digital Elevation Model (DEM) in their analysis. However, they stated that their regression models may not be transferable to other watersheds with substantially different characteristics.

Physically-based rainfall-runoff models rely on DEMs, soil and land use data, initial soil moisture conditions, estimates saturated hydraulic conductivity, infiltration, and/or Manning’s roughness coefficients (Jinkang et al., 2007, and Weissling et al., 2007). In Beven’s (2004) view, as computers continue to get more powerful, distributed hydrological models will become more complex, and closely coupled to geographical information systems (GIS) for inputting the data, analysis, and display of results.

These types of models need actual field data and may not be suitable for ungauged watersheds in the developing world where little or no data exists at field scale. Therefore, a simple hydrological model that can be transferable to other regions in the world for estimating monthly streamflow is desirable.

This study attempts to parameterize the relationship between monthly streamflow and MAI in order to develop a simple streamflow prediction model that can be applied to ungauged watersheds in different regions of the world. In this paper, monthly MAI, streamflow, and LAI along with watershed characteristics such as terrain slopes (%), and soil infiltration rates were used in the parameterization of the streamflow model. Data from Honduras and Bolivia were used. These countries are among the poorest in Latin America according to the UNESCO (2007), and although these countries possess a large water resource potential the majority of their watersheds are not monitored for streamflow.

Materials and Methods

Study Area

Data from 10 watersheds were used in the development and evaluation of a simple monthly streamflow estimation model. Nine of them are from Honduras located in Central America and one from Bolivia located in South America (Fig. 1). Of these ten watersheds, five watersheds from Honduras were selected at random for the streamflow model development (Table 1) and the remaining five for the model verification (last five in Table 1).

The climate in Honduras is characterized by a long, wet season in the north and a long, semiarid season in the south. Precipitation events usually originate from the northeast winds and are irregular. The annual mean temperature varies from 22 to 24ºC (Hargreaves, 1992). The climate consists of a dry season (higher temperature values occur from March to April) and a rainy season (higher temperature values occur from May to December) (Hirt et al., 1989). More than half of Honduras might experience rainfall more than 300 mm within 24 hours (Hargreaves, 1992). Rainfall in the valleys is approximately 1200 mm per year, while upland forest-covered areas receive an annual average of 2000 mm (Hirt et al., 1989). More details can be found in Rivera et al. (2002).

Soils are diverse in Honduras where eight of the ten world soil orders exist. Most of these soils are classified under high to very high erosion risk group (Simmons and Castellanos, 1968). In addition, the terrain in Honduras is steep with about 75% of the territory having slopes greater than 30% (Honduras 1991). Most soils are underlain by poorly permeable material so that deep percolation of water is limited, increasing runoff (Hargreaves, 1992). Erodible soils, steep terrain, runoff, and inadequate land management practices combine to produce a great deal of soil erosion (Rivera, 2001). Hargreaves (1997) and Simmons (1969) describe Hondura's climate, hydraulic potential, soils, crops, crops potential, irrigable lands, etc in detail.

The Bolivian watershed selected for this study is located in the Upper Rio Grande River basin (URGRB). In the URGRB, about 7.8% of the area is arid, 92.1% is semi-arid, and 0.1% is wet-dry (Hargreaves et al., 2001). The URGRB annual average depth of runoff is 136 mm (Chavez, 1999). BSEDEM (1996) describes the soils of the URGRB as being shallow to moderately deep with variable texture ranging from loam to sandy loam with stone and gravel presence. The physiography is described as mountainous, steep slopes, and both with the presence of open and closed valleys. BSEDEM (1996) adds that basin displays three levels of erosion: moderate, strong, and severe mainly caused by water, poor land management, no crop rotation, cropping on steep slopes, and overgrazing. The vegetation cover loss varies from moderate to strong.

Streamflow Data

Monthly streamflow data were extracted from Ffolkes (1980), for the Honduran watersheds. Fflokes used a gamma probability analysis to obtain surface water flow per unit area, reporting flow in units of L s^{-1} km^{-2}.

