Tank Model Application for Runoff and Infiltration Analysis on Sub-Watersheds in Lalindu River in South East Sulawesi Indonesia

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Abstract. Improper land management often causes flood, this is due to uncontrolled runoff. Runoff is affected by the management of the land cover. The phenomena also occurred in South East Sulawesi, Indonesia. This study aims to analyze the flow rate of water in watershed of Lalindu River in North Konawe, South East Sulawesi by using a Tank Model. The model determined the magnitude of the hydrologic runoff, infiltration capacity and soil water content several land uses were evaluated in the study area. The experimental and calculation results show that the runoff in the forest is 2,639.21 mm /year, in the reed is 2,517.05 mm/year, in the oil palm with a slope more than 45% is 2,715.36 mm/year, and in the oil palm with slopes less than 45% is 2,709.59 mm/year. Infiltration in the forest is 30.70 mm/year, in the reed is 7.51 mm/year, in the palm oil with a slope more than 45% is 24.13 mm/year and in the palm oil with slopes less than 45% is 29.67 mm/year. Runoff contributes to stream flow for water availability.

1. Introduction

Changes in land use in the watersheds (WS) provide a dominant influence on flood discharge [1,2]. The greatest influence changes in land use on the sustainability of water resources is the changes from forest land to other uses such as agriculture, farming, residence or industry. If these activities are not well-managed, it will result in water excess (flood) during the rainy season and drought during the dry season. Unwisely changes in land use and is not accompanied by conservation measures will largely become runoff. Watersheds can be viewed as a hydrological system in which precipitation is the input from streams, and evapotranspiration is the system output. Furthermore, the watershed is the place where the simultaneous processes happen and become a part of the hydrological cycle.

The expansion of oil palm plantations keeps going in Indonesia, including in Southeast Sulawesi, which is spread almost all over North Konawe Regency, especially in Wiwirano District [3]. The changes of land cover grow rapidly and it is one of areas used as a priority area of oil palm development. It can be viewed from the increasingly growing oil palm plantation during the last five years, both operated by the community and by private plantations. The land use ignoring sustainability aspect, such as deforestation will put impact on the reduced water discharge in Lalindu watersheds. The deforestation is a consequence of the land function transfer. Land use transfer has resulted in changes of land structure. During dry season, the soil becomes hard and barren due to absorption strength of the sun, penetrating into the soil. If various trees still exist, the sun heat will be muffled in the foliage and the soil will stay fertile for the stable humidity. In addition, travel time of the water is relatively short, thus the rate of water infiltration by land is slower than the runoff rate. It is influenced by a number factors, among others; by concave topography of Mount Wiwirano (although the nature of the soil supports the absorption of water into the soil) resulting in most rainwater that will be lost through runoff and later run towards the river and eventually into the sea, before the rain water fills the underground water through infiltration and percolation process. A settlement is located surrounding this valley, thus during heavy rains, floods will occur.

To investigate the problem, a tank model is applied to determine watershed parameters in this area. The tank model base on the hypothesis that the runoff flow and infiltration is a function of the water amount presents in the soil [4-6]. The tank model can be constructed in such a way, thus representing the function of sub-watersheds area, or represents the difference in the structure/ type of land in each layer. Besides explaining the lost of initial rainfall and the dependence on prior rain, the tank model can also present some of the components forming the runoff flow, which have specific period and time lag. The tank model structure is the closest model to each watershed [4,5]. A tank with wasting channel on its side represents runoff, lower wasting channel represents infiltration, and saving component represents the runoff processes in one watershed or in watershed partly. Several parallel similar tanks can represent a large watershed [6]. In this study flow rate is analyzed by using a model consisted of runoff parameter, infiltration capacity and ground water content.

