RAINWATER INFILTRATION RATE AND GROUNDWATER SUSTAINABLE MANAGEMENT IN THE DAKAR REGION

Sylvestre DASYLVA[1], Claude COSANDEY[1], Didier ORANGE[2], Soussou SAMBOU[3]*

[1] Laboratoire de Géographie Physique P. Birot - U.M.R. 8591 CNRS - Univ. Paris 1, France
[2] Laboratoire de Biogéochimie Isotopique, I.R.D. - U.M.R. 7618, Univ. Paris 4, France
[3] UCAD / Université Cheikh Anta Diop – Dakar Sénégal

* 1 place A. Briand 92195 Meudon Cedex ; Gilbert.Dasylva@cnrs-bellevue.fr
Tel. 00 33 (0)1 45 07 55 77 ; Fax 00 33 (0)1 45 07 58 30

Abstract

The aim of this study is to contribute to the solution of recent problems in the Dakar region due both to surface water (runoff hazards and waterlogging) and to groundwater recharge deficit. The rainwater infiltrating volume to the groundwater is a key-element for the understanding and the solution of these problems. Given that rain is the only refill parameter (Béture-Sétame, 1988), the groundwater dynamics (especially, the refill and the static level annual balance) is studied in relation to rainfall variability, in order to propose solutions adapted to the current pluviometric context. Piezometric data of the NSQ (Nappe des Sables Quaternaires) from 1953 to 1990, are used to evaluate the groundwater dynamics. The method is based on the addition of groundwater top-level monthly height changes in the aquifer –in others words, on the addition of the "relative" static level changes between two consecutive months. During one hydrological year, the refill and the static level balance of the groundwater are calculated for three annual pluviometric scenarios: 1/ yearly rainfall (529 mm), close to the regional average (484 mm); 2/ rainfall excess (10 years recurrence: 712 mm); and 3/ rainfall deficit (20 years recurrence: 220 mm).
Compared with precipitation heights, results allow to determine the natural annual values (in rainwater height equivalent) of: 1/ the refill (= 107 mm/year) in the current pluviometric context, corresponding to the refill in average rainfall periods, 2/ the refill generating a positive evolution of the groundwater static level (= 217 mm/year), which is equivalent to the recharge observed in rainfall excess periods. By comparing these two results, we estimate 3/ the refill deficit (= 110 mm/year) in today's pluviometric context, and 4/ the infiltration rate needed for a sustainable management of water resources (50% of total annual rainfall). To obtain this rate, the infiltrating rainwater volume -height equivalent- feeding the groundwater should be increased from 107mm to 217mm by artificial recharge.

Keywords : *Rainfall deficit, Groundwater dynamics, Floods, Integrated rainwater management, Sustainable management, Public health*

Introduction

In the sub-Saharan zone of west Africa, the recent pluviometry decrease has had dramatic consequences on the groundwater recharges. The top-level of the NSQ (Nappe des Sables Quaternaires) groundwater is falling, since 1885 (Hubert, 1921), in relation to this precipitation decrease (Dasylva *et al*, 2003b). This evolution is leading to a progressive drying of the "niayes". The "niayes" are agricultural bottom-lands located in the dunes sands, where the groundwater top-table reaches or overflows the bottom-land surface. They are exploited by traditional farming practices based on irrigation. The rainfall evolution trends from 1918 to 1998 in the "Dakar Yoff" pluviometric station illustrates the precipitation decrease trend (Figure 1). After 1969, the annual rainfall is characterized by a severe water shortage shown by the annual precipitation averages before and after 1969: 1918-1969 = 573 mm ; 1970-1998 = 342 mm. Thus, the annual average rainfall deficit of the post-1969 dry phase is 231 mm (or 60% of the previous average amount).