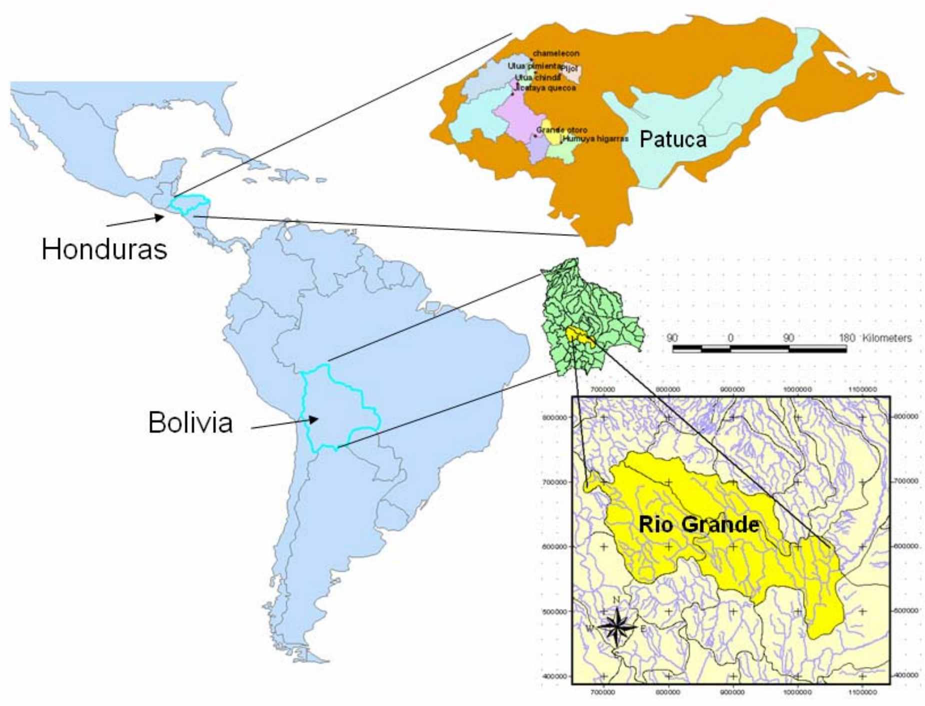

Figure 1. Honduran and Bolivian watersheds location.

The Honduran watersheds had streamflow data records of 11-15 years while the Bolivian watershed had 23 years of records. Flow data for the Bolivian watershed was obtained from the PRONAR, the official Bolivian National Irrigation Project Agency (Herbas, 1998). Table 1 lists the watersheds and their geographic location, mean elevation above sea level, area, years of record, and main river length.

Table 1. Watershed characteristics (remove location information, add average slope, flow data).

Watershed Name	Years of Records	Latitude (decimal degrees)	Longitude (decimal degrees)	Average Elevation (m)	Area (km^2)	River Length (km)
Humuya at Las Higuaras	15	14.35	-87.63	580	1098	40
Humuya in La Encantada	14	14.51	-87.66	500	1933	62
Ulua at Pimienta (Bridge)	14	15.433	-88.02	30	9002	202
Ulua at Chinda	13	15.267	-87.97	90	8848	166
Chamelecon at Chamelecon (Bridge)	14	15.1167	-88.20	40	3231	137
Pijol at Pijol	11	15.233	-87.65	230	630	42
Jicatuya en Quecoa	13	14.98	-88.26	150	4251	118
Grande de Otoro at La Gloria	13	14.43	-87.96	600	940	44
Patuca river basin	14	14.71	-85.73	300	24000	600
Upper Rio-Grande river basin	23	-18.93	-63.48	2000	59000	650

Monthly streamflow per unit area was correlated to MAI and one or more watershed characteristic: soil infiltration rate, terrain slope, and/or a vegetation cover index. Different correlation methods were used, ranging from linear and power to exponential. Depending on the time of concentration, runoff from upland areas may take some time to reach the watershed outlet. To account for the time of concentration, a lag time of 15 days was considered and denoted as Q75L15. The value of Q75L15 (L s^{-1} km^{-2}) was computed as the average of the 75% probable stream flow (Q75, defined below) for a given month with those of the next month.

