SUSTAINABLE WATER MANAGEMENT IN THE DAKAR AGRICULTURAL BOTTOM-LANDS.

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ABSTRACT

In Sub-Saharan region of Africa, the rainfall amount decrease has dramatic consequences on the hydric resources. The today annual precipitation does not permit any “efficient” recharge of groundwaters. That is the case in the Dakar agricultural bottom-lands which are depressions located in the sand dunes. The main characteristic of these lands is that the top-table quaternary sand groundwater (Nappe des Sables Quaternaires or NSQ) reaches or overflows the soil surface. Thereby, agricultural activities are based on irrigation using generally traditional farming practices; production supplying Dakar city in fruits and vegetables. Because of recent climatic crisis, the groundwater depletion threatens the agricultural activity on the long time.

Concerning strategies used to solve the surface water problems, some management practices existing in the African cities are matter of debate, more precisely in Sahalian zones. For example in the case of Dakar, rainwater management techniques are diverting waters toward the sea or evaporation basins. In a rainfall scarcity context, and with the possibility of storing drained waters in the sand dunes and reusing them for irrigation, this strategy leads to a loss of resource. This study aims to promote an innovating approach and technical measurements for increasing rainwater