Report for 2004TX150B: Estimating Water Availability and Sustainable Yield in a Coastal Semi-Arid Region of South Texas

- Articles in Refereed Scientific Journals:
  - A manuscript describing the application of fuzzy regression and single-county mass balance model has been prepared and is being finalized for submission to Environmental Geology by April 1, 2005.
  - A Manuscript detailing the application of fuzzy optimization and Watershed Scale model will be prepared for possible submission to a peer-reviewed journal by June 1, 2005.

Report Follows

Estimating Water Availability and Sustainable Yield in Coastal Semi-arid Region of South Texas

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Introduction

Groundwater is a precious resource that critically affects the growth and development of a region as well as nourishes the aquatic environment (Glennon, 2001) and must therefore be managed effectively. From a sustainability viewpoint, groundwater resources must be available to the future generations as they are now. Therefore, decision makers entrusted with managing groundwater resources must effectively reconcile between the competing objectives of economic development and environmental protection. Approaches to quantify, how much water can be safely extracted without causing damage to the environment are necessary to develop pertinent aquifer management policies. Therefore, there is a need for tools and technologies that enable a holistic assessment of groundwater availability and sustainable yield. From a practical standpoint, these methodologies must be scientifically credible and yet transparent and easily understood by a wide range of audiences. In addition, these approaches should account for imprecision in available data and theories and be easy to implement with available or readily measurable data.

A methodology to assess water availability by accounting for anthropogenic and ecological withdrawals was developed by coupling the fundamental concept of mass balance (water budget) and fuzzy-optimization schemes. The approach is easy to implement and incorporates the decision makers' confidence in the water budget assessment. The utility of the approach in developing groundwater management rules is illustrated and discussed by using the model to assess groundwater availability in Refugio county and Mission river watershed in Texas.

Study area

Refugio County, Texas, is located in the coastal bend of Texas between Corpus Christi and San Antonio cities. Several large-scale water supply projects are being planned in this region. Mission river watershed covers an area of approximately 690

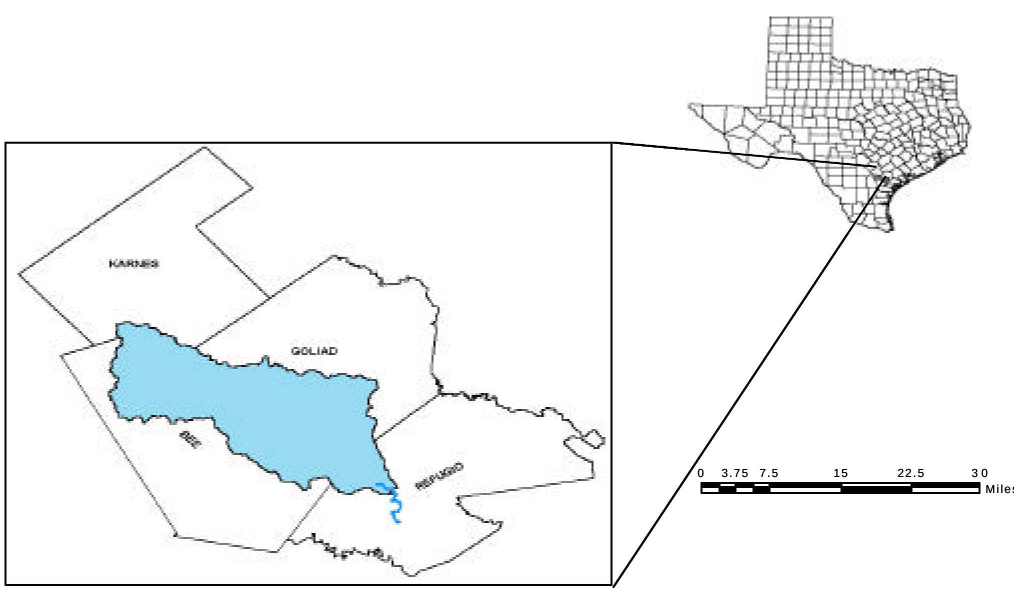

Figure 1. Study Area - Mission river watershed

square miles covering Bee, Goliad, Karnes, and Refugio counties. The underlying Gulf-coast aquifer is characterized by Chicot, Evangeline, Burkeville, Jasper and Catahoula formations. Figure 1 shows the study area.

