Preliminary Investigations on Localized Rainfall Interception Losses Under Real Field Observations

M. L. Gaur and Saket Kumar

Abstract Even under prevailing advanced science era, hydrological loss functions remain the weakest link and thus governs the ultimate success of any rainfall-runoff modeling on natural catchments. Among various such loss functions, interception happens to be the first and foremost element, on which research efforts are almost negligible, being truer for India and particularly middle Gujarat region. Present study is a preliminary effort, where field-based experimentations were conceived and conducted during rainy season of 2014, by adopting natural trees of different varieties and equipping them with certain low-cost alternative simple gauging setups to record daily magnitudes of stemflows, throughfalls and rainfalls. Two diverse sites were earmarked at newly developed College of Agricultural Engineering and Technology (CAET) Godhra in Gujarat, encompassing about 40 trees of 13 different types/varieties at 2 different sites. Simplified standard protocols and methodological steps were adhered, for measuring the stemflows, throughfalls, and actual rainfalls during active monsoon. Canopy interception (daily) was determined along with stemflow, by equipping the tree barks with reused half-cut tires and flexible plastic pipes and containers beneath it. Appropriately measured tree canopy area and rainfall were utilized in computations. Preliminary results as obtained and communicated herein are indeed an effort to visualize and attempt gap filling for this mistreated hydrological component. The observed range of average values of stemflows and throughfalls was found extremely heterogeneous depending upon rainstorms as well as physiological attributes of trees (8–20 and 5–35%, respectively). Though the individual observed values of intercepted rains remained small, but their cumulative magnitudes had visible hydrological impacts (soil moisture patterns, infiltration patter, overland flows, and re-distribution of raindrops) on land surface located beneath the tree canopy. Results revealed significant influences of vegetative physiognomies on several such impacts from intercepted rainfall, owing to heterogeneous trees and their physiological architecture (canopy area, tree height, types and shape of leaves, bark/branches).

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The qualitative analysis of intercepted rainwater was also performed and reported herein. Larger trees such as *azadirachta indica* (neem), *mangifera indica* (mango), tamarind (emlee), *Saraca asoca* (ashoka) showed higher interception magnitudes, even for identical rains, showing influence of their high aerodynamic roughness. The observed magnitudes and patterns of rainfall interception from this study are expected to be of vital utilities for futuristic hydrological modeling efforts in study region.

Introduction

In the field of hydrology, interception by trees/plants is deliberated essentially in view of two aspects; (1) as component of catchment water balance and (2) as element of water flow in the atmosphere-tree stand-soil system. In dynamic hydrology, the concept of interception embraces the processes ongoing within whole catchment area and includes long-term periods of precipitation as well as of water evaporation from plant surfaces, even during the periods in between rainstorms (Okonski 2007). Interception topic has been widely contemplated in textbooks (Crockford and Richardson 2000), where it is well recognized that in any natural catchment, it remains very difficult to get evaluate it. It happens because of the reason that it requires ground-observed data, which often remained a neglected area, presuming magnitude of interception as almost negligible. Under prevailing climatic change situations, such assumption could never be a wise/correct postulation, as it all together imposes high degrees of uncertainties/imbalances in hydrological processes/constituents. Hence, the rainfall interception is believed to play an important role in the water balance of catchments and plant ecosystems as whole. It is often defined as the rainwater that is retained on vegetation canopies and lost to atmosphere as water vapor (Rao 1987). Caldier (1979) and Gash et al. (1980) reported that owing to higher interception losses, there could be a reduction in water yield even up to almost a zero level after forestation. On the other hand, for Indian conditions, Rao (1987) has reported that a similar reverse impact could occur due to conversion of forest into agricultural lands. If we traverse the previous research reviews, it is evident that there exist very vague/uncertain estimates of interception losses, which remain confined and applicable to local situations only, without any potential for its wider extrapolations. Reporting all such estimates here is considered out of scope; moreover, for Indian conditions, such observations are hardly available.

Asdak (2010) reported that rainfall interception loss in the tropical rain forests remains about 11% of total rainfall and solely depended upon kind of plant. The highest levels of rainfall interception (@ 30% of total rains) are reported for natural forests, which ultimately gets re-evaporated back into the atmosphere. Variability in respect of stemflows and throughfalls was too found extremely uncertain and poorly gauged; the throughfall percentage also increases significantly with decreasing tree height in tropical forest (Horton 1938). There can be enormous reasons with which

the quantum and rates of intercepted water vary. Researchers have well demonstrated that it varies not only with forest type, but also with geographical location. But still, it remained an important factor of hydrological cycle, and majority of hydrological models demand its proper parameterization (Wang et al. 2007), which indeed remains a big challenge for hydrologists. If we visualize the physics of interception, it is quite evident that when rain falls on forest canopies, a proportion reaches the forest floor as throughfall (TF) and stemflow (SF), and the remainder is retained on canopy and subsequently evaporated. TF being part of gross rainfall (GR) drips from foliage or branches of canopy or reaches the forest floor by passing directly through tree canopies (Ahmadi et al. 2009; Rao 1987). SF too remains yet another important constituent of GR, whose volumetric magnitudes, under a tree/vegetation are greatly influenced by specific physiological attributes of trees/vegetation, namely species, crown size, leaf shape and its orientation, branch angle, and also the bark roughness (Levia and Frost 2010). Rao et al. (2012) reported certain important findings on rain interception over bamboo plants in the location nearer to present study.