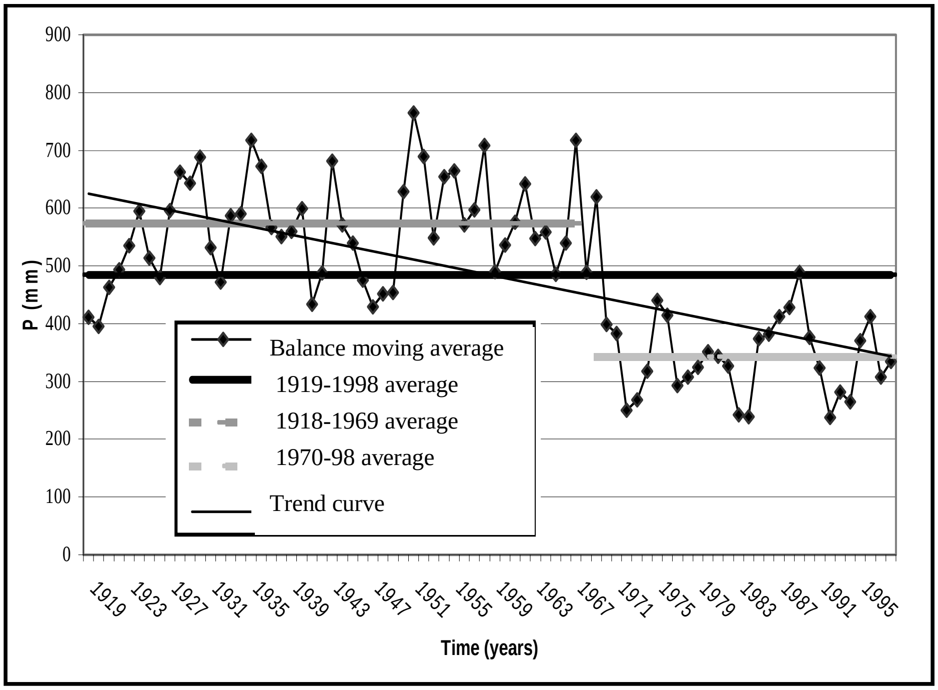

Figure 1 : Rainfall evolution trends at "Dakar-Yoff" station, from 1919 to 1998

In the Dakar city suburbs, the dramatic social pressure on the environment has led to the urbanization of the "niayes" and other depressions where runoff concentrates. In these areas, the pluviometry decrease does not prevent the aggravation of the nuisances (floods and malaria) due to the surface waters. Rainwater management practices existing in the African cities have been insufficient until now for providing solutions to these surface water problems. Rainwater management "classical" systems in Dakar drain waters toward the sea and/or evaporation basins; in a rainwater scarcity context, this strategy favors a loss of resource, as rainwater must not be considered as a harmful element but as a resource. A performance improvement of rainwater management systems requires to find solutions before, during and after the runoff occurrences. In our previous studies, we recommended management measures based on a new approach allowing to preserve rainwater by increasing the rainwater infiltrating rate in the dune sands through artificial recharge (Dasylva et *al*, 2004; Dasylva et *al*, 2003a; Dasylva et *al*, 2002; Dasylva, 2001). This solution also allows the lowering-down of the runoff volume and favors the increase of the groundwater refill.

Approach

The rainwater infiltrating volume feeding the groundwater is a key-element for the understanding and the solution of the surface water and of the groundwater depletion problems. Researches presented here aim at estimating the refill rate necessary for ensuring an efficient recharge or a positive static level annual balance of the dune sands groundwater in the current pluviometric context, where annual precipitation recorded since 1970 (except the year 1989) never exceeded the regional average (Figure 1). The calculation of this refill rate is based on a three-steps approach:

1/ calculating the refill and the annual balance of the groundwater static level evolution. Obtained data are related to rainfall variability, according to Béture-Sétame (1988), rainfall is the only input parameter (Table 1);

2/ calculating the refill deficit, in order to determine the infiltrating volume increase necessary for compensating the groundwater deficit recharge in the current pluviometric context;

3/ evaluating the impacts on the lowlands hydrology in case of an increase of the infiltration rate, if the proposed solution is applied.

	INPUTS			*OUTPUTS*		Balance
	Rain	*Evaporation*	*Losses to the sea*	Agriculture	*SDE**	
	0.133 m	0.1 m	0.18 m	0.245 m	0.205 m	
Total	*0.133 m*			*0.163 m*		- 0.03 m

Table 1 : Average annual hydric assessment of the NSQ from 1972 to 1984
(Béture Sétame, 1988)

Methods

Given that the rain is the only refill parameter (Béture-Sétame, 1988), the groundwater dynamics (especially, the refill and the static level annual balance) is studied in relation to rainfall variability. Piezometric data concerning the groundwater level altitude of the NSQ (Nappe des Sables Quaternaires) from 1953 to 1992, are used to illustrate the groundwater dynamics. Our method using the height variation of the groundwater table, is an original approach when compared to previous researches in this zone. Most of these previous studies, realized by hydro-geologists, are focused on the hydro-geological characteristics and give results in volume (m^3) (Anonyme, 1963; Béture-Sétame, 1988; Fohlen & Melka, 1989; (Gaye *et al*, 1977 and 1998; Géohydraulique, 1972; Henri, 1921 and 1922; Martin, 1969 and 1970; OMS, 1972; Tandia, 1993 and 1997). They do not take into account the hydrological relations between the groundwater and the "niayes". Only one reference in the literature we searched, uses such an approach when studying the hydrological dynamics of the "Mbao" temporary river (Chaperon, 1975).