As previously defined, MAI is expressed as the ratio P75/ET_o, where P75 can be calculated from a gamma probability distribution or from the mean precipitation (P_m) and the standard deviation (SD). The equation is:

$$P75 = P_m - (0.74 \times SD) \tag{1}$$

For purposes of planning, monthly irrigation requirements are frequently estimated as reference crop evapotranspiration (ET_o) in excess of 75% probable precipitation (P75). ET_o can be computed following the Food and Agricultural Organization of the United Nations (FAO) guidance (Allen et al., 1998) or from maximum and minimum temperatures and extraterrestrial radiation (Hargreaves and Merkley, 1998). Similarly, 75% probability of exceedance for monthly stream flow (Q75) values can be obtained as:

$$Q75 = Q_m - (0.74 \times SD) \tag{2}$$

where Q_m is the mean monthly stream flow.

In this study, monthly MAI values were obtained from the “World Water and Climate Atlas,” (IWMI, 2004) available as digital maps or GIS raster layers (grids). The Atlas incorporates climate data covering the entire world from over 30,000 weather stations between 1961 and 1990. The Atlas temporal coverage is reported as annual, monthly and 10-day summaries. The largest dimension of the grid squares is 16 km^2 at the equator (2.5 minute grid postings). It contains data on total precipitation, 75% precipitation probability, number of days with precipitation, precipitation standard deviation, average air temperature, mean daily minimum air temperature, mean daily maximum air temperature, reference evapotranspiration (Penman), Moisture Adequacy Index (MAI), net crop moisture, humidity, hours of sunshine, wind speed, total number of days without rainfall, and days without frost. The Atlas data applications include: identifying areas suitable for rain-fed agriculture, determining how much irrigation is needed in relation to what the climate provides, providing inputs for hydrological modeling of river basins, and extracting climate inputs for crop modeling. Hargreaves and Olsen (1999), Lacroix et al. (2000) and Hargreaves et al. (2001) among others have used the Atlas data for water resources potential assessment.

Mean monthly MAI grids were subset to the individual watersheds’ boundary layers to average the MAI pixels within the watershed’s limits. Urbano et al. (1998) supplied the GIS layers such as sub-basin boundaries, soils types, rivers network, land use/cover, and elevation contour lines for the Honduran watersheds. The land use/cover theme included the following classes: forest, protected forest, pine forest, harvested forest, rotational crops, seasonal crops, intensive cropping, extensive cropping, permanent vegetation, and exclusion. For the URGRB, Rocha (1997) provided similar set of GIS data.

Land use classes were translated into vegetation leaf area index (LAI) using the Scurlock et al. (2001) classification method. LAI is very distinct for different types of vegetation covers. It has values ranging from crops, grassland, shrubs, plantation, to different types of forest. Scurlock et al. (2001) reported LAI values ranging from 1.31±0.85 for deserts and grasslands, to 8.72±4.32 for tree plantations. Forests have LAI values mostly in the 5 to 6 range while the value was 3.6±2.1 for crops. LAI is a key parameter for global and regional models of biosphere/

atmosphere exchange of carbon dioxide, water vapor, and other materials. LAI also plays an integral role in determining the energy balance of the land surface, thus influencing how much water is consumed as evapotranspiration and how much water is left for infiltration and/or runoff. LAI was transformed into a vegetation cover index (fc) using Norman et al. (1995) equation:

$$fc = 1 - e^{\left(-0.5\,LAI\right)} \tag{3}$$

The different soil texture types found in the watersheds were related to general-broad "basic infiltration rates", i.e. to long-term steady state rates, in mm hr^{-1}, as presented by Brouwer et al. (1988) and Hargreaves and Merkley (1998).