Methodology

The methodology was developed in a two-stage approach of increasing complexity. As a first-step, a water budget was developed for Refugio County, assuming the Chicot and Evangeline formations to be a homogeneous entity described using effective hydraulic properties. In the second-step, the water budget was carried out for the Mission river watershed, by explicitly modeling Chicot and Evangeline formations of the Gulf coast aquifer. The Burkeville formation was used as the bottom no-flow boundary in both the cases, as it is characterized by low hydraulic conductivity. Groundwater divide along the watershed boundary was used to delineate Chicot formation, while inflows and outflows across the Evangeline were also considered. Cross-formational flow between Chicot and Evangeline aquifer was also incorporated Anthropogenic water demands such as domestic, agricultural and industrial demands cause water levels in the aquifer to drop, while injection of treated wastewater will cause the water levels to rise were incorporated into the modeling methodology as well. Historical water level data and baseflow separation techniques were used to characterize stream-aquifer interactions in both models. The basic mass balance expressions pertinent to each model is presented next.

Single-layer County-scale model

For Refugio County (Figure 2), the following mass balance expression was established.

Accumulation = In – Out ± Source/Sinks (1)

$$S\frac{\partial h}{\partial t}A_s = \sum_{i=1,..n} Q_i + (I - ET)A_s - (L - B) + (R - W) \quad (2)$$

Where, **S**: aquifer storage term (specific yield),

A_s: area of cross-section parallel to the groundwater table (Ac),

h: hydraulic head measured above a pre-specified datum (ft),

Q_i: volumetric flowrate of water entering or exiting along the i^{th} face of the aquifer (Ac-ft/yr),

I: infiltration rate (ft/yr) caused due to precipitation,

ET: rate of evapotranspiration (ft/yr) from below the water-table,

L: percolation of water from surface water bodies (Ac-ft/yr),

B: baseflow (or flow of groundwater into the surface water bodies) (ft/yr),

R: direct recharge of groundwater due to direct injection (Ac-ft/yr) and

W: total withdrawal of water due to anthropogenic demands (Ac-ft/yr).

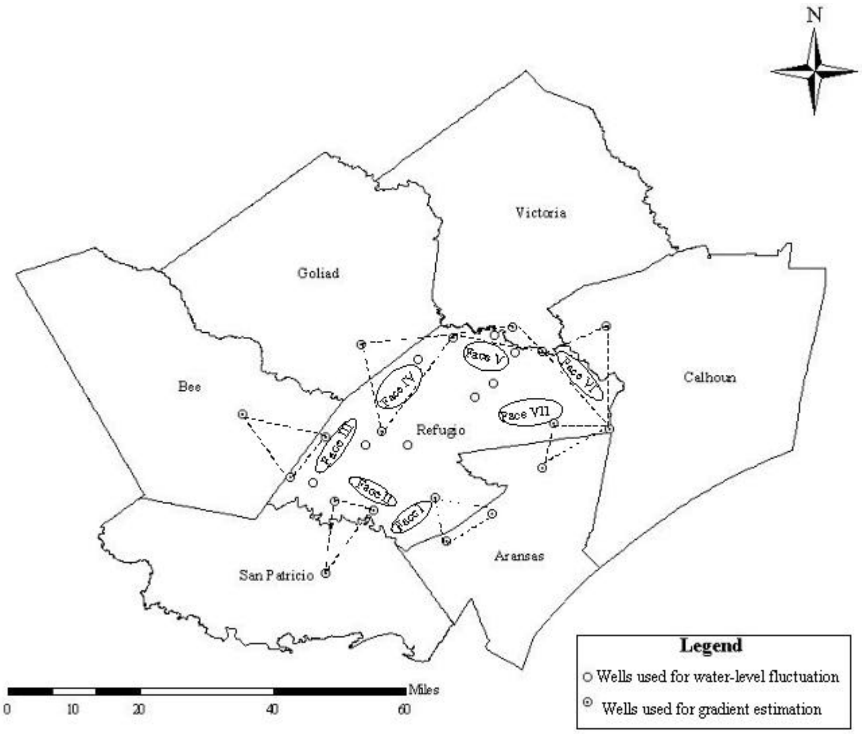

Figure 2. Study area- Single-layer County Model

The unknown parameters, S (storage coefficient) and excess water availability, were estimated by plotting the Water level fluctuations Vs. Water budget as shown in Figure 3.

