Assessing the Efficiency of Alternative Best Management Practices to Reduce Nonpoint Source Pollution in the Mississippi-Atchafalaya River Basin (MARB)

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Abstract

We conducted biophysical simulations using MAPSHED to determine the effects of adopting best management practices to reduce nutrients and sediment in a watershed dominated by row crop agriculture and poultry production. Reduction of three water pollutants nitrogen, phosphorus and sediment from adopting different BMPs are used in the cost reducing optimization model. We considered three weather scenarios (dry, normal and wet) and various levels of BMP parameter efficiencies. The nutrient management plan and vegetative buffer are the dominant cost-effective BMPs in the normal and wet weather conditions. In the dry weather scenario, vegetative buffer and stream-bank stabilization are the most cost effective BMPs. The cost of per kilogram of phosphorus reduction ranges from $10 to $40 depending on levels of desired phosphorus level reduction and efficiency parameters used in the model. It is costly to reduce phosphorus in a dry weather scenario perhaps because runoff is minimal and total costs associated with BMPs do not get distributed much on a per unit effluent basis.

Keywords: best management practices, cost minimization, nutrient and sediment reductions, optimization

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Agriculture activities are a leading cause of nonpoint source (NPS) pollution in the United States. Nonpoint source pollution in Louisiana's rural watersheds comes primarily from row crop agriculture and repetitive applications of poultry manure on the same parcel of land. These practices have resulted in nutrient runoff and leaching and sediment runoff to nearby water bodies. Realizing the difficulty of regulating nonpoint sources of pollution from agriculture, the United State Department of Agriculture/Natural Resource Conservation Service (USDA/NRCS) has proposed that farmers adopt best management practices (BMPs). These BMPs are adopted on a voluntary basis with a certain percentage of cost share provided by the USDA/NRCS based on the land characteristics (a complex scoring system reflecting land characteristics) and economic wellbeing of farmers (based on whether a farmer is a limited resources farmer or not). With the implementation of the total daily maximum load rule by the United Stated Environmental Protection Agency, there is a certain water quality standard that each water segment must meet. Though there are several ways to meet this standard in an agricultural dominated watershed, one of the best ways is through the adoption of best management practices by farmers.

Statistics from the Environmental Protection Agency (EPA) reveals that about 67% of reservoirs and 53% of the river systems in the U.S. are classified as impaired and need immediate actions to improve water health (USEPA, 2013). The impairment in the water is due to the accumulation of nutrients and sediment. Nutrient and sediment accumulations could cause serious problems such as oxygen deficiency and poor water quality unsuitable for recreation, drinking and agricultural and industrial uses (Carpenter et al, 1998). Good watershed management leads to effective management practice to protect water resource (UNEPA 2003). Past efforts have been mainly focused on the management and control of point pollution whereas non-point pollution control has not been properly addressed because of its spatial distribution and temporal variation (Carpenter et al, 1998). Agricultural runoff is a significant contributor of nonpoint source pollution in the rural area which contributes about 65% of the nitrogen pollution to the Gulf of Mexico (USEPA,

2000). Each part of the watershed play its own role for nutrients and sediment contribution which depends on its physiographic structure such as soil type, land use & land cover, and gradient. These area sometimes more vulnerable for in terms of nutrients and sediment contribution and watershed management and these area are known to be Critical Source Areas (CSAs). These areas are extremely important from the economical point of view for watershed management. There are numerous studies (Nonpoint source Task Force, 1984; Tim et al., 1992; Zou and Goa, 2008) recommended for the identification of such CSAs for watershed management. Such areas could be identified either by water monitoring from the sub-watershed level or by simulation model or combination of both (Sharply et al., 2002). Direct sub-watershed monitoring is not feasible because it is labor intensive, time consuming and financially prohibitive. An alternative to monitoring is to use watershed models such as Soil and Water Assessment Tools (SWAT) (Arnold et al., 1998) and Generalized Watershed Loading Function (GWLF) (Evans et al., 2002). These models avoid some limitation of the field study and help to identify and prioritize watershed for cost effectiveness of best management practices (Tripathi et al., 2005; Ouyang et al., 2008; Georgas et al; 2009).