There exists a plethora of review out of which only few bits are being portrayed here. Fathizadeh et al. (2013) studied hydrological balance of forest ecosystems on seasonal variability of rainfall interception and canopy storage capacity by individual trees, where interception was accounted for 84.9 mm (20%) of GR that significantly differed between the leaf (47.4 mm or 30% of GR) versus leafless (37.7 mm or 14% of GR) periods. Panwar et al. (2012) attempted a study on partitioning of rainfall and runoff measurement in *Terminalia chebula* (8 × 8 m) and *Emblica officinalis* (6 × 6 m) plantations with additional measurements on TF, SF, and canopy interception. TF was measured by placing collectors beneath tree canopy, and SF was collected by diverting water flowing through stem to a collector. Ramser's samplers were established to collect runoff water and compare runoff among 2 plantations, where it was reported that SF varied from 0.5 to 3.7% in *T. chebula* and 0.3 to 3.2% of GR in *E. officinalis*-based system. TF was reported slightly higher in *E. officinalis* (90–97.5%) as compared to *T. chebula* (86.64–97.8%). Wani and Manhas (2012) revealed some results on observations of rainfall interception in relation to the tree architecture and other features for *Pinus wallichiana* stand in Dal Lake catchment in Kashmir Himalayas, where SF (mm) was significantly influenced by tree diameter at breast height (DBH, cm), tree height (m), nature of bark, and attachment angles of lateral branches in tree height. Smooth-barked trees gave about 5% more of SF than rough-barked ones. TF was found negatively correlated with downward branching pattern. Of the total average rainfall of 66.5 mm during the course of study, TF, SF, and interception for whole tree stand were reported as 26.7, 36.3, and 36.9%, respectively. Interception percentage decreased significantly with increase in rainfall. Gurav et al. (2012) studied the partitioning of GR into TF and canopy interception loss in 2 different shade levels of Indian coffee agroforests. TF ranged from 84 to 91%, and interception loss ranged from 8.9 to 15.7% of GR in the high and low shade levels of coffee agroforestry systems. TF was reported significantly higher, and interception loss was significantly lower in high-shade-level system compared to low-shade-level

system. Alfiansyah et al. (2012) studied pattern of rainfall interception on plants/trees in a coffee plantation in Indonesia adopting 15-year-old plants of 1.5 m height 4.56-m^2 canopy area. Rainfall interception loss was determined based on water balance approach of daily rainfall, TF and SF data, followed by empirical regression equation between rainfall interception loss and rainfall to arrive a model to estimate rainfall interception loss. It was reported that coffee plants can intercept even 76% of annual rainfall. Global estimates were presented giving an interesting finding that the interception loss is responsible for evaporation of about 13% of total incoming rainfall over broadleaf evergreen forests, 19% in broadleaf deciduous forests, and 22% in needle leaf forests. Zhang et al. (2009) performed the similar studies in China, on rainfall interception loss by shrubs, and found that TF passes through crowns, adopting 73 rain events and giving canopy water storage capacities in the ranges of 0.52–0.68 mm, and free TF coefficient in between 0.47 and 0.62 for prevailing vegetation. Friesen et al. (2008) revealed canopy interception as 60% of annual rainfall.

Vegetation in tropical regions often represents a type of ecosystem that has a large influence on hydrological processes (Jetten 1996), which mostly remains a physical process, but sometimes chemical too. The trees intercept a large part of the rainfall, whose internal circulation involves the transfer of nutrients from the vegetation to the soil through the process of canopy leaching, defined as rainfall on the canopy that passes through it and reaches the soil surface by directly falling or through stemflow (Parker 1983). In these steps of internal circulation, process remains continuous and most likely involves the recycling of nutrients over rainy periods. As described by Casartelli et al. (2008), the chemistry of precipitation is a concern in developing countries, because it is an efficient mechanism of removing pollutants from the air. The majority of studies published in western parts of globe are giving importance to chemistry of precipitation looking at solute contribution to the biogeochemistry cycle in order to explain nutrient input to ecosystem. Dry and wet deposition of water on leaves can be an important nutrient source for plants and soils.