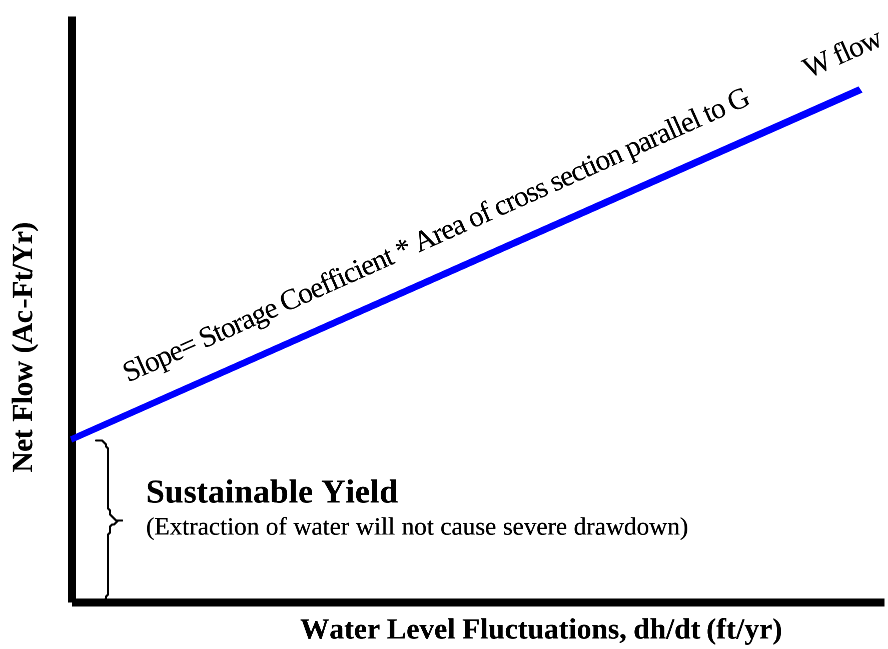

Figure 3. Water level fluctuations Vs. Water budget

A fuzzy regression approach (Peters, 1994) employed to develop the necessary relationship to incorporate the uncertainties arising from limited data and simplistic model conceptualization.