All piezometers we selected are located around *Sangalkam* (Figure 2). In this area, the groundwater dynamics is considered as "normal" because it responds to rainfall variability and not to SDE (Sénégalaise des Eaux) pumpings and saline water intrusions. According to these piezometric data, the groundwater top-level altitude is characterized by an important variability in space, keeping us from comparing the whole set of sites. In order to solve the problems generated by this heterogeneity and to be able to compare all sites on similar bases, the annual recharge and balance of groundwater top-level evolution are calculated on the basis of the monthly "relative" variation –or altitude change- in static level altitude of the aquifer.

Values of refill and annual balance of groundwater dynamics are obtained by adding the monthly static level variations during one hydrological year. The maximum point of the cumulative curve represents the refill value and the minimum point indicates the annual balance of the static level evolution. The balance is positive when the final level is above zero and is negative when the final level is below zero.

The natural annual refill and balance of the groundwater static level are calculated according to three annual pluviometric scenarios : 1/ annual rainfall (529 mm) close to the regional average (484 mm) ; 2/ excess annual rainfall (10 years recurrence : 712 mm) and 3/ deficit annual rainfall (20 years recurrence : 220 mm). These precipitation data are the annual averages recorded respectively in 1960, 1969 and 1970 in four pluviometric stations of the region (Appendix 1).

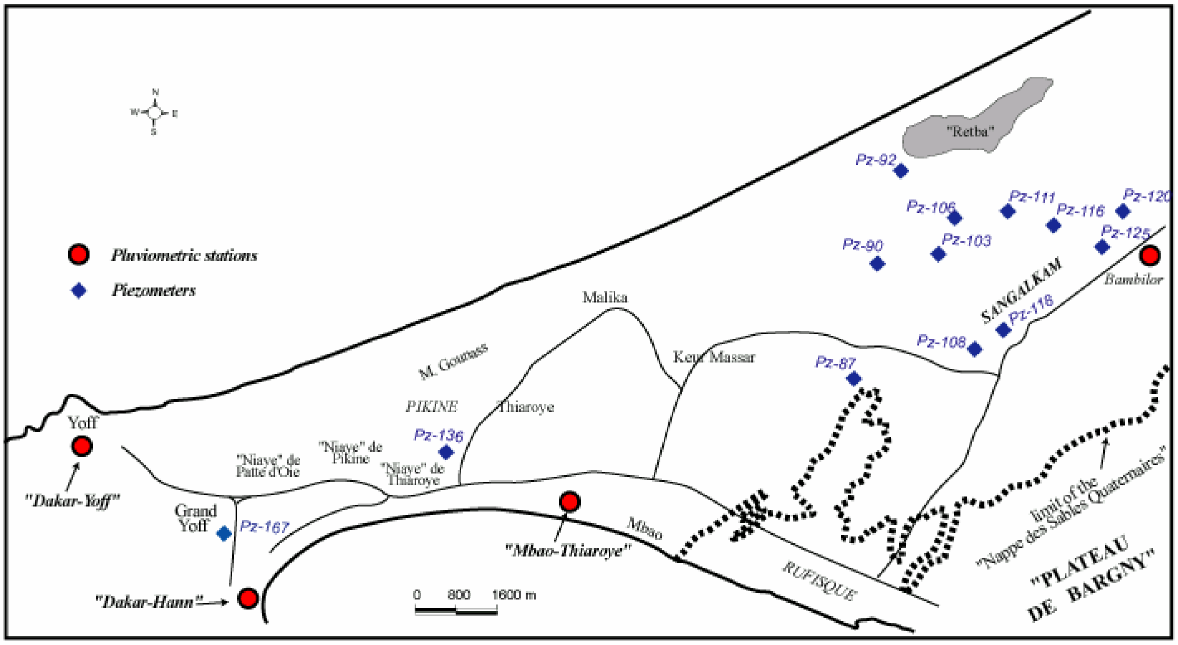

Figure 2 : Location of reference pluviometric stations and piezometers

Results and discussion

Characteristics of the groundwater annual refill and the static level balance in relation to rainfall

In order to apprehend the "relative" evolution of the static level in natural conditions and in relation to rainfall variability, three piezometers have been selected (figure 1). The main results concerning the refill and the static level balance for the three pluviometric scenarios retained are: 1/ for a 529 mm yearly precipitation (close to the annual average regional value), the balance is negative (figure 3) ; this result indicates that the groundwater hydric balance is negative in the current pluviometric context where annual precipitation rarely exceed the regional average (figure 1); 2/ the annual variation is positive when annual precipitation is about 700 mm; this result means that in such a situation, the natural refill is sufficient to allow a positive variation of the static level.