2. Material and Method

The research was conducted on sub-watersheds in Lalindu, North Konawe, one of the districts in Southeast Sulawesi, Indonesia. Observations made on hydrological conditions on 4 sub-watersheds which were parts of the Lalindu sub-watershed. The placement of 4 sample plots in each sub-watershed represented the three types of vegetation or land cover in the sub-watershed. The vegetations are the forest, reeds and palm oil. Palm oil itself was divided into two by the steepness, i.e. palm with steepness > 15% and palm oil with steepness <15%. The model was verified by observing the sample plots to obtain parameter value of the first tank (Fig. 1)

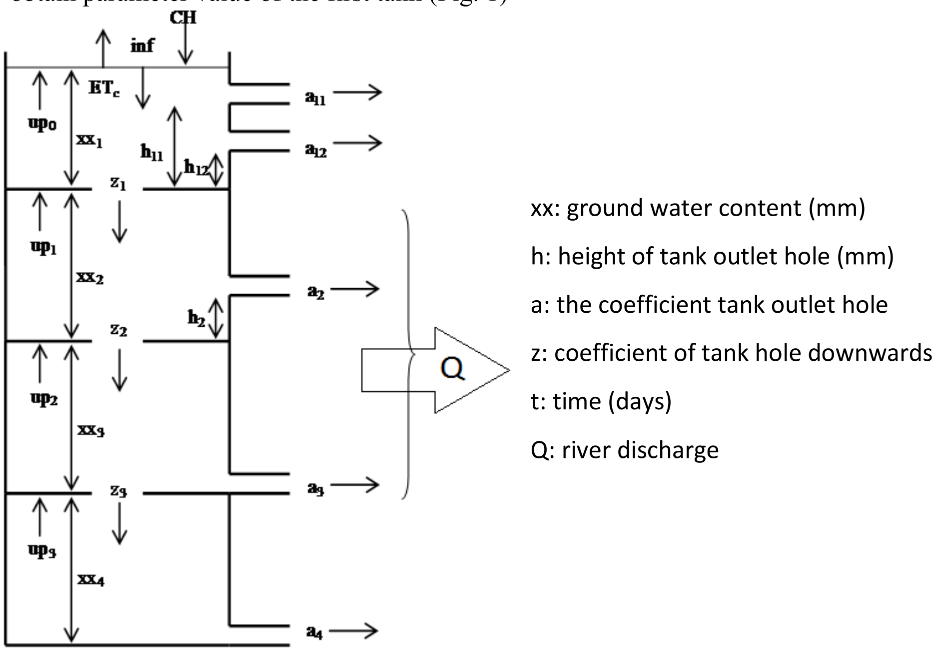

Figure 1. Tank model used in the research

The runoff parameters can be formulated as following equations. The basic equation for the first tank is as follows:

$$xx_1(t) = xx_1(t-1) + CH - ET_c - z_1.xx_1(t-1)$$
$$-[(xx_1(t) - h_{11})a_{11} + (xx_1(t) - h_{12})a_{12}] \quad (1)$$

The equation for the second tank is as follows:

$$xx_2(t) = xx_2(t-1) - z_2.xx_2(t-1) + z_1.xx_1(t-1)$$
$$-[(xx_2(t) - h_2)a_2] \quad (2)$$

The equation for the third tank is as follows:

$$xx_3 = xx_3(t-1) - z_3.xx_3(t-1) + z_2.xx_2(t-1) - xx_3(t).a_3 \quad (3)$$

The equation for the fourth tank is as follows:

$$xx_4(t) = xx_4(t-1) + z_3.\,xx_3(t-1) - xx_4(t).\,a_4 \quad (4)$$

The runoff discharge from river (Q) is calculated by the following equation:

$$Q(t) = [(xx_1(t) - h_{11})a_{11} + (xx_1(t) - h_{12})a_{12}] + [(xx_2(t) - h_2)a_2] + xx_3(t).\,a_3 + xx_4(t).\,a_4 \quad (5)$$

where:

xt : height of ground water content
h_{ij} : height of stored water (outlet hole level)
z_i : infiltration coefficient
a, b : outlet hole coefficient
CH : rainfall depth
ETc : actual evapotranspiration
t : time (days)
i :1,2,3,4

The data used in this research were primary and secondary data. The primary data included water discharge data on sample plots, sub- watersheds and sub-watershed of one year observation. Secondary data was the climate data, soil-type data and biophysical conditions. The data analysis was performed on the amount of rainfall, infiltration, evapotranspiration and runoff. Furthermore, tank model creation was made to describe runoff processes occurring in the watershed.

Tank model was validated by using daily rainfall and daily actual discharge data from the results of direct measurements in the field. The actual discharge data used in this validation process was the actual discharge data in the sub watersheds of gardens and other lands located in the surrounding garden location of the research.