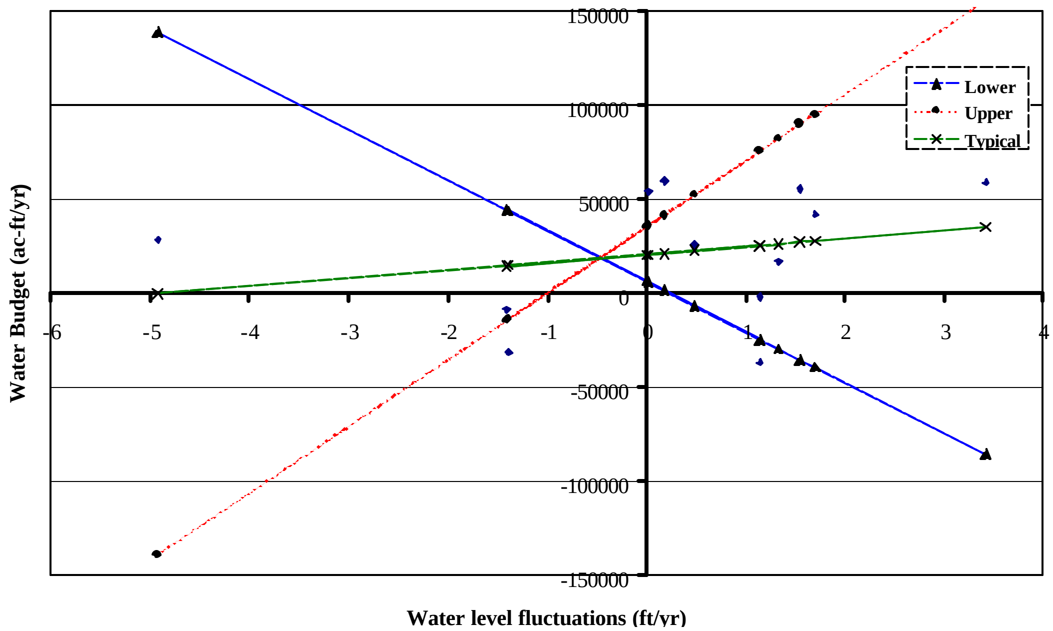

Figure 4. Fuzzy regression

The data on groundwater fluxes, baseflows, water accumulation and withdrawals were utilized with the parameter estimation method to develop estimates for sustainable yields. The regression-based parameter estimation scheme indicated that on an average 20000 Ac-ft of water (Figure 4) could be safely withdrawn from Refugio County without altering the aquifer water levels and maintaining requisite baseflows to Mission River. Also, the average storage coefficient of the aquifer was estimated to be 0.008 and is within the ranges presented in the literature (Freeze and Cherry, 1979).

Two-layer Watershed scale Model

For the control volume depicted in Figure 1, the fluctuations in the water-levels and the various natural and anthropogenic processes affecting them can be related using the fundamental concept of mass-balance as follows:

For Chicot,

$$S_1 \frac{\partial h_1}{\partial t} A_C = R_C - W_C - B_F + Q_F - ET \qquad (3)$$