Measuring and Modeling Interception

To model the interception, three kinds of models are explained by the researchers. First the conceptual Rutter model and its revised sparse canopy version; second, the often used analytical, i.e., Gash model (original and revised sparse canopy version); finally the third one under the categories of stochastically based models. Today, interception is one of the most underestimated processes in rainfall-runoff analysis. It has often been disregarded in hydrological models because it is difficult to measure. Models that consider interceptions take it as a minor flux and either combine it with evaporation and transpiration or take it as a fixed percentage of rainfall. It is commonly accepted that interception volume is directly related to the size of the surface of the aboveground plant part. In earlier studies, there were
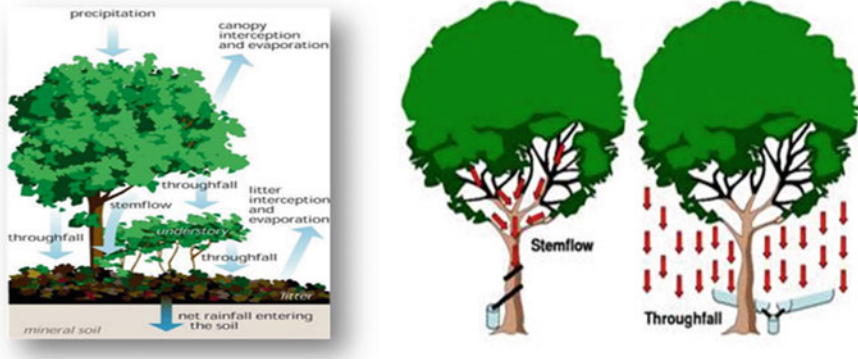
Fig. 1 Conceptual process framework of interception losses

efforts undertaken to describe tree surface area based on its similarity to other tree or stand biometric features. Telkehaimanot et al. (1991) had assumed a linear relationship between interception and number of trees per hectare. At the present time, in the majority of the studies on interception, the crown area is determined with the use of leaf area index, and it is later regressed/correlated with interception magnitudes. There have been certain base models too that amply describe the interception volume. Same could be generally divided into two main groups: (1) based on physical features of the process of water interception by tree canopy (Rutter et al. 1971; Gash 1979; Gash et al. 1980) and further modified and (2) regression equations of purely academic character or further founded on natural determinants (Horton 1938; Calder 1986). The Sacramento model, for instance, combines interception with the upper soil's tension water volume. Disregarding or lumping up interception with other processes introduces errors in hydrological modeling. Researchers have many a time revealed that evaporation of intercepted precipitation merely replaced transpiration, and that interception does not need to be considered as an additional 'loss' separate from transpiration (Gaurav et al. 2012; Gash et al. 1995; Hormann et al. 1996 and Yoshida et al. 1996) . A broad simplistic conceptual process framework of interception losses is depicted in Fig. 1, which is kept in focus taking timescale of interception as short, ending within hours after rainfall. A study carried out by Owens et al. (2005) revealed that 35% of the bulk rainfall falling on Juniper trees can be intercepted by tree canopy.

Material and Method

Description of Study Area

The study was performed in CAET campus Godhra (latitude 22.50N; longitude 73.40E; MSL 121 m) and its experimental research farm Kakanpur (latitude 22.50;
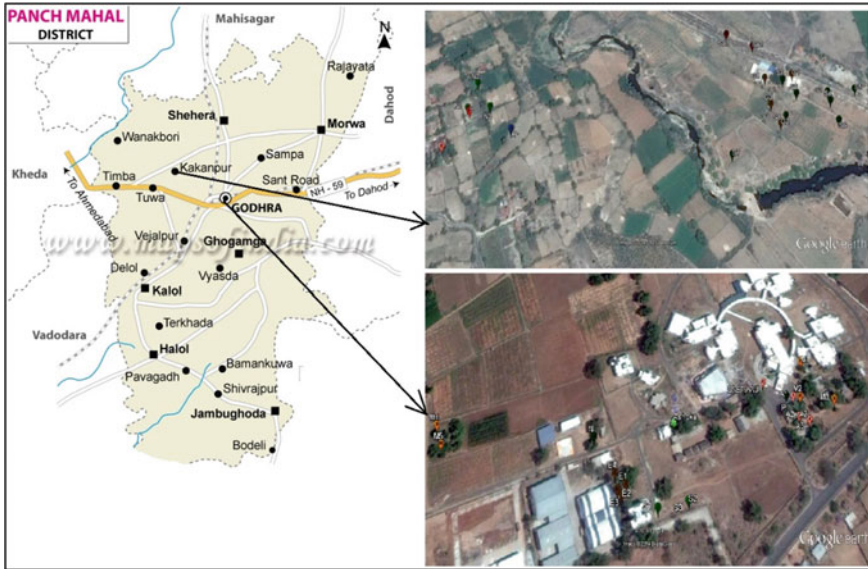
Fig. 2 Geographical and location details of study area as well as identified trees there in

longitude 73.30E; MSL 70 m). The representative geographical details of study sites are illustrated in Fig. 2, where the spatial distribution of identified trees as adopted in the study is reflected. The detailed information of location of trees was earmarked with GPS to depict about 40 natural trees as adopted in this study.