3. Results and Discussion

Daily rainfall and evapotranspiration (ETc) data from the calculation results of climate data in the garden in 2011 are presented in Fig. 2. The data is used as an input value in the analysis of the tank model.

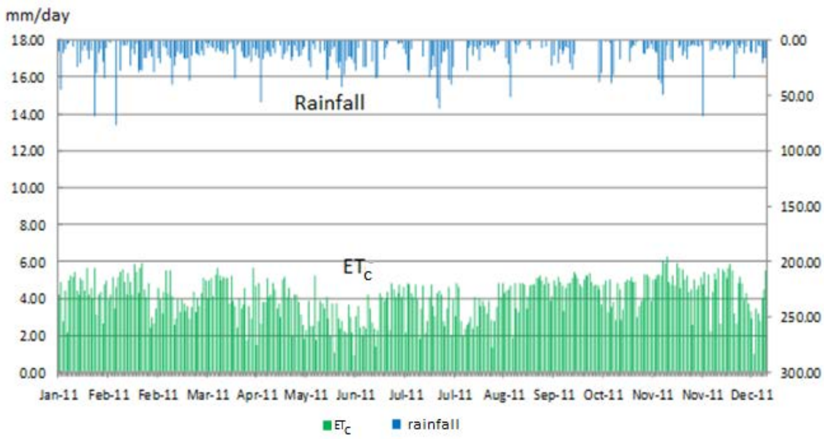

Figure 2. Daily rainfall and evapotranspiration data of ETc value in the garden of 2011

The discharge measurement of sample plots on four types of land cover is forest, reeds, and palm oil land, with a steepness > 15% and <15%. The discharge data for sample plots of the size 16 m^2 is shown in Fig 3.

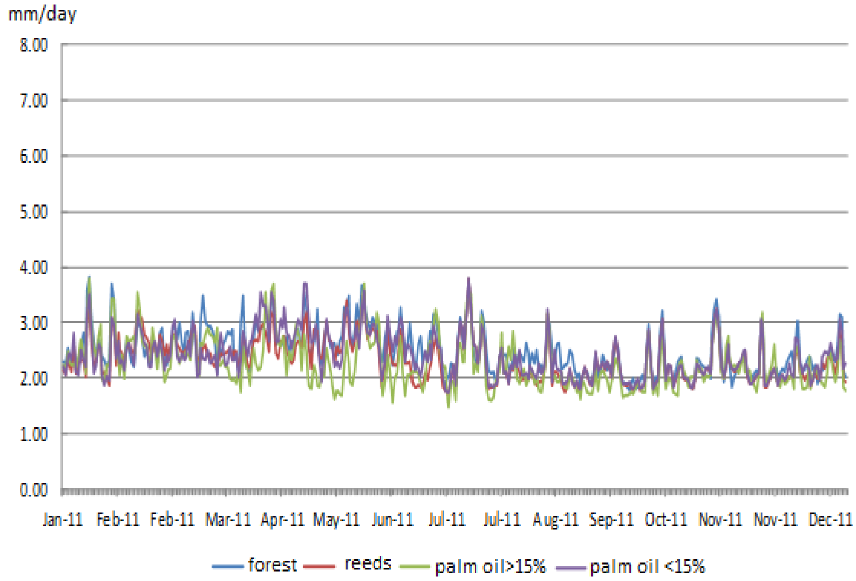

Figure 3. Discharge measurement graphs for each land-use in sample plots

In addition, the discharge measurement is conducted at sub-watersheds in the area of 20.000 ha. The discharge measurement data at the sub-watersheds is influenced also by run-off from the garden area in the surrounding area of the watershed. The discharge data of sub-watersheds from direct measurement is presented in Fig. 4.