GWLF model has widely been used to identify CSAs (Markel et al., 2006; Georgas et al., 2009) and stream flow, nitrogen, and phosphorus loading (Swaney et al., 1996; Lee et al., 2000). Similarly, SWAT has been used in the different part of the world for identification and prioritization of CSAs (Tripathi et al., 2005; Ouyang et al., 2008; White et al., 2009; Ghebremichael et al., 2009; Panagopoulos et al., 2011; Shang et al., 2012; Niraula et al., 2012a). It has also been used for predicting stream flow, nutrient, and sediment from the watershed (Spruill et al., 2000; Kirsh et al., 2002; Veith et al., 2005; Shrivastava et al., 2006; Jha et al., 2007; Niraula et al., 2012a,b).

To conduct biophysical simulations, we used MAPSHED, an open source model developed by Penn State University. We simulate the effects of alternative BMPs to reduce nutrient and sediment pollution within Johnson Chute watershed, Louisiana that is dominated by row crop agriculture and poultry operations. Our objectives are:

1. Simulate the effects of different best management practices to reduce nitrogen, phosphorus and sediment in Johnson Chute watershed by using MAPSHED, and

2. Determine the most cost effective combination of best management practices under alternative phosphorus reduction goals with dry, normal and wet weather situations.

Method

2.1 Study area

Johnson Chute (HUC 1114020605) watershed covers portions of four Louisiana parishes namely De Seto, Red River, Natchitoches, and Sabine (Fig.1) This watershed is chosen for the study because Louisiana Department of Environmental Quality considers this a priority watershed to comprehensively study to understand the role of alternative best management practices to reduce nutrient and sediment pollution. The watershed is located between latitude $31^0 35'0''$ and $31^0 53'00'' N$ and longitude $93^0 10'00''$ and $93^0 30'00''$ W. Its area is 57,600 hectares with relatively flat land, varying from 24 m above the sea level to 133 m above the sea level. The total length of the stream in this area is 106.2 km, out of which 47 km stream lies in the agricultural area. This watershed is dominated by broiler production. Watershed area is dominated by the temperate climate minimum temperature recorded -$1^0 C$ and maximum temperature $32^0 C$. The annual rainfall in the watershed is 124mm. Louisiana Department of Environmental Quality (LDEQ) is currently developing water quality initiatives in different watersheds in Louisiana. The findings from this study should help in their effort.

2.2 Modeling method

We utilized MAPSHED to perform biophysical simulations (Evans et al., 2002). The MAPSHED model is embedded with ArcView Generalized Watershed Loading Function (AVGWLF), which generates all the necessary information to run the model. This Generalized Watershed Loading Function (GWLF) model can simulate runoff, nutrient, and sediment from different watersheds. This model simulates runoff by water-balance

technique, based on daily precipitation, daily temperature, land use, and soil data. This model is known to be a distributed/lumped parameter model because of its characteristics of distribute in the surface loading by taking various land use covered scenarios while for a lumped parameter model it takes sub-surface loading. In GWLF, precipitation is separated between direct runoff and infiltration by using a form of the Natural Resource Conservation Service's (NRCS) Curve Number method (SCS, 1986). Erosion and sediment yield are computed in GWLF model based on Universal Soil Loss Equation (USLE). Sediment delivery ratio which is the key factor to compute sediment yield is based on watershed size and a transport capacity. The daily runoff volume which transport sediment is computed by using CN which is the function of soil and land use/cover. Dissolved nutrients load and sediment transporting through rural areas are computed by multiplying their respective coefficients with runoff. In GWLF, all the N and P from the urban areas are considered to be in solid state and the model uses exponential accumulation and wash-off function for estimation of urban loadings. The sub-surface loses in the watershed is estimated by using dissolved N and P concentrations where watershed is considered to be single lumped-parameter contributing area (Evan et al., 2002).