Measuring Physiological Attributes of Trees Under Study

A large number of natural trees (7 nos at CAET, Godhra, and 8 nos at Instruction Farm CAET, Kakanpur) were identified and adopted in this study, which were having tremendous variations in their physiological attributes. A condensed pictorial scenario of these trees is illustrated in Fig. 3, incorporating their spatial configurations and standard botanical nomenclature as well. Height measurement of trees under study at two specific sites was performed by using tangent clinometers, levels, and levelling staff/measuring taps. Canopy area of the trees was determined by number of canopy diameter measurements using measure tap and vertical ranging rods simultaneously. Crown projection area (CPA) was estimated for individual trees which were later utilized for calculation of the SF equivalent depth. The standard method of measuring the CPA is to surface (Delphis and Levia 2004). The corresponding SF depth of each selected tree was measured by dividing the collected SF volume by the CPA. Finally, the SF depths of the 9 selected trees were averaged to determine the mean SF depth for each event.
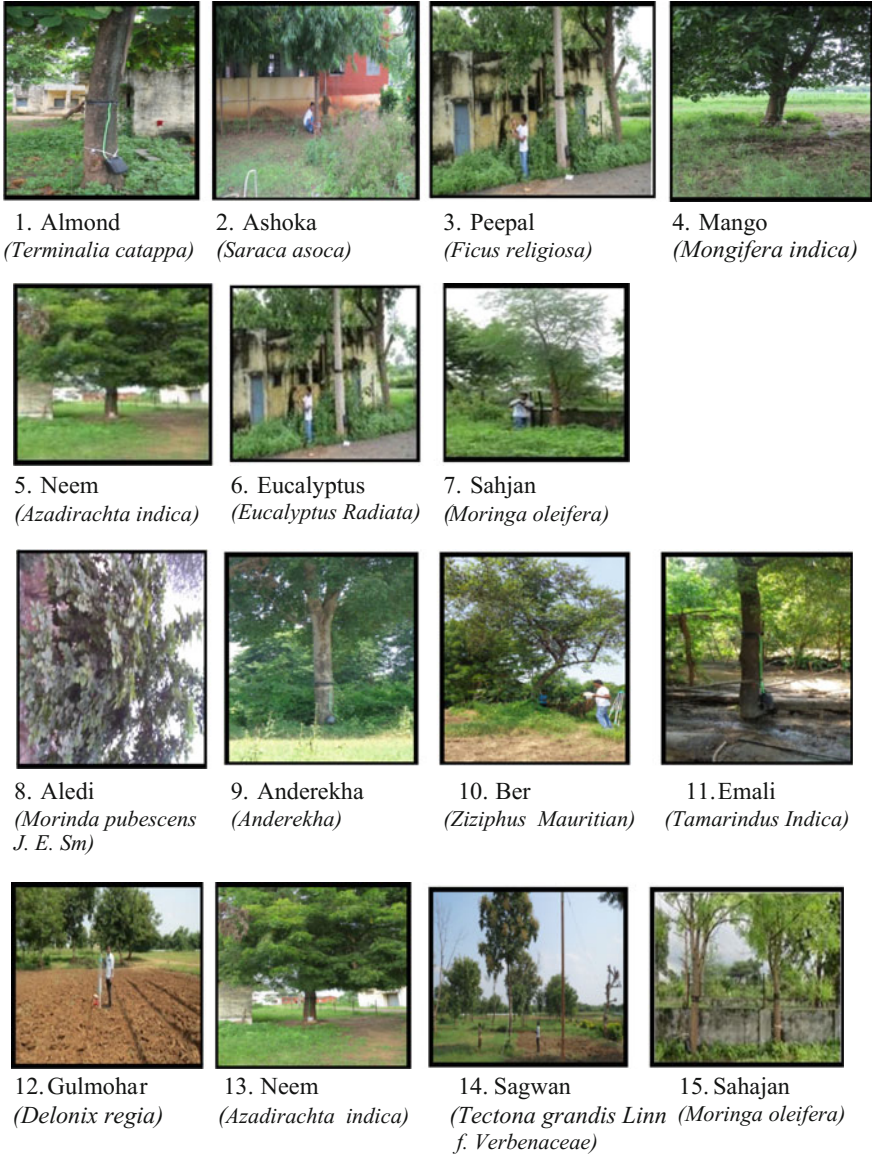
1. Almond
(Terminalia catappa)