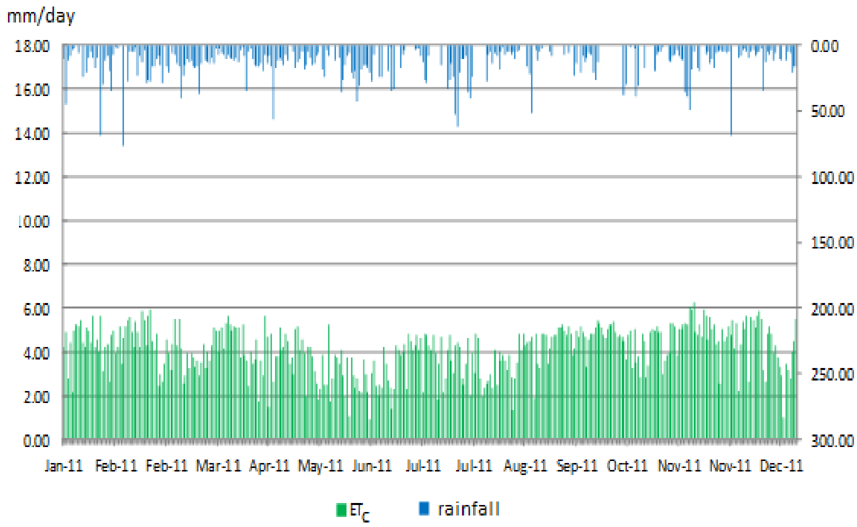

Figure 4. Discharge data of direct measurement on sub-watersheds

3.1 Tank Model Calibration in Sample Plots

The measurement result data in sample plots is used as a basis for calibrating the tank model to determine the magnitude of the tank model coefficient in the first tank. The calibration of each type of land result on sample plots for the first tank on tank models are presented in Table 1. The analysis of tank model of on the sample plots is conducted to determine the land cover characteristic towards the water.

Table 1. Calibration result of each land type on sample plots for the first tank

Parameter	Coefficient Value	Forest	Reeds	Palm oil > 15%	Palm oil < 15%
Ground water content of tank 1	xx1	200	150	180	185
The outlet coefficient of tank 1-1	a11	0.65	0.7	0.6	0.65
The outlet coefficient of tank 1-2	a12	0.55	0.6	0.5	0.45
The outlet height of tank 1-1	h11	75	50	85	80
The outlet height of tank 1-2	h12	60	45	70	65
The coefficient of tank 1 downwards	z1	0.009	0.003	0.004	0.005

3.2 Tank Model Calibration in Sub-Watersheds

In Table 2, the parameter coefficient values of the tank model calibration results in sub-watersheds is determined by using the data of 2011. From the calibration results, the coefficient of determination is obtained to be more than 70% for each land use.

Table 2. Tank model coefficient value of calibration results at the sub-watersheds

Parameter	SW I	SW II	SW III	SW IV
Ground water content of tank 1	500	300	850	900
Ground water content of tank 2	1100	800	1400	1300
Ground water content of tank 3	1500	1300	1800	1800
Ground water content of tank 4	2100	1800	2100	2000
The outlet coefficient of tank 1-2	0.8100	0.8500	0.8100	0.7900
The outlet coefficient of tank 1-2	0.7700	0.8200	0.7800	0.7700
The outlet coefficient of tank 2	0.7400	0.8000	0.7500	0.7600
The outlet coefficient of tank 3	0.0500	0.0500	0.0500	0.0500
The outlet coefficient of tank 4	0.0300	0.0300	0.0300	0.0300
The outlet height of tank 1-1	210	175	205	200
The outlet height of tank 1-2	180	170	190	195
The outlet height of tank 2	170	160	175	180
The coefficient of tank 1 downwards	0.0009	0.0003	0.0007	0.0008
The coefficient of tank 2 downwards	0.00005	0.00002	0.00005	0.00006
The coefficient of tank 3 downwards	0.00003	0.00001	0.00004	0.00005

Based on coefficient values of tank model from the calibration result, it is shown that the coefficient of the tank outlet is smaller to the lower part. It is due to the deeper soil layers, the ability of the soil to have water run-off is smaller. Similarly, the coefficient value of the tank downward (z) is smaller downward. That is due to the deeper layers of the soil, the soil capacity to carry water into the deeper layers (percolation) is getting smaller. From the results of the calibration tank model, it is known that ground water content (xx) is mostly found in the fourth tank. The water content in the soil at each level of the tank depth is greatly influenced by the type of plants that living above, as each model of discharge model outcome approaches the actual discharge model. In the process of model validation, the coefficient value of tank models that have been obtained from the calibration results in 2011 from the previous stage is used. The calibration results of tank in model of sub-watersheds are later validated in the downstream region which is a part of the Lalindu Watershed. The discharge validation data results in gardens sub-watershed and the surrounding other land of 2011 are presented in Fig. 5. The Figure shows the relationship among rainfall, discharge models, and actual discharge of the model validation process.