2.3 Data

The necessary input data layers needed for MAPSHED are collected from various

sources. Since this is a GIS based model therefore several raster and vector data are

needed to run the model. Watershed vector files of the study area, the country polygon

layer which shows the parishes boundaries, has simple function to show its vector shapes

are extracted from the Louisiana water mapping service

(http://sslmaps.tamu.edu/website/srwp/Louisiana/viewer.htm). The DEM, which is a

requisite data to calculate slope related information used in the model is obtained from

the Louisiana GIS CD (\\gid-store.lsu.edu\gis). The land use/cover is a raster layer which

help to estimate nutrient flows throughout the watershed obtained from the GIS CD

(http://atlas.lsu.edu). The stream layer which is a vector data shows stream location in the watershed is obtained from USGS site. The physiographic provinces (polygon) layer contains area with hydraulic parameters such as warm rain erosion rate, cool rate erosion rate, and groundwater recession rate were digitized from the USGS map of physiographic regions compatible with the MAPSHED model. The animal feeding operation (AFO) layer is used to hold animal population. This is a point vector data. Total animals in the watershed are obtained from the LSU Agricultural five-year summary, which provide agricultural data for the 2006-2010. Average of five year animal census minimize the yearly fluctuation of animals in a parish of an individual year. Realizing the availability of the weather data the most recent animal census is selected for the study. The soil layer which is one of the most important input for the MAPSHED model, holds hydraulic properties, erodibility factor, and water holding capacity. The MAPSHED model requires both raster and vector data of the soil which is extracted from the Louisiana GIS CD. Weather data is taken from a nearby station located at $32^0 09'57''N$ and $92^0 06'14''W$ that comprises of min and max temperatures, and total daily precipitation. These data were obtained from the National Ocean and Atmospheric Administration's (NOAA) (http://www.ncdc.noaa.gov/cdo-web/search). We did not consider other data like Groundwater N (Grid), Unpaved Roads (line), Water extraction (point), and Urban Area (Polygone) because of these are the beyond our study.

2.2.1 BMP Reduction Coefficients and Optimization Technique

We considered eight best management practices for their abilities to reduce nitrogen, phosphorus and sediment pollution. These eight best management practices are Cover

Crops (BMP1), Conservation Tillage (BMP2), Conservation Plan (BMP4), Nutrient Management (BMP6), Agland Retirement (BMP8), Stream Length with Vegetated Buffer Strips (BMP9), Stream Length with Fencing (BMP10), and Stream length with Bank Stabilization (BMP11). BMP reduction coefficient determine its effectiveness. These coefficients indicate the amount of nutrient or sediment reduction by one unit (hectare for watershed area and meter for stream- based BMPs) increase in BMP adoption. To get the coefficients of each BMPs, regression analysis are carried out on simulation output. The simulation outputs are subtracted from the baseline output (no BMP adoption) to obtain amount of nutrient reduction at each level of adopted BMP. The coefficients of BMP9, BMP10 and BMP11 are calculated by varying 1 unit of stream length while the coefficients of remaining BMPs are calculated by varying 2% of corresponding BMPs values. A regression analysis is performed between the amounts of nutrients reduction for each level of adoption and the amount of land associated with their level which gives nutrient reduction coefficient. This coefficient indicates how many unit of nutrients or sediment are reduced per unit of land.

An algorithm for optimization model adopted to determine the land cover at least cost and at different level of pollution is shown below. The objective of this optimization model is to achieve maximum pollution reduction at lowest cost. To achieve such a goal, constraints are placed on resources and minimum requirement of nutrient reduction rates. Phosphorus is taken as a primary nutrient for reduction because of its prime role on surface water pollution, eutrophication and hypoxia in the Gulf of Mexico. Similarly, nitrogen and sediment reduction are also taken as secondary goals. In each watersheds and dry & wet years various levels of phosphorus reduction are analyzed.

Min $\sum_{i}^{j} c_i B_i$

Subject to,

Nitrogen: $\sum_i^j n_i B_i \geq 0$

Sediment: $\sum_i^j s_i B_i \geq 0$

Phosphorus: $\sum_i^j p_i B_i \geq \alpha I_p$

Other: $\sum_i^j o_{ik} B_{ik} \geq R_k$, for all k = 1,..........K

$B_i \geq 0$

$B_i = BMP_i$

c_i = Cost of BMP_i

n_i = Nitrogen reduction by BMP_i

s_i = sediment reduced by BMP_i

p_i = Phosphorus reduced by BMPi

α = Some fraction of total phosphorus.

I_p = Total phosphorus loading

$O_{i,k}$ = Land unit covered by BMPi for land use k

R_k = Maximum allowable land usage for use k

Results and discussion

Various combination of the BMPs with normal, wet and dry weather conditions including

reduction of phosphorus at various level, were calculated in the Johnson Chute watershed.