The spatial analyst module in ArcGIS v9.1 and ArcView 3.2 (ESRI Inc., Redlands, CA) was used to process and analyze the GIS data. Soil, slopes and land use data, for each watershed, were summarized by areas in tables. These tables listed the different amounts of area for a given soil textures, vegetation cover type and slopes. Slope values in percent were extracted according to a weighted average calculated considering areas (%) under different slope classes, i.e. 0 to 3%, 3 to 6% and so on in increments of 3% up to 30%.

LAI values were attributed to each land use class found in the watershed using a LAI classification table provided by Scurlock et al. (2001). The weighted LAI average for each watershed was calculated based on the percentage of area under each land use/cover class. Similar procedure was followed for the infiltration rate. Soil texture classes were used to derive infiltration rates and a weighted average infiltration rate was obtained based on the percentage of area under each soil texture class.

Statistical Method

The deviation of Q75L15 estimated from the Q75L15 measured was reported as absolute differences and in percent errors through the Mean Bias Error (MBE) and Root Mean Square Error (RMSE) analysis. These are the mean and standard deviation errors respectively. Another statistical tool used in this study was the index of agreement (d), which reflect the degree to which the predicted variation accurately estimates the observed variation (Willmontt, 1981). Finally, the linear least squares regression method was utilized in describing how well the stream flow model compared to measured values.

Results and Discussion

Monthly Q75L15 values were plotted along MAI values for all watersheds. For example, Figure 2 illustrates the trends and magnitude of Q75L15 and MAI for the Humuyas watershed in Las Higuaras. The trend of the Q75L15 closely followed that for MAI. Similar comparison was found for all watersheds in the study.

Table 1 lists the five watersheds (first five) that were used in the development of the streamflow model. Figure 3 displayed the data used in the model development. An exponential model fitted the data well with the coefficient of determination (R^2) of 0.74. The model had the following form:

$$Q75L15 = a\,e^{\left(b\,MAI\right)} \tag{4}$$

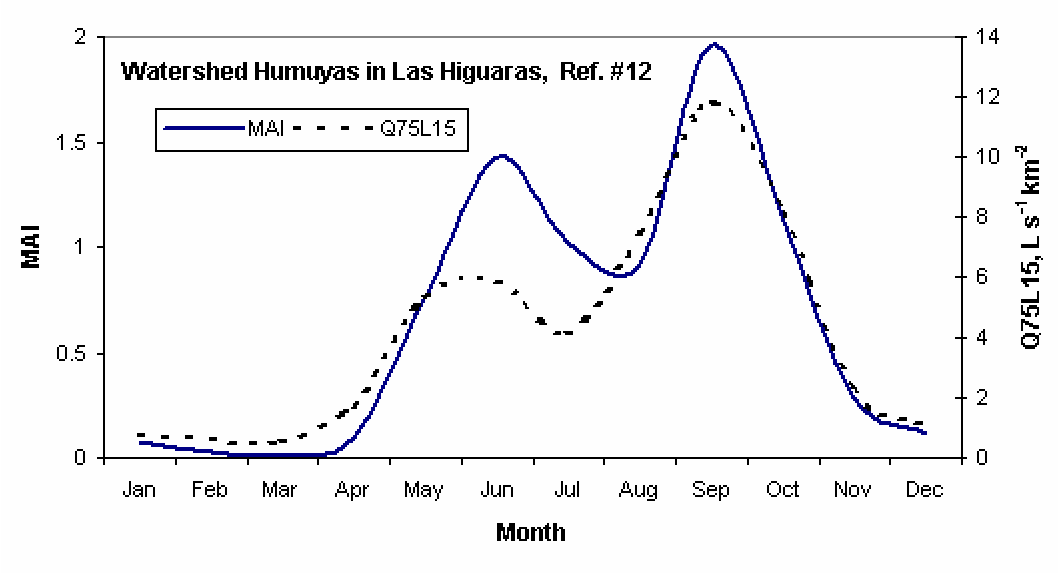

Figure 2. Monthly 75% probable stream flow, with a 15 day lag time, (Q75L15) versus MAI.