For Evangeline,

$$S_2 \frac{\partial h_2}{\partial t} A_E = Q_E + R_E - W_E - Q_F \qquad (4)$$

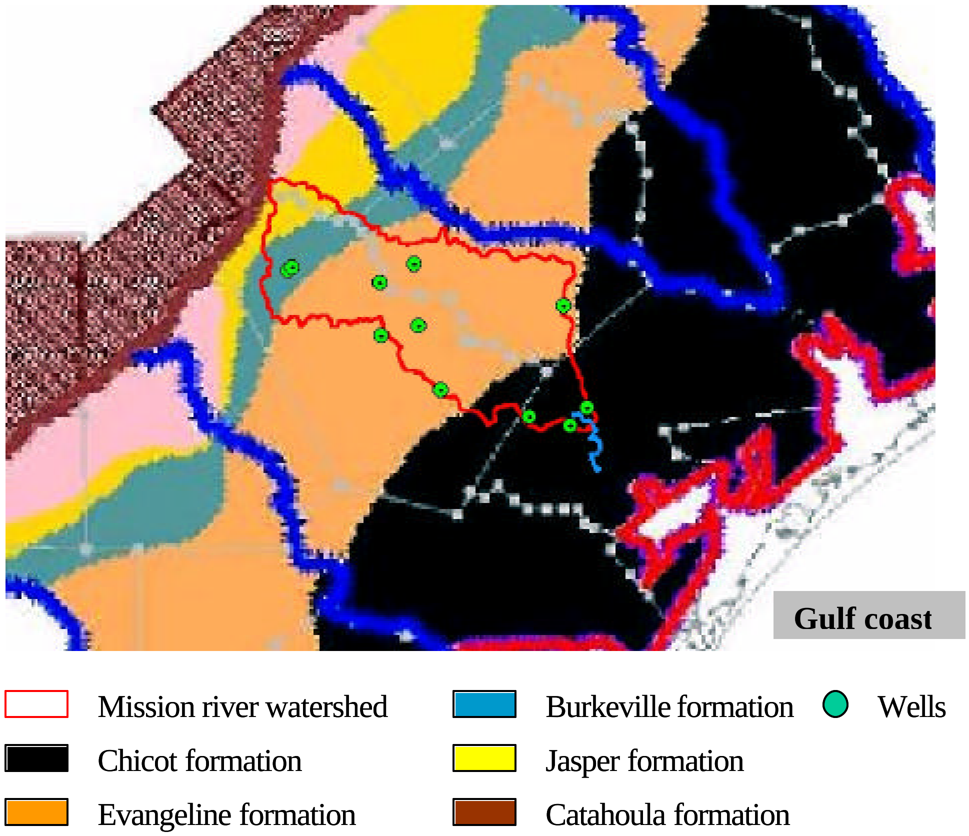

Figure 5. Gulf-coast aquifer

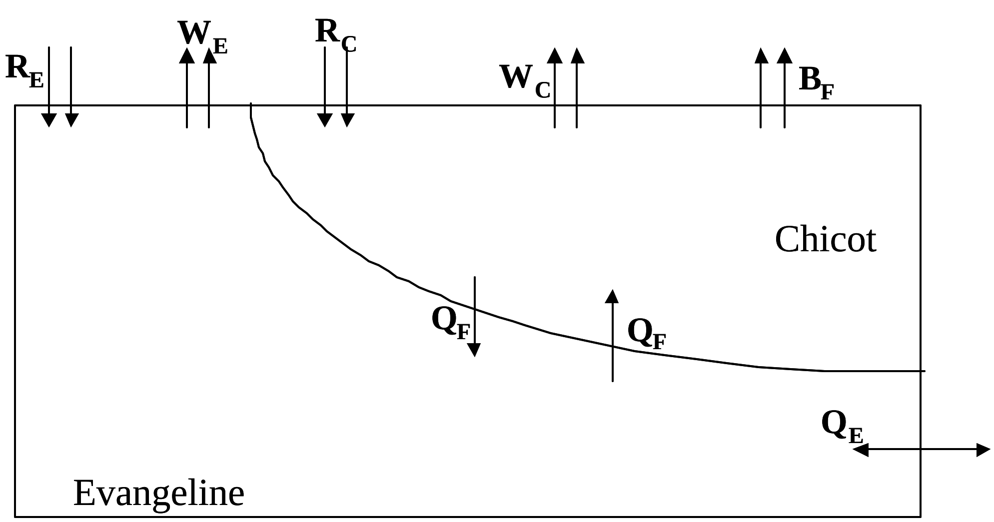

Figure 6. Conceptual Two-layer Watershed scale Model

Combining equations (3) and (4) we obtain,

$$S_1 \frac{\partial h_1}{\partial t} A_C - S_2 \frac{\partial h_2}{\partial t} A_E = (R_C - R_E) + (W_E - W_C) - B_F + 2Q_F - ET \tag{5}$$

Where S_1 and S_2 are the aquifer storage terms (specific yield) for Chicot and Evangeline aquifer, defined as the volume of water released per unit surface area of the aquifer per unit decline in the water table (Freeze and Cherry, 1979). A_C and A_E are areas of cross-section parallel to the groundwater table, h is the hydraulic head measured above a pre-specified datum (ft). Q_E is the volumetric flowrate of water entering or exiting along the north and south faces of the aquifer (Ac-ft/yr). R_C and R_E are the recharge (Ac-ft/yr) caused due to precipitation in Chicot and Evangeline formations, and W is the total withdrawal of water due to anthropogenic demands (Ac-ft/yr). B_F is the baseflow (or flow of groundwater into the surface water bodies) (ft/yr). Q_F is the cross-formational flow of water between Chicot and Evangeline formations. The subscripts C and E denote Chicot and Evangeline formations. The volumetric flowrate of water entering or exiting along the north and south faces of Evangeline aquifer (Q_E) can be computed from Darcy's law as:

$$Q_i = K_r \frac{\partial h}{\partial s} A_i \tag{5}$$

Where K_r is the hydraulic conductivity (ft/yr) along the direction of flow s, the derivative term is the hydraulic gradient (ft/ft) and A_i is the area of cross-section normal to the direction of flow along the face. For unconfined aquifers, the area of cross-section is also a function of the water level (h) measured along each face.

Inflows and Outflows Across the Aquifer Boundaries

Two sets of three well clusters that fall on the Evangeline formation in and around the Mission river watershed were identified to quantify the inflows and outflows of water into the Evangeline formation. Water levels measured on an annual basis between the periods of 1985 – 1994 were obtained from the Groundwater Database developed by Texas Water Development Board (TWDB, 2003). The water level fluctuations were then used to compute gradient using the procedure suggested by Pinder et al., (1982). The hydraulic conductivity of the aquifer was assumed to be uniform, and an average value of 10^{-4} ft/day was used based (Mason, 1963). The annual volumetric fluxes in and out of the aquifer were then computed via the application of Darcy's law. The flow into the watershed (control volume) was assumed to be positive while outward flows were assumed to be negative.