In the wet weather condition, higher runoff containing the higher amount of nutrients and

sediment can be reduce effectively by adopting BMPs whereas in the dry weather

condition, it generates less discharge containing the less nutrients and sediment, in such

condition BMPs do not play a significant role to reduce nutrients. Various combination of

BMPs were tested by varying targeted phosphorus under the BMP efficiency change by

+10% or -10% scenarios. The nutrient management plan and vegetative buffer are the

dominant cost-effective BMPs in the normal and wet weather conditions. In the dry weather, cover crops, agland retirement, and fencing are also chosen in the optimal solution as we increased the level of desired phosphorus. The baseline nutrients and sediment loading without adopting any BMPs are 1,149 tons of nitrogen, 228 tons of phosphorus, and 30,038 tons of sediment. Similarly, cost of implementing these BMPs are found to be $322,874 and total nitrogen reduction of 74 tons, phosphorus reduction of 23 tons, and sediment reduction of 4797 tons. To reduce one unit of nitrogen costs $4 / kg, phosphorus costs $14/kg and sediment costs $67/ton. These calculations are performed by imposing constraints 1,740 ha of land (10% of Row Crops) and 18,800 m (40% of stream in the agricultural area). Results reveal that in all three cases namely wet, dry, and normal under 10% reduced BMP efficiency, cost increases from $ 7,82,115 to $8,42,144 in wet scenario, $4,94,476 to $5,49,636 in dry scenario, and $3,22,875 to $3,43,721 in normal scenario. These values indicate that in a wet scenario BMPs implementation cost is more than the other scenarios because of the more nutrient and sediment contains in the higher runoff condition. Similarly, in dry and wet weather conditions, cost of BMPs vary less (Table 1). Likewise, per unit cost in the normal condition under the decreased efficiency scenarios become $5/kg for nitrogen, $19/kg for phosphorus, and $77/kg for sediment. For the same case under increased efficiency scenarios per unit cost becomes $5/kg for nitrogen, $16/kg for phosphorus, and $77/kg for sediment (Table 1). The unit cost of reduction of nutrients and sediment increase as the phosphorus reduction level increases. The most cost effective BMPs for the normal and wet conditions in the watershed on the per hectare basis are nutrient management and vegetative buffer and other BMPs also appear in their respective

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maximum cases, which leads to soar in the cost for per kg reduction level. In the dry weather scenario, vegetative buffer and bank stabilization are the most cost effective BMPs.

Table 4 reveals the shadow prices, which indicates the price of reducing one extra kg of phosphorus. From 10 to 15% phosphorus reduction scenario, shadow price jumps from $14 to $35 due the appearance of the vegetative buffer decision variable in the optimal solution. This value increases more than two times as new decision variable agland retirement come in the solution but after appearances of another CRP constraint its value shoots up to $626 in the 21% reduction level.

Table 5 reveals the reduced cost for each BMPs, which indicates the alternative cost for the optimal solution. For example, if one hectare of cover crops is imposed into the solution then the total cost would increase by $164. This cost also indicates that which BMPs are more feasible to impose into the optimal solution. For example fencing decision variable is more cost effective at 10% phosphorus reduction level than in the 15% reduction level.

The relationship between phosphorus reduction per unit cost for all the three conditions like normal, wet, and dry are also plotted (Figs. 3 to 5) to checking their effect on the Johnson Chute watershed.

4. Conclusions

Many studies can be found about the point source pollution but due to spatial variation and difficult to monitor, non-point pollution controlling and monitoring are time consuming, labor intensive, and highly expensive. Biophysical simulation models followed by

optimization are appearing in the recent years to address these problems. A user friendly GIS based MAPSHED model developed by Pennsylvania University is used in this research to understand the effects of adopting different BMPs under various weather and BMP efficiency scenarios.

Phosphorus is a limiting nutrient in many waterbodies. We changed efficacy of BMPs to understand the variability of its adoption in differing physiographic situations. Simulation is carried out in three different scenarios namely normal, wet, and dry weather conditions. For the normal and wet weather condition the ideal combination of BMPs are nutrient management and vegetative buffer whereas in the dry weather condition feasible combination are Vegetative buffer and Bank stabilization. The BMPs in the wet weather condition general has higher pollution reduction coefficient than the normal and dry weather condition due to more nutrient pollutant carrying by runoff in this condition. This leads to more total costs than the remaining conditions.