A similar curve fitting was performed for each watershed and their resulting corresponding “*a*” and “*b*” coefficients (Eq. 4), as well as R^2 values are presented in Table 2. Higher coefficients of determinations were obtained for the two larger watersheds: Patuca River basin and the Upper Rio Grande River basin in the study area (Table 2).

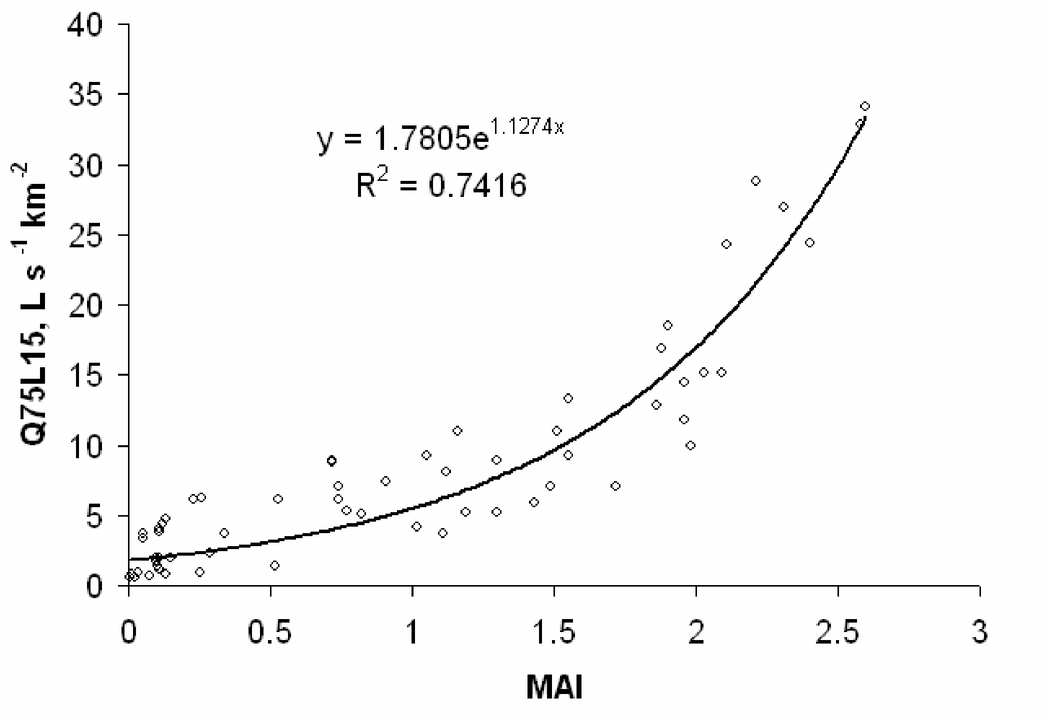

Figure 3. Monthly Q75L15 vs. MAI with an exponential model.

Table 2. Derived watershed characteristics and exponential model coefficients.

Watershed Name	Infiltration (mm hr^{-1})	Slope (%)	LAI (m^2 m^{-2})	Vegetation cover (fc)	"*a*"	"*b*"	R^2
Humuya at Las Higuaras	10.5	8.6	4.00	0.86	0.969	1.52	0.82
Humuya in La Encantada	11.6	9.2	3.70	0.84	1.436	1.32	0.82
Ulua at Pimienta	13.2	9.1	4.80	0.91	5.048	0.77	0.81
Ulua at Chinda	14.3	10.0	5.00	0.92	4.784	0.76	0.73
Chamelecon	12	8.9	4.30	0.88	1.213	1.15	0.71
Pijol at Pijol	15	10.0	5.00	0.92	11.637	0.63	0.67
Jicatuya en Quecoa	12.7	9.0	3.75	0.85	3.71	0.88	0.82
Grande de Otoro	13.5	9.4	4.00	0.86	4.95	0.81	0.8
Patuca river basin	12	10.0	3.10	0.79	3.995	1.44	0.95
Upper Rio Grande	7.5	17.0	1.95	0.62	0.617	3.85	0.93