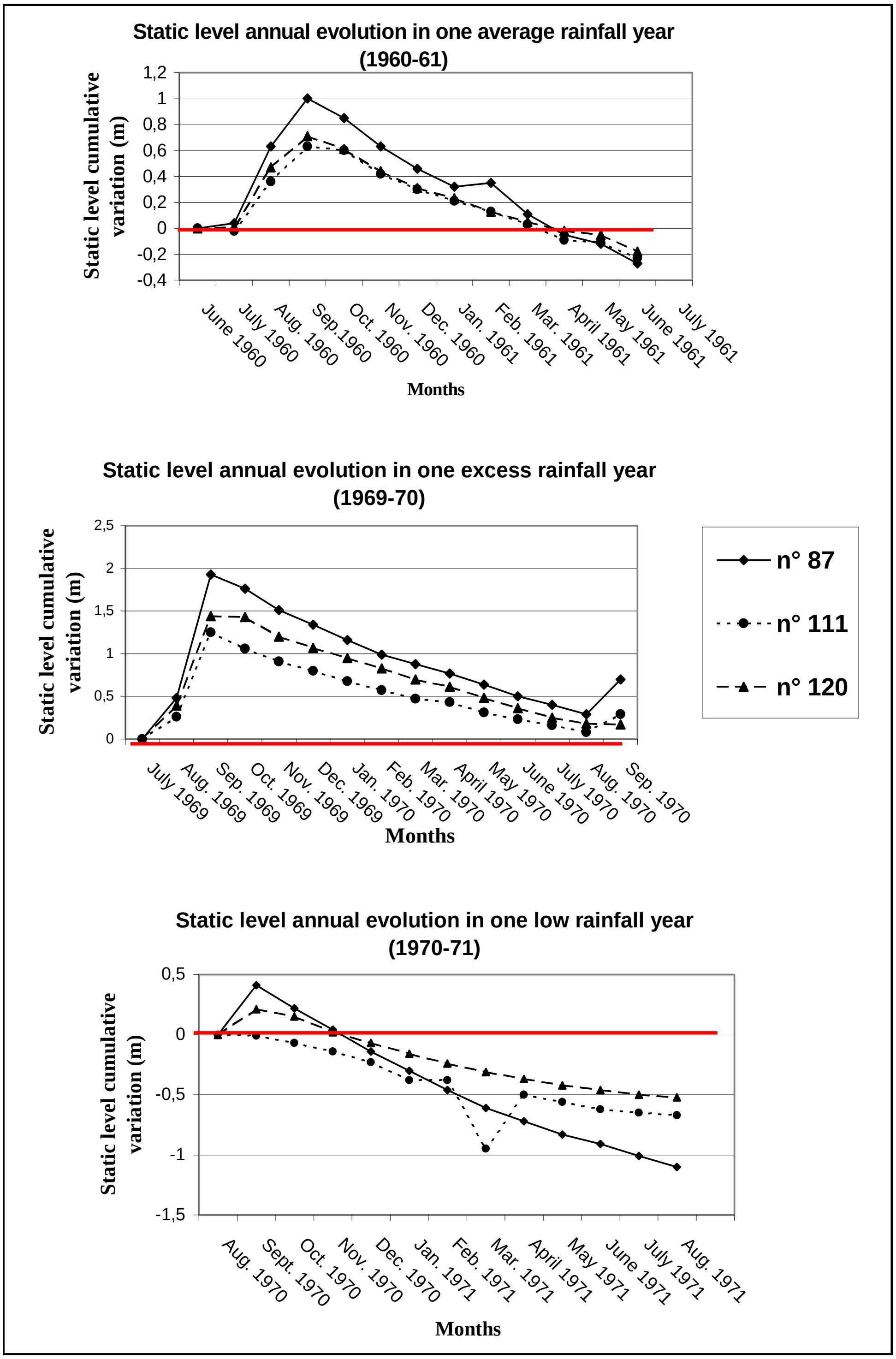

Figure 3 : "Relative" evolution of NSQ groundwater static level in relation to rainfall variability in the "Sangalkam" area

The positive variation of the groundwater static level observed during the 1969-70 hydrological year, is due to the increase of the infiltrating water volume caused by excess precipitation. The equation modeling the groundwater lowering trend shows a some similarity between average and excess rainfall occurrences (figure 4). The correlation coefficients (0.95 for the first and 0.90 for the second) indicate that the equations are representative of the lowering trend of the groundwater static level. We can thus deduce that any increase in infiltrating water volume will benefit to the groundwater. As the piezometric maximum depends entirely on the pluviometric maximum (Dasylva *et al*, 2003b), the recharge starts with the first rains.