5. Acknowledgement

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Table 1: Summary of BMP adopted and Land Use in Johnson Cute watershed (Normal year)

Scenario	BMP1	BMP2	BMP4	BMP6	BMP8	BMP9	BMP10	BMP11	Total Cost ($)	N Level (kg)	P Level (Kg)	S Level (tonnes)	Unit cost ($) of N reduction	Unit cost ($) of P reduction	Unit cost ($) of sediment reduction
10%						17105			322875	74452	22821	4797	4	14	67
10% -ve10	0	0	0	233	0	18800	0	0	364566	74809	18821	4745	5	19	77
10% + ve10	0	0	0	233	0	18800	0	0	364566	74809	22821	4745	5	16	77
15%	0	0	0	7788	0	18800	0	0	678642	124938	34231	5272	5	20	129
15% -ve10	0	0	0	11025	0	18800	0	0	813246	128573	31231	4745	6	26	171
15% + ve10	0	0	0	11025	0	18800	0	0	813246	128573	34231	4745	6	24	171
19%				17304	95	18800			1088824	179338	45641	5402	6	24	202
19% -ve 10 max	2069	0	0	13590	1740	18800	28200	0	1721745	175590	42359	8538	10	41	202
19% +ve 10 max									1721745	175590	43359	8538	10	40	202
21% max				15659	1740	18800	24066		1407317	200312	47923	8330	7	29	169

Note: BMP1=Cover Crops, BMP2=Conservation Tillage, BMP4=Conservation Plan, BMP6=Nutrient Management, BMP8=Agland Retirement, BMP9= Vegetative Buffer, BMP10= Fencing, BMP11=Bank Stabilization.

Table 2: Summary of BMP adopted and Land Use in Johnson Cute watershed (Wet year 2009)

Scenario	BMP1	BMP2	BMP4	BMP6	BMP8	BMP9	BMP10	BMP11	Total Cost ($)	N Level (kg)	P Level (Kg)	S Level (tonnes)	Unit cost ($) of N reduction	Unit cost ($) of P reduction	Unit cost ($) of sediment reduction
10%	0	0	0	17399	0	3113	0	0	782115	135463	27710	1074	6	28	729
10% -ve10	0	0	0	17399	0	9473	0	0	902173	138263	27710	2940	7	33	307
10% + ve10	0	0	0	16727	0	0	0	0	695411	133853	27710	4000	5	25	174
12%	0	0	0	17399	0	14562	0	0	998219	168156	33251	5021	6	30	199
11% -ve10	0	0	0	17399	0	15834	0	0	1022231	154609	30481	4914	7	34	208
15% + ve10	0	0	0	15858	1541	18800	0	0	1249848	226341	41564	9971	6	30	125
14% max	2822	0	0	12837	1740	18800	28200	0	1827782	200323	38793	12113	9	47	151
13% -ve 10 max	0	0	0	17399	0	9473	0	0	3113672	153772	36022	15979	20	86	195
16% +ve 10 max	14035	0	0	1624	1740	18800	28200	0	3405920	180577	44335	20940	19	77	163

Note: BMP1=Cover Crops, BMP2=Conservation Tillage, BMP4=Conservation Plan, BMP6=Nutrient Management, BMP8=Agland Retirement, BMP9= Vegetative Buffer, BMP10= Fencing, BMP11=Bank Stabilization.