Aquifer Recharge due to precipitation

To estimate the amount of precipitation actually recharging the aquifer, we have used the Power law equation developed by Bureau of Economic Geology at University of Texas at Austin (Scanlon et al., 2004). Power law equation is,

$$y = ax^b$$

Where, x is the average yearly precipitation in mm, a and b are the coefficients for four different modeling scenarios; (i) non-vegetated, monolithic sand, (ii) vegetated, monolithic sand, (iii) non-vegetated, layered soil profiles, and (iv) vegetated, layered soil profiles. In this case, we have considered vegetated, layered soil profiles ($a = 3.24*10^{-9}$; $b = 3.407$). Precipitation data is from National Oceanographic and Atmospheric Administration (NOAA). The precipitation data was interpolated for each formation in ArcInfo 9.0 and the average annual recharge was calculated using raster calculator in ArcInfo. The reasonableness of the power law expression was evaluated using double-ring infiltrometer measurements carried out at various locations in the study area.

Surface water - Groundwater interactions (Baseflows)

Mission river is a perennial river and the groundwater levels in the areas adjoining Mission river tends to be slightly higher than the average river stage, indicating potential groundwater discharges (baseflows) to the streams. The surface water-groundwater interactions in other creeks were not considered. The annual baseflow contribution to Mission river from underlying aquifer for the period of 1985-1994 was estimated using a hydrograph separation technique. Streamflow data from USGS gaging station (Station ID: 08189500) were used in conjunction with the computer program HYSEP (Pettijohn, 1979) to obtain necessary estimates.

Accumulation within the Aquifer Control Volume

Accumulation represents, the left hand side of Equation (2). A total of 4 wells within the Chicot formation, and 7 wells within the Evangeline formation were selected to estimate water accumulation. Annual accumulation over the period of 1985-1994 was estimated using measured water-table elevations and first-difference approximation using the equation,

$$\frac{\partial h}{\partial t} \approx \frac{h_t - h_{t-1}}{\Delta t}$$

Where Δt is the measurement time-step (years) and h is the water-level elevation measured from a pre-specified datum at times t and t-1 respectively.

Anthropogenic withdrawals

Based on the *2002 Water Use Survey Summary Estimates by County* developed by TWDB (www.twdb.state.tx.us), water demand due to municipal, manufacturing, mining, steam electric, irrigation, and livestock was calculated per square mile area. And from this data, the anthropogenic withdrawal (W) was estimated for both Chicot and Evangeline formations.

Initial Results for Two -Layer Regional Scale Model

Results of the water-balance is as shown below. Coupling of fuzzy optimization with mass-balance in currently in progress.

Year	dh/dt (ft/yr)	R_C (Ac/ft/yr)	W_C (Ac/ft/yr)	B_F (Ac/ft/yr)	WB (Ac-ft/yr)
1985	0.05	6200.16	566.03	11886.99062	-6252.86
1986	1.48			1047.15288	4586.98
1987	0.67			0	5634.13
1988	2.63			527.187312	5106.94
1989	4.23			86.660928	5547.47
1990	0.46			15707.2932	-10073.16
1991	9.07			7460.061552	-1825.93
1992	0.25			9388.2672	-3754.14
1993	0.25			0	5634.13
1994	8.65			0	5634.13

Area of Chicot, A_C = 54707.26 acres

Table 1. Water budget for Chicot formation

Year	dh/dt (ft/yr)	Q_E (In/Out)	R_E(Ac/ft/yr)	W_E (Ac/ft/yr)	WB (Ac-ft/yr)
1985	15.74	10441.96	26038.83	4172.831084	32307.96
1986	3.44	10216.32			32082.32
1987	44.55	6897.35			28763.34
1988	6.50	13353.93			35219.93
1989	6.99	11383.86			33249.86
1990	2.49	18153.61			40019.61
1991	0.80	17901.93			39767.92
1992	1.71	14242.30			36108.29
1993	1.71	11127.54			32993.54
1994	1.47	14111.02			35977.02

Area of Evangeline, A_E = 390582.38 acres

Table 2. Water budget for Evangeline formation

Parameter Estimation

In the two-layer watershed scale model, the model requires 3 unknowns to be estimated, the storage coefficients S_1 and S_2, and cross-formational flow Q_F. A fuzzy regression based parameter estimation procedure is being utilized to estimate these unknown coefficients (Simões, 2001).

Dissemination of Results

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Another Manuscript detailing the application of fuzzy optimization and Watershed Scale model will be prepared for possible submission to a peer-reviewed journal by June 1, 2005.

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