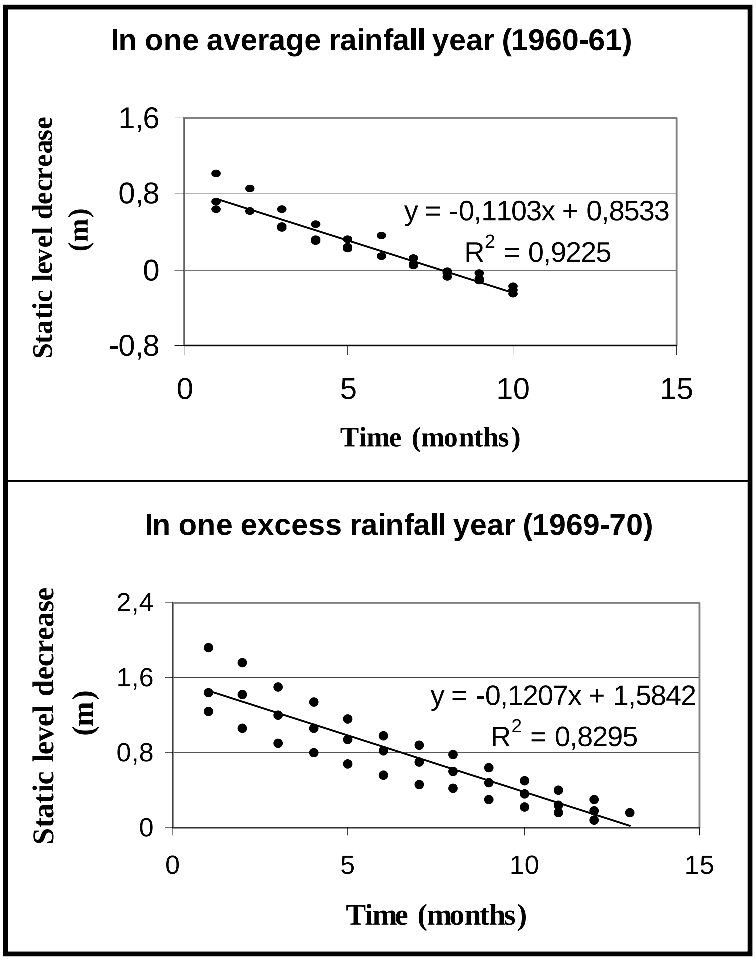

Figure 4 : Groundwater lowering process in the “Sangalkam” zone, in average and excess rainfall years

During both hydrological years 1960-61 and 1969-70, in figure 3, the static level evolution of the groundwater shows a rebalancing process in the course of the time. Practically, the final balance gives identical values, in spite of the refill variability. This behaviour can be explained by the fact that the sands containing the groundwaters are characterized by a hydraulic continuity (Géohydraulique, 1972). Solutions, in order to be efficient, must thus be applied at the regional scale and not at the local scale.

Estimation of the refill deficit and the infiltrating rate increase during one year

- Estimation of the refill deficit in natural conditions

Only piezometers providing enough data to calculate the annual averages of the refill have been selected. In the current pluviometric context, refill deficit (R_d) can be deduced by comparing both average recharges during the 1969-70 and 1960-61 hydrological years : refill obtained for 1969-70 (R_{er}) is representative of the groundwater efficient recharge, while the 1960-61 data is the refill obtained in average rainfall (R_{ar}), e.g. representative of the current low rainfall context. Results are shown in Table 2 : values in meters (m) represent the height variation of the groundwater static level in the aquifer, and values in millimeters (mm) represents this variation equivalent in precipitation height, based on the 0.15 value of dune sands porosity (Béture-Sétame, 1988).
The refill deficit estimation is based on the following formula :

$$R_d = R_{er} - R_{ar}$$

According to our results, the annual refill deficit necessary for producing an efficient recharge of the groundwater is 0.4 m/year (height of underground table elevation) or 110 mm/year (precipitation height equivalent).

- Estimation of the infiltrating rate permitting the efficient recharge in the average rainfall context

During an average rainfall period, calculation of the infiltrating rate of rainwater reaching the groundwater is based on the following ratio :

$$R / P_{an}$$

where, R is the recharge and P_{an} the annual precipitation.