2. Ashoka
(Saraca asoca)

3. Peepal
(Ficus religiosa)

4. Mango
(Mongifera indica)

5. Neem
(Azadirachta indica)

6. Eucalyptus
(Eucalyptus Radiata)

7. Sahjan
(Moringa oleifera)

8. Aledi
(Morinda pubescens J. E. Sm)

9. Anderekha
(Anderekha)

10. Ber
(Ziziphus Mauritian)

11. Emali
(Tamarindus Indica)

12. Gulmohar
(Delonix regia)

13. Neem
(Azadirachta indica)

14. Sagwan
(Tectona grandis Linn f. Verbenaceae)

15. Sahajan
(Moringa oleifera)

Fig. 3 Physiological look of representative trees as adopted for observing rainfall interception at two different sites. (*words in parenthesis are botanical name*) (location of trees 1–7 @ CAET Godhra Campus; 8–15 @ Kakanpur Farm of CAET)

Measuring Interception Components

Measuring the interception components like SF and TF needed a thorough effort to adjudge the best suitable simpler means where some of the innovative options were evolved, and accordingly, measuring systems were fabricated and installed on pre-identified trees at two specific study sites. Low-cost-used materials like worn-out tubes/tires and used containers/plastic canes and tubes were procured and suitably utilized in the study, after their need-based fabrication/assemble for the intended purpose. The structural configurations of these setups were made extremely simple (Fig. 3), where the magnitudes of rainfall, stemflows, and throughfalls were computed by having a regular observation on important rainy days at fixed point of time (8–8.30 am). The stemflows stored inside the plastic canes were suitably measured in its volumetric units and later converted to depths by using the measured dimensions of projected tree canopy areas of individual trees. Similarly, the measurements for throughfalls were conducted by placing the tin containers in different quadrants beneath the trees and measuring TF volumes periodically. The materials utilized for fabrication of interception measuring complements included plastic sheets, trays, tubes, cans, nonrecording rain gauges, and other sampling means. The observations from standard recording type rain gauge as well as automatic weather station (installed at CAET Godhra and Kakanpur farm) were too utilized for the purpose.

To analyze the qualitative attributes of intercepted rainwater in contrast to nonintercepted water, standard methods were adopted while collecting and conducting analysis of the water samples. Digital oven dryer, digital weighing balance, measuring cylinders, glass beaker/stick bold marker, digital PH conductivity, temperature meter, and other facilities in water quality laboratory were suitably used to obtain certain basic attributes. Parameters like pH and total solids for intercepted and nonintercepted rainwater were worked out utilizing pH meter and water sample oven drying/weighing, respectively. Similarly, dissolved oxygen too was evaluated for above-cited two groups of sampled rainwater.

The gross precipitation was measured in the open field, away from canopy influences. SF was measured by an open flap of tire wrapped around the trunk of tree, and nails are placed outside of wrapped flap of tire with the help of hammer and to control leakage water by M-seal and pipe placed into gallon. During rainfall, the SF was stored into wrapped flap and delivered water into gallon through pipe, which could be later measured volumetrically. Measuring TF was a bit difficult because the canopy of various trees was not homogeneous, but it was attempted by placing number of containers (fixed cross-sectional area) under canopies.

Result and Discussion

Rainfall

Though there observed a plethora of rainfall records at both the study sites, the number of rainy events during the year of study were remained extremely limited. Out of those, only 10 storms with maximum possible common dates were identified with sizeable observed rainfall at both the study sites, and looking into accomplishment of feasible observations in regard to stemflows, throughfalls, and other sampling on said dates. The observed 24-h precipitation on these dates for both the study sites is illustrated in Table 1. Results show that range of observed rainfall depths across 18 different storms was varying in the range of 2.8–37.0 mm with sizeable differences at 2 study sites even on similar dates. Owing to various field limitations/constraints, the storm size and data ranges remain a bit small, but generated and used in best possible manner.

Quantitative Variations in Interception Components

The quantitative variations in net interception values were highly heterogamous and did not have any set trends. The values were influenced by many parameters including tree physiology as well as the prevailing storm characteristics. These values were arrived after measuring the components like throughfalls and the stemflows on various trees as adopted in this study. In all about 40 trees were identified out of which observations could be feasible on 38, across August and September months of 2014 active monsoon period. The in-depth description in regard to observed values and their trends is summarized in below given paragraphs:

Throughfall Values: The preliminary analysis of observed records revealed that the throughfall values were changing a lot depending upon the integrated effects of plant physiological parameters as well as input rainwater values. In general, the values of throughfall were ranging from two in all sets of conditions at Godhra campus. The stemflow in mango trees was significant and was in the range of 0.15–3.75%, which could be having further scope of refinement. The similar values of stemflows in almond trees were in the range of 0.05–0.78% of rain. The values in regard to eucalyptus were in the range of 1.57–13.76%, which is of special significance to depict the role of tree architecture. The values of stemflows in sahjan tree were in between 0.41 and 2.51 and in neem trees 0.03 and 0.33% which is of very interesting to reflect partitioning factors of rains, may be specific density pattern of leaves and branches. In Peepal trees, it was 0.32–2.12%, while in ashoka trees it was 0.21–2.4%. The date-wise as well as tree-wise variability of TF for CAET, Godhra, as well as Kakanpur site is illustrated in Fig. 4, which is self-speaking in its contents.