Results of tabulating percentages of watershed surface area under a certain soil texture class and land use/cover class using GIS software are shown for Pijol in Table 3. This table is an example of the percentages of a given watershed area that were used in the weighting average procedure for soil infiltration rates (Table 2). Similarly land use/cover percent areas, as displayed in Table 3, were used to attribute LAI values from Scurlock et al. (2001) LAI table and to produce a LAI weighted average for each watershed (Table 2). Area weighted average terrain slopes were reported in Table 2 as well.

Most of the soil textures were loam to clay and/or silty loam with rather medium to somewhat low infiltration rates, for the Honduran watersheds. The predominant vegetation cover was rotected forest, pine forest and intensive/extensive crops. For this reason the LAI values were in general rather high. The forest was mainly found in slopes ranging from 6 to 30% while crops were grown more in slopes ranging from 0 to 8%.

Table 3. Pijol watershed land use and soil texture surface area percentages.

Land Use/Cover	Soil Texture					
	Clay Loam	Clay	Clay Silty Loam	Non	Area Km^2	Area %
Forest (Pine), protector VII.1	237.4	2.8	28.7	1.7	295.6	46.9
Rotational crops	4.2	0.0	13.5	0.0	17.71	2.8
Intensive and extensive crops	48.9	34.2	0.0	0.0	83.1	13.2
Forest exclusion and selective	9.7	0.0	27.8	0.0	37.5	6.0
Forest (pine) protector VII.3	106.2	6.3	29.5	0.0	196.1	31.1
Area, km^2	406.5	68.3	99.5	1.7	630.0	100.0
Area, %	73.1	10.8	15.8	0.3	100.0	

The values of soil infiltration rate (I), terrain slope (S), and vegetation cover (fc) from the first five watersheds (Table 2) were used in the correlation to determine the values for the coefficients "*a*" and "*b*" (Table 2). Different combinations of the variables I, S and fc and curve models were tried. The coefficient "*a*" was fit best by a power function with fc/I as the independent variable. The coefficient "*b*" was fit best by a linear model with I/S as the independent variable. Equations (5) and (6) show the models which resulted with a R^2 of 0.82 and 0.97, respectively.

$$a = 1E - 08\left(\frac{fc}{I}\right)^{-7.2474} \tag{5}$$

$$b = -3.2951\left(\frac{I}{S}\right) + 5.33 \tag{6}$$

Ranking of the coefficients "*a*" and "*b*" (Table 2) from high to low, resulted in Q75L15 equation that had an "*a*" coefficient that decreased in magnitude for lower Q75L15 values while the "*b*" coefficient increased. By fitting fc/I and I/S with Eqns. (5) and (6) it seems that the more vegetation cover a watershed had, the greater was the runoff yield or streamflow. This resulted because the opportunity (time) for the rainfall to infiltrate was increased as the vegetation (and mainly trees) reduced the raindrop kinetic energy, resulting in greater sub-surface lateral flow. On the other hand, the lower the infiltration rate and the greater the terrain slope (I/S), the greater was the chance for flash floods and erosion, the "*b*" then was high, i.e. in general contributing to lower Q75L15 from sub-surface lateral flow.