In average rainfall conditions, the value for a natural recharge obtained (18%, table 2) is too low for generating the efficient recharge of the groundwater. The budget balance thus needs to be higher. The calculation for identifying the necessary rainwater infiltrating rate increase needs a procedure capable of determining the value indicating a positive evolution of the groundwater static level; in others word this procedure has to produce a recharge close to the refill obtained during the 1969-70 hydrological year. In order to estimate the efficient refill in the current pluviometric context, we thus solved the following equation :

$$ERR = R_{pb} / P_{an}$$

where, ERR is the efficient refill rate ; R_{pb} is the recharge necessary for obtaining a positive balance and P_{an} is the average precipitation amount during a “normal” year.

Average rainfall : Ex. 1960-61 ; P = 529 mm												
Pz 87	Pz 90	Pz 92	Pz 103	Pz 106	Pz 108	Pz 111	Pz 116	Pz 118	Pz 120	Pz 125	*Average (m)**	*Average (mm*
1	0.7	0.68	0.48	0.7	0.92	0.71	0.54	0.47	0.62	0.92	*1.00*	107
-0.27	-0.51	-0.11	0	-0.11	-0.13	-0.18	-0.21	-0.2	-0.21	-0.83	*-0.257*	
26	18	18	12	18	23	18	14	12	16	23	*18*	

Excess rainafll : Ex. 1969-70 ; P = 712 mm												
Pz 87	Pz 90	Pz 92	Pz 103	Pz 106	Pz 108	Pz 111	Pz 116	Pz 118	Pz 120	Pz 125		
1.93	1.75	1.26	1.47	1.23	1.58	1.25	1.05	1.28	1.44	1.69	*1.448*	217
0.29	0.52	0.06	0.63	0.31	0.18	0.08	0.07	0.24	0.18	0.44	*0.273*	
38	34	25	30	32	31	25	21	25	29	34	*29,45*	

: variation of the groundwater static level variation in the aquifer
ight variation equivalent in precipitation height

Table 2 : Annual average values of the recharge and of the static level final balance in average and excess rainfall years in the “Sangalkam” area

Given 217 mm for an efficient refill, the rainwater infiltrating rate should reach 50% of the annual rainfall amount, in the current pluviometric context. “Alternative” technics of rainwater management, little used in Africa, could allow to reach this rate. As shown by an experiment led by a EIER research group (Ecole d’Ingénieur de l’Equipement Rural), “filter trenches” built for collecting and infiltrating rainwater at Ouagadougou, provoked a retention of approximately 50% of the total rainwater (Kerspern & Ouédraogo, 2002).

Impacts of an increase in rainwater infiltrating rate by artificial recharge on lowlands hydrology in the urbanized lowlands

A rainwater infiltrating rate increase by artificial recharge and/or an interruption of the SDE pumping, may generate changes in the lowlands hydrology, with especially, the top-level of the groundwater rising up above the ground surface (Martin, 1969 ; Géohydraulique, 1972 ; Dasylva, 2001). In order to calculate the level induced by any rainwater infiltrating rate increase (called here the “theoretical” level), we used the following formula :

$$TL = L_{max} + V_{ai}$$

where, *TL* is the “theoretical” level ; L_{max} is the maximum level during the rainy season ; V_{ai} is the “additional” water height variation resulting from infiltration.

According to the piezometric data available in the area and during one hydrological year, the comparison of the altitude between the “theoretical” groundwater table obtained by our formula and the lowlands altitudes, indicates that the infiltration rate increase generates highly variable impacts on the hydrological behavior of the lowlands (figure 5).

In locations where the static level rises today above the ground level, the groundwater “theoretical” level rarely exceeds the lowlands bottom altitude. According to our field observation and in case of a 50% rainwater infiltrating rate increase, only a few sectors are concerned by floods during one hydrological year. The only amplification of the groundwater height observed occurs in the *Thiaroye* “niaye”, where the groundwater is anyhow emerging all year long. Naturally, the districts located around this zone are also concerned by flooding hazards. The risk occurred during the last years of the piezometric data, coinciding with a rainfall increase. Figure 6 shows that during periods of low rainfall, the “theoretical” level did not, indeed, exceed nor reach the lowland ground surface. The risk of flooding in the lowlands during a dry rainfall period is thus inexistent, if the increase in rainwater infiltrating rate is increased up to 50%.