Table 1 Observed values of daily rainfall at two study sites

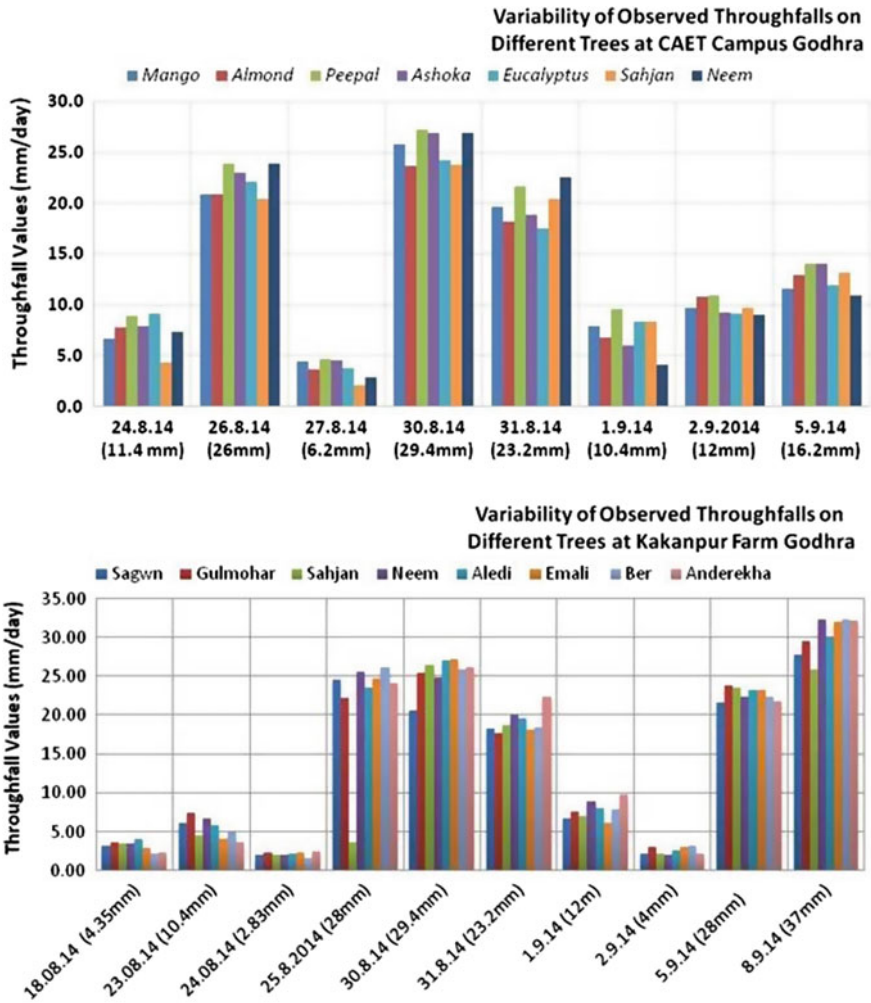| Storm dates/study sites	Observed values of 24-h rainfall in mm on different dates at 2 sites										
	18.08.2014	24.08.2014	26.08.2014	27.08.2014	30.08.2014	31.08.2014	1.09.2014	2.09.2014	5.09.2014	8.09.2014
CAET Godhra (18 trees)	–	11.4	26.0	6.2	29.4	23.2	10.4	12.0	16.2	–
Kakanpur farm (20 trees)	4.4	10.4	2.8	28.0	29.4	23.2	12.0	4.0	28.0	37.0

Fig. 4 Variability of observed throughfalls on different trees at two study sites

Stemflow Values: For CAET, Godhra site, the composite range of SF magnitudes across various trees as well as period of observation was found to vary between 0.5 and 7% depending upon the prevailing combinations of settings. Eucalyptus, Ashoka, and Mango trees gave higher magnitudes of stemflows in comparison to other trees. It indirectly reflected reduced interception losses on these trees when compare to other trees under study area. For Kakanpur site, the composite range of SF magnitudes across various trees as well as period of observation was found to vary between 0.1 and 8.5% depending upon the prevailing combinations of settings. sagwan, sahjan, and neem trees gave higher magnitudes of throughfalls in comparison to other trees. It was due to the higher density of leaves with closed

overlapping to offer larger surface catchments for catching raindrops. It indirectly reflected reduced interception losses on these trees when compare to other trees under study area. The date-wise as well as tree-wise variability of SF at both the study sites is illustrated in Fig. 5, which is self-speaking in its contents.