Table 3: Summary of BMP adopted and Land Use in Johnson Cute watershed (Dry year 2011)

Scenario	BMP1	BMP2	BMP4	BMP6	BMP8	BMP9	BMP10	BMP11	Total Cost ($)	N Level (kg)	P Level (Kg)	S Level (tonnes)	Unit cost ($) of N reduction	Unit cost ($) of P reduction	Unit cost ($) of sediment reduction
5%	0	0	0	11899	0	32578	0	0	494673	45435	59172	5256	11	8	94
5% -ve10	0	0	0	13221	0	0	0	0	549636	45435	8360	5026	12	66	109
5% + ve10	0	0	0	13221	0	0	0	0	449702	45435	8360	0	10	54	0
10%	0	0	0	7788	0	18800	0	0	678642	96646	50736	3363	7	13	202
8% -ve10 max	0	0	0	17399	0	11844	0	0	946922	74843	13376	1719	13	71	551
8% + ve10	0	0	0	17399	0	11844	0	0	719524	72696 17559	13376	0	10	54	0
11% max	9544	0	0	6115	1740	18800	28200	0	2773918	0	150824	8538	16	18	325
10% -ve 10 max	13103	0	0	2556	1740	18800	28200	0	3274794	74007	16720	7962	44	196	411
10% + max	13103	0	0	2556	1740	18800	28200	0	975554	93830	16720	2371	10	58	412

Note: BMP1=Cover Crops, BMP2=Conservation Tillage, BMP4=Conservation Plan, BMP6=Nutrient Management, BMP8=Agland Retirement, BMP9= Vegetative Buffer, BMP10= Fencing, BMP11=Bank Stabilization.

Table 4 : Shadow price of different constraints in Johnson Chute watershed

Scenarios	Phosphorus level	land	Agland retirement land restriction	Vegetative buffer land restrictions	River length for fencing restriction	CRP land restriction	River length use
10%	14						
10% -ve10	39			-28			
10% + ve10	13			-28			
15%	35			-28			
15% -ve10	39			-28			
15% + ve10	32		-63	-28			
20%	89		-63	-99			
19% -ve 10 max	1495		-1539	-1770		-1578	-6
19% +ve 10 max	32			-28			
21% max	626		-694	-816		-675	

Table 5 : Reduced cost of BMPs in Johnson Chute watershed

Phosphorus Reduction	BMP1	BMP2	BMP4	BMP6	BMP8	BMP9	BMP10	BMP11
10%	164	64	23	25	119	0	5	86
10% -ve10	137	52	18	0	67	0	5	86
10% + ve10	164	64	23	25	119	0	5	86
15%	137	52	18	0	67	0	5	86
15% -ve10	137	52	18	0	67	0	5	86
15% + ve10	137	52	18	0	67	0	5	86
20%	131	85	67	0	0	0	5	85
19% -ve 10 max	0	853	1221	0	0	0	0	78
19% +ve 10 max	137	52	18	0	67	0	5	86
21% max	75	413	561	0	0	0	0	80

Note: BMP1=Cover Crops, BMP2=Conservation Tillage, BMP4=Conservation Plan, BMP6=Nutrient Management, BMP8=Agland Retirement, BMP9= Vegetative Buffer, BMP10= Fencing, BMP11=Bank Stabilization.
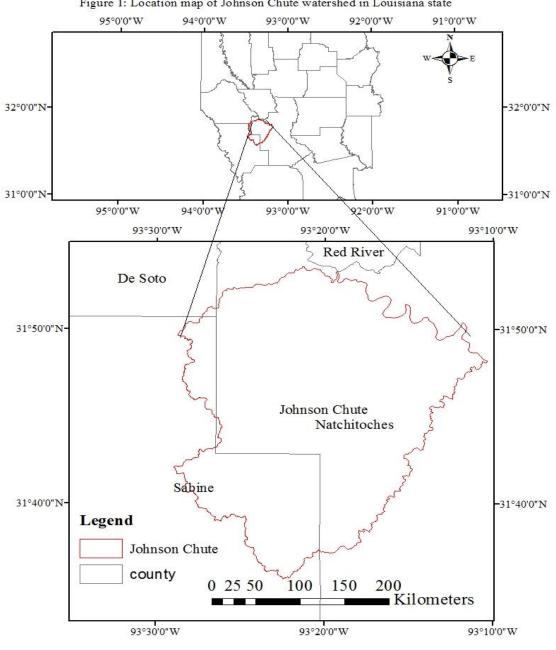
Figure 1: Location map of Johnson Chute watershed in Louisiana state

Fig.3: Phosphorus reduction per unit cost at Johnson Chute watershed for normal year

Fig.4: Phosphorus reduction per unit cost at Johnson Chute watershed for wet year (2009)

Figure 5: Phosphorus reduction per unit cost at John Chute watershed for dry year (2011)

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