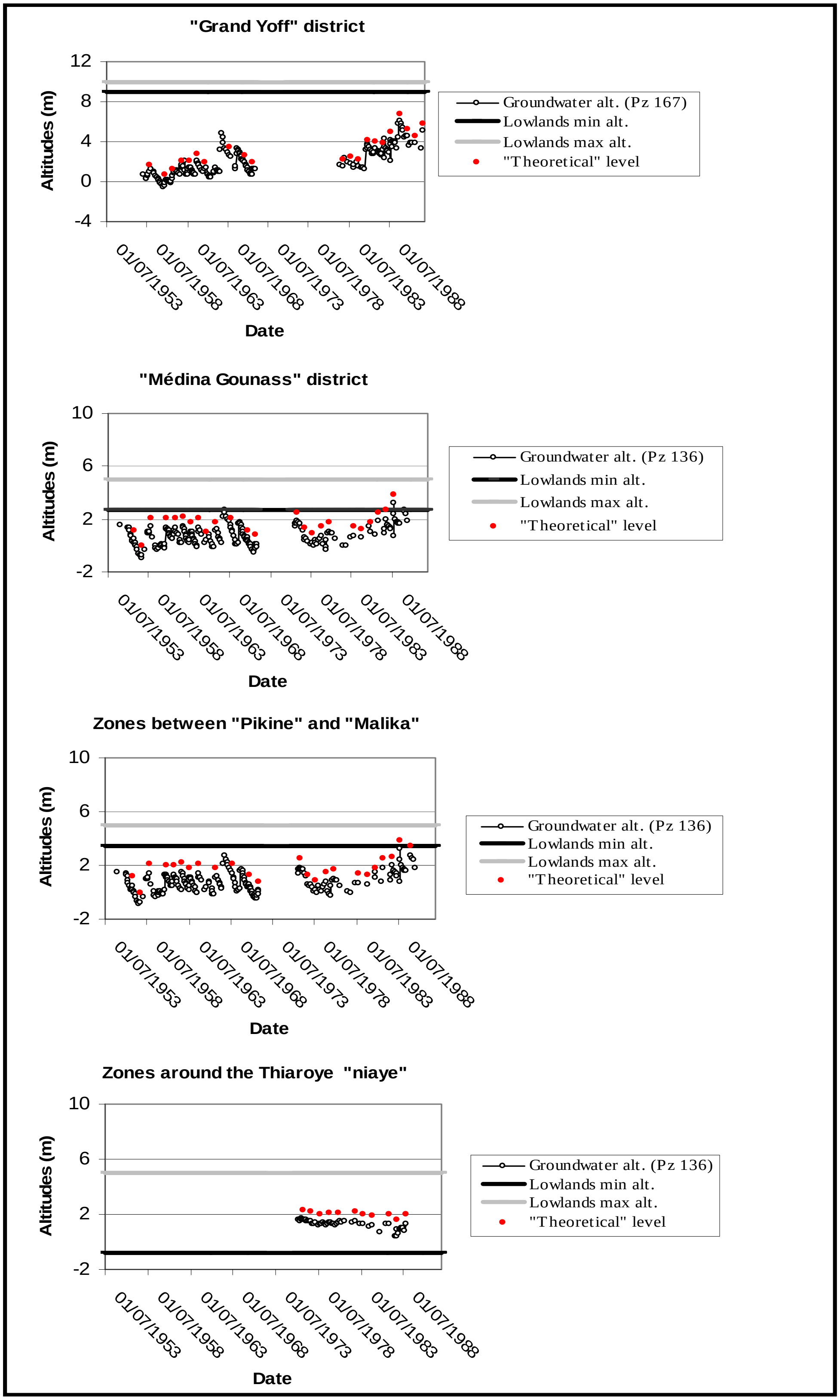

Figure 5 : Estimation of the groundwater "theoretical" altitude in case of a 50% increase of the rainwater infiltrating volume in urbanized depressions

Conclusion

The lowering of the groundwater top-level is compromising the existence of the “niayes” and the future preservation of agricultural activities. In the sub-Saharan zone of west Africa, today’s annual precipitation does not permit any “efficient” recharge of the groundwater. In the Dakar area, a 700 mm annual pluviometry is necessary to ensure an “efficient” recharge of the NSQ groundwater. Given the low rainfall recorded for the last 30 years (Figure 1), any rainfall increase seems nowadays hypothetical, so that the “efficient” recharge is not and probably will not be occurring in the near future. Then, alternative solutions have to be found. Complementary solutions may emerge from improving runoff management, with the application of measures increasing the volume of infiltrating rainfall. For example, the groundwater level decrease in the “niayes” could be stopped by increasing the rainwater infiltrating rate of the rainfall to 50% by means of sediment filled wells as already used locally for wasted water collection.