The verification of the stream flow (Q75L15) estimated by the models shown in equations (4), (5) and (6) was carried out using the validation data. This included the large and distinct watersheds Patuca (Honduras) and Rio Grande (Bolivia). Figure 4 shows the 1:1 comparison between estimated and measured Q75L15 (dashed line). In average, Q75L15 was estimated with a 3.5% under-prediction (-0.34 L s^{-1} km^{-2}) having an overall error standard deviation of 26.5% (3.01 L s^{-1} km^{-2}), Table 4. The monthly 75% probable stream flow (lagging 15 days) estimation model explained about 90% of the variation in the measured values. The index of agreement was 0.97, thus indicating that streamflow was well estimated.

In general, the streamflow exponential model (Equation 4) with the parameterized "*a*" and "*b*" coefficients seems to predict well measured Q75L15 values and could be evidence that the model dependence on the selected watershed climate, bio-physical and geophysical characteristics such as MAI, infiltration, slope, and LAI is a suitable and region transferable model, for monthly runoff estimation for water resources development planning purposes.

Table 4. Statistics of the comparison between predicted and measured Q75L15.

Statistic	In units of L s^{-1} km^{-2}	In Percent (%)	Linear regression	Index of agreement
MBE	-0.34	3.48		
RMBE	3.01	26.48		
Intercept			0.61	
Slope			0.92	
R^2			0.89	
d				0.97

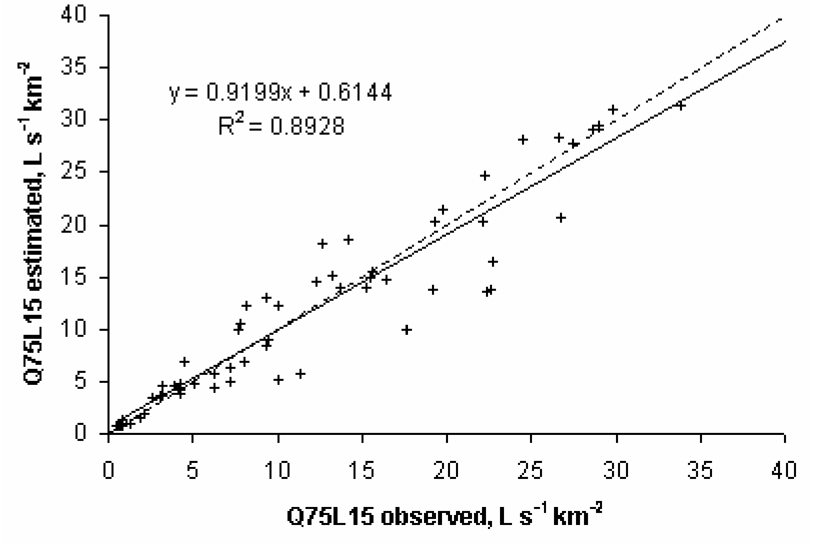

Figure 4. Comparison of monthly Q75L15 predicted with measured values.

More research is needed to verify these findings utilizing a range of data from watersheds around the world. Assigned infiltration rates and vegetation cover values should be verified with actual field data. Nevertheless, the methodology presented in this paper may be a useful tool for ungauged watershed with limited or no field data.

Conclusion

It was possible to predict monthly streamflow with a probability of exceedance of 75% and with a lag time of 15 days (Q75L15) using an exponential model. The streamflow model was primarily a function of the MAI. This model was parameterized with a vegetation cover index, terrain slope (%), and long-term steady state infiltration rates (mm hr^{-1}) obtained from tabulated values and data available through the Internet.

The Q75L15 model performed well when tested with an independent streamflow dataset. The MBE and RMSE were 3.5 and 26.5%, respectively. The stream flow estimation model explained about 90% of measured values and resulted with an excellent index of agreement of 0.97 between estimated and measured Q75L15 values. The parameterized streamflow model seems to be a useful tool for assessing runoff levels at ungauged watershed with no field data. Further evaluation of the model is needed including a wide range of watersheds covering a large range of measured physical and biomass watershed characteristics besides considering a variable runoff lag time (function of watershed size) and perhaps a variable seasonal LAI.

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