Net Interception Values: At Godhra site, the interception components were observed on 18 trees (Mango-5, Almond-3, Peepal-1, Ashoka-1, Eucalyptus-4, sahjan-3, and Neem-1). Results revealed that magnitudes of daily interception
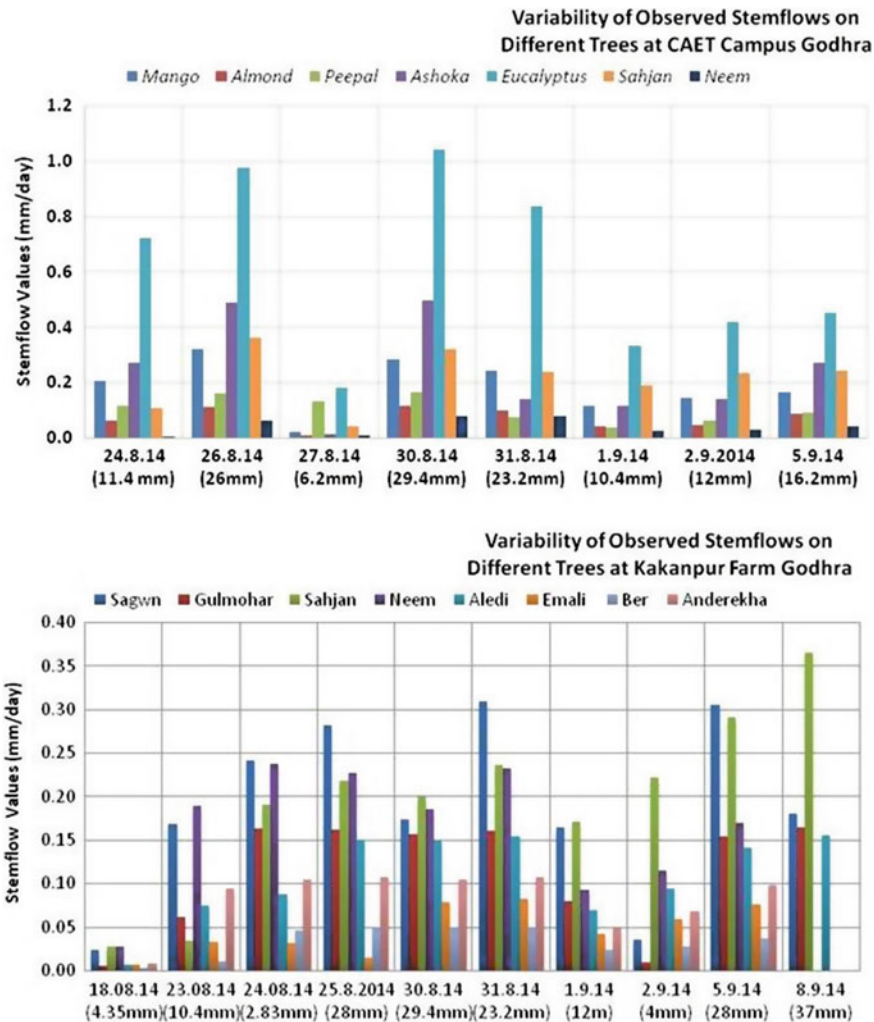

Fig. 5 Variability of observed stemflows on different trees at two study sites

values varied widely across the types of trees with significant influences of input rainfall. On mango trees, it varied in the range of 1.1–6.8 mm per day while facing storms in the ranges/magnitudes. Similar ranges of values for Almond, Peepal, Ashoka, Eucalyptus, sahjan, and Neem were found as 0.4–7.1, 0.8–2.3, 1.6–4.3, 0.6–8.6, 1.0–9.6 mm, respectively. The net magnitudes of so arrived interception values were having multiple influences from tree physiological constituents as well as storm characteristics. The variations in regard to total interception values worked out for various trees at Godhra campus were found in the range of 3.36 to as high as 60% of input rainfall values. It was highly depended upon the magnitude of rainfall and its temporal spread in particular the earlier day rains and later on the basis of plant physiological architecture at specific location under study. Similarly for Kakanpur experimental farm location, the interception components were observed on 20 trees (sagwan-7, Gulmohar-4, sahjan-2, Neem-3, aledi-1, emali-1, ber-1, anderekha-1). Results revealed that magnitudes of daily interception values varied widely across the types of trees with significant influences of input rainfall. On mango trees, it varied in the range of 1.1–6.8 mm per day while facing storms in the ranges/magnitudes. Similar ranges of value for sagwan, Gulmohar, sahjan, Neem, aledi, emali, ber, and anderekha were found as 0.2–8.9, 02–6.9, 0.2–7.7, 0.1–6.9, 0.3–6.9, 0.8–6.5, and 0.7–7.7 mm, respectively. The net magnitudes of so arrived interception values were having multiple influences from tree physiological constituents and storm characteristics.