APPENDIX

	DRY RECURRENCES					Med.		WET RECURRENCES				
	0,01	0,02	0,05	0,1	0,2	0,5	Aver.	0,8	0,9	0,95	0,98	0,99
	1/100 years	1/50	1/20	1/10	1/5	1/2		1/5 years	1/10	1/20	1/50	1/100
STATIONS												
Dakar-Yoff	130	154	200	249	318	472	484	642	734	811	898	956
Dakar -Hann	139	158	195	237	299	443	460	610	704	784	875	936
Mbao-Thiaroye	148	168	207	251	317	473	493	657	760	848	949	1017
Bambilor	157	183	231	280	348	493	501	647	728	795	870	919
Regional average	143	165	208	254	320	470	484	639	731	809	898	957

Appendix 1 : Recurrence characteristics of annual rainfall from 1919 to 1998 in Dakar Region

REFERENCES

Anonyme (1963) – *Etude hydrologique des « niayes » du Cap-Vert. Synthèse des données existantes*, 28 p.

Béture-Sétame (1988) - *Renforcement de l'approvisionnement en eau de la région de Dakar*. Béture-Sétame Ltd. Dakar. Tome 1

Chaperon P. (1975) - *Etude hydrologique de la zone de Mbao*. IRD. Dakar.

Dasylva S (2001) - *Les bas-fonds des sables dunaires de la Région de Dakar. Potentialités agricoles et contraintes urbaines*. Thèse de Doctorat, Université Paris 1, 406 pp (*unpublished*)

Dasylva S, Cosandey C, Orange D (2002) - Proposition de gestion « intégrée » des eaux pluviales pour lutter contre les problèmes liés à l'eau dans la banlieue de Dakar. *Colloque Envirowater 2002,* Ouagadougou.

Dasylva S, Orange D, Sambou S, Kane A (2003a) – Integrated management of the rainwater in the area of Dakar : estimation of the increase of the rainwater infiltration rate in the current pluviometric context. *Colloque Envirowater 2003,* Albacete, Espagne.

Dasylva S, Cosandey C, Orange D, Sambou S (2003b) – Assèchement des « niayes » (bas-fonds agricoles) de la Région de Dakar durant la période 1960 – 1990 : variabilité spatiale et rôle joué par la pluviosité. *Sud Science et Technologie*, 11, 27-34

Dasylva S, Cosandey C, Sambou S (2004) – Acuité des problèmes lies à l'eau et la nécessité d'une gestion « intégrée » des eaux pluviales dans le domaine des sables dunaires de la Région de Dakar. *Colloque Développement Durable : leçons et perspectives,* Ouagadougou.

Fohlen D & Melka J (1989) – *Etude des ressources en eau du Sénégal. Synthèse des récentes campagnes de prospection géophysique*, BRGM, Dakar, 60 pp.

Gaye C B, Faye A, Gelinas P J, Therrien P (1977) - *Analyse des processus de minéralisation et de dégradation de la qualité de l'eau dans les nappes infra-basaltiques et des sables quaternaires*. Projet CRDI 3-P86-1014. Dakar.

Gaye C B, Faye A, Sarr F (1998) - *Utilisation des isotopes pour l'études de la ré-alimentation des aquifères de la presqu'île du Cap-Vert*. OMS. Dakar

Géohydraulique (1972) - *Etude sur modèle mathématique du système aquifère de la presqu'île du Cap Vert*. OMS. Dakar.

Henry H (1921) - *Eaux superficielles et souterraines au Sénégal*. Larose. Paris

Henry H (1922) - *Etudes hydrologiques en vue de l'alimentation en eau des villes de Dakar et de Rufisque*. (*unpublished*).

Kerspern Y, Ouedraogo B (2002) – Les tranchées d'infiltration, une technique alternative pour la collecte et l'infiltration des eaux pluviales : cas d'étude de Tanghin au Burkina Faso. *Sud Sciences et Technologies*, 8, 16-27

Martin A (1969) - *Interprétation des variations naturelles du niveau des nappes aquifères en Mauritanie et au Sénégal. Nappe de la presqu'île du Cap-Vert*. BRGM. Dakar.

Martin A (1970) – *Les nappes de la presqu'île du Cap-Vert, leur utilisation pour l'alimentation en eau de Dakar*. BRGM, Dakar, 56 pp + cartes.

OMS (1972) - *Etude hydrogéologique de la nappe des sables quaternaire*. Malostranske Nam. Prague.

Tandia A A (1993) - Origine, évolution et migration des formes de l'azote minéral dans les aquifères du Sénégal : cas de Thiaroye (banlieue non assainie). *Rapport de Recherche* Contrat n°7272/RB, AIEA, Dakar.

Tandia A A, Gaye C B, Faye A (1997) - Origine des teneurs élevées en nitrates dans la nappe phréatique des sables quaternaires de la région de Dakar, Sénégal. *Sécheresse,* 8 (4) : 291-294