This validation process is obtained from the model discharge in the sub-watersheds of gardens and other surrounding land, describing the response towards the rainfall. The validation result has determination coefficient of 74.52%, and a tank model is then used to perform scenario of land conversion into oil palm plantation using conservation methods.

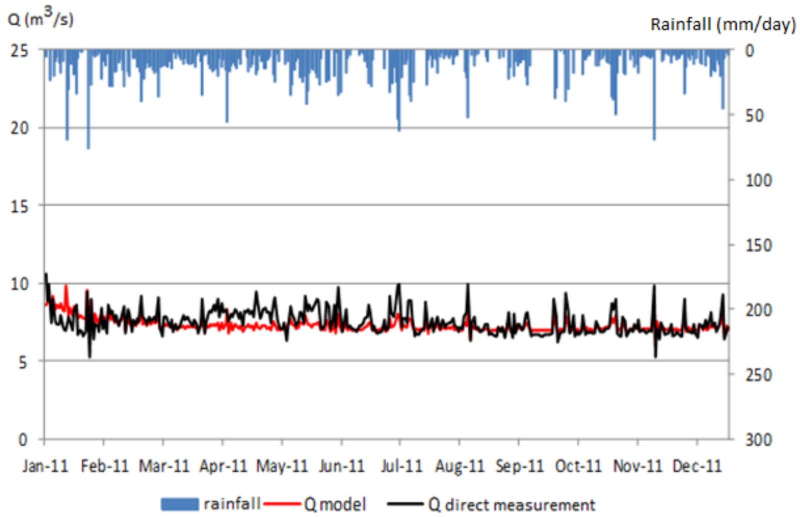

Figure 5. Discharge validation result data in sub-watersheds of gardens and . other surrounding land

3.3 The Analysis of Land Cover Changes on Water Supply

The next stage is to analyze the model in order to determine the total runoff and the total infiltration value of each different land cover. The total runoff and total infiltration value from the model analysis results in sub-watersheds at each different land cover is presented in Figure 6 and 7. The amount of runoff and infiltration rate is used to determine the state of water in Lalindu sub-watersheds for the amount comparison of the runoff value, and the infiltration is being simulated for area of 500 hectares from each land cover type.

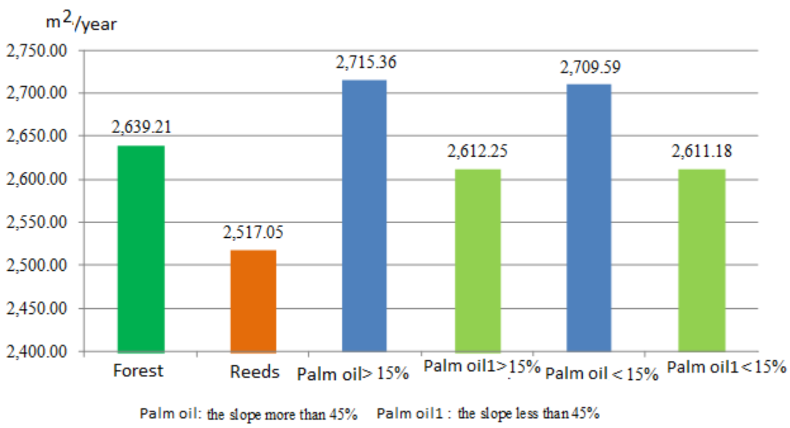

Figure 6. Total discharge runoff of each land cover at sub- watersheds

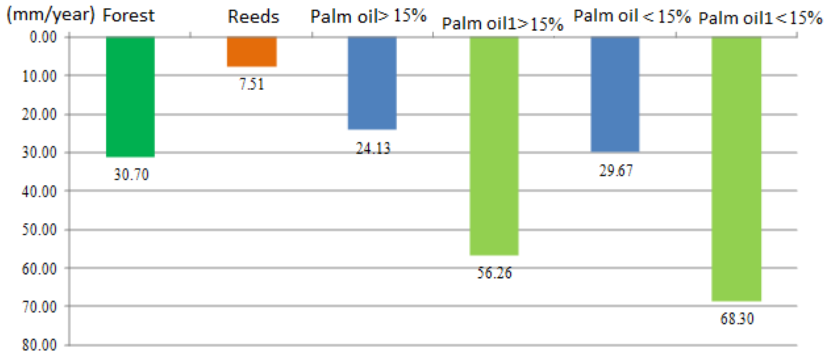

Figure 7. Real condition of total infiltration of each land cover at sub-watersheds