Qualitative Variations in Intercepted Water

Some of the important quality parameters/indicators of intercepted rainfall were judged to reveal variations in pH, appearance, dissolved oxygen, and total solids. An interesting fact was observed while evaluating the pH values of samples of direct rainfall, and the intercepted and throughfall part of rainwater. By coming in contact with stems, barks, and leaves, the pH of water was significantly altered and increased even up to 25–30% of normal values as in original rainwater. These variations were found to get significantly influenced by types and varieties of trees whose external and internal physiological architectures were different as depicted in various pictorial illustrations (Fig. 6). Intercepted rainwater continuously travelled over or along leaves and tree bark till it reaches either to ground or back to atmosphere. Chemistry of intercepted precipitation used to be an efficient mechanism of removing pollutants from the air and its transportation toward soil surface or soil columns too.
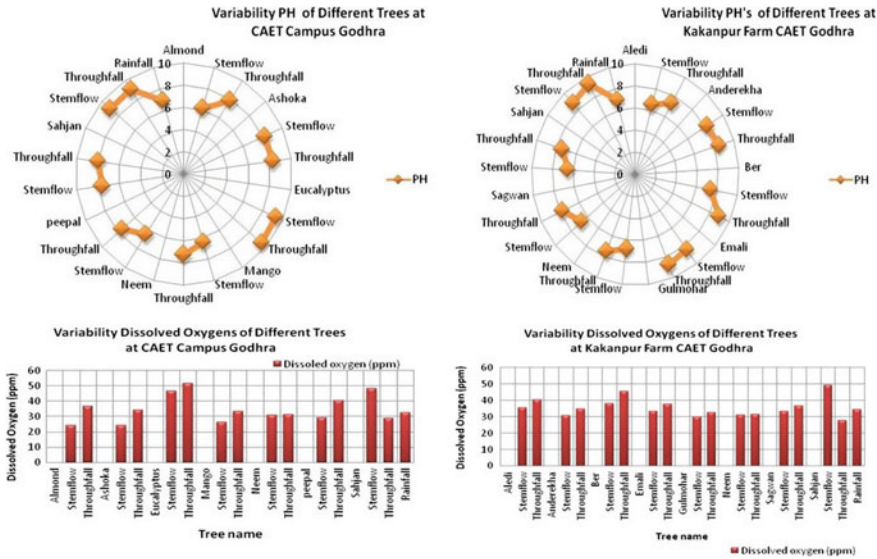
Fig. 6 Variability of pH and dissolved oxygen in intercepted rainwater for different trees

Conclusions

The process of interception by vegetation is an important factor in hydrological models, but very fewer efforts are made for its reliable quantitative estimations. Hydrological models could provide more accurate results if this important gap of hydrological observation is fulfilled by putting realistic data for the region under study. The present study was a preliminary effort and performed at two locations in middle Gujarat region of western India by encompassing about 38 natural trees and observing rainfall and its interception components using 10 natural storms as observed during active monsoon in 2014. Types and species of trees were identified and earmarked for observing the magnitudes of stemflows, throughfalls, and at last the interception values on daily basis for 10 daily events. The trees at Godhra campus were Mango, Almond, sahjan, Neem, Ashoka, Peepal, and Eucalyptus, while at Kakanpur these were aledi, anderekha, sagwan, ber, emali, Neem, Gulmohar, and sahjan. Magnitudes of daily interception values varied widely across the types of trees with significant influences of input rainfall. On mango trees, it varied in the range of 1.1–6.8 mm per day, while for sagwan, gulmohar, sahjan, neem, aledi, emali, ber, and anderekha trees, these were found as 0.2–8.9, 02–6.9, 0.2–7.7, 0.1–6.9, 0.3–6.9, 0.8–6.5, and 0.7–7.7 mm, respectively. Although the collected data and its results are only from one short season with thin records, still these preliminary findings provided certain logical ranges of values to unfold this undiscovered part of hydrological cycle in the region. Futuristic studies will supplement these observations and could yield better local estimates for improving

modeling framework on rainfall-runoff studies, provoking researchers to lay line of sight toward this important hydrological parameter. Results from this preliminary study, visualized 'Leaf Area' as one of the most dominating variable to influence magnitude & intensities of rainfall interceptions. Present benchmark information was generated during active monsoon period, and it might be further researched & refined for its futuristic extension in similar neighbourhood.

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