3.4 Analysis of the relationship among soil components, water and vegetation

The runoff total and infiltration on model analysis are then used to examine the relationship among land of soil components, water and vegetation of each unit. There is a close relationship among the soil components, water and vegetations. Land is a medium for the vegetation growth. Different soil types will have distinctive characteristics in terms of the soil physical, biological, and chemical properties. Soil properties can determine the type of nutrients in the soil, amount of water that can be stored in the soil, and root systems reflecting the circulation of water movement in the soil. The soil ability in absorbing water is reflected in the vegetation types at the ground level. The vegetation function can effectively reflect the ability of the soil to absorb rainfall, maintain or increase the infiltration rate, and demonstrate the ability in restraining water or water retention capacity [7,8].

4. Conclusion

Tank Model was successfully applied in Lalindu watersheds to determine magnitude of the hydrologic runoff, infiltration capacity, and soil water content.

1. The hydrological condition in Lalindu sub-watersheds can be presented by Tank Model with coefficient calibration (R^2) of 74.52%.
2. The analysis of runoff the Tank Model at each land cover showed that the runoff discharge in the forest is 2,639.21 mm/ year, in the reeds is 2,517.05 mm /year, in the oil palm with a steepness of more than 45% is 2,715.36 mm/ year and in the oil palm with steepness less than 45% is 2,709.59 mm/ year.
3. The analysis of infiltration in the tank model at each land cover resulted that the infiltration in the forest is 30.70 mm/ year, in the reeds is 7.51 mm/ year, in the palm oil with steepness more than 45% is 24.13 mm/ year and in the oil with steepness of less than 45% is 29.67 mm/ year.

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References

[1] R. Jayadi, Application of Fuzzy Relationship Theory to Analyze the Similarity of Two Catchment Areas, J. the Faculty of Engineering, Universitas Gadjah Mada, Vol. 23, pp. 187-196 (2008).
[2] A. Hayakawa, M. Shimizu, K. Woli, K. Kuramochi, R. Hatano, Evaluating stream water quality through land use analysis in two grassland catchments: Impact of wetlands on stream nitrogen concentration, J. Environmental Quality, 35, 617–627 (2006).
[3] S. Wirdhana Ahmad, Water resource conservation model on sustainable palm oil (Case study: Sub-watershed Lalindu, North Konawe, South East Sulawesi province), Doctoral Thesis, Bogor Agricultural University (2013).
[4] M. Sugawara, Tank model and its application to Bird Creek, Wolombi Brook, bikin River, Kitsu River, Sanaga River and Nam Mune. Research Note of national Research Center for Disaster

Prevention, No. 11, pp. 1-64 (1974)

[5] T. Kenji, O. Yuzo, X. Jun, K. Tomofumi, Tank Model And Its Application To Predicting Groundwater Table In Slope, Chinese Journal of Rock Mechanics and Engineering, 27[12],pp.2501-2508 (2008).

[6] A.N. Mulyana, C. Kusuma, K. Abdullah, L.B. Prasetyo, B.I. Setiawan, Aplication of Tank Model for Predicting Water Balance and Flow Discharge Component of Cisadane Upper Catchment. J. Manajemen Hutan Tropika. 17(2), 63-70[2011].

[7] G. O. Schwab, D.D. Fangmeir, W.J. Elliot, R.K. Frevert, Soil and Water Conservation Engineering. Four Edition, John Wiley & Sons. Inc, NewYork, 1992.

[8] T. F. Qiang, H. H. Ping, L. Z. Dong, Thermodynamic watershed hydrological model: Constitutive relationship, Science in China Series E: Technological Sciences, 51[9], pp. 1353-1369 (2008).

[9] M. Hernandez, D.J. Semmens, S.N.Miller, D.C. Goodrich, and W.G. Kepner, Development and application of the automated geospatial watershed assessment tool. Modeling and Remote Sensing Applied to Agriculture, USDA-INIFAP, U.S. and Mexico, pp. 127–158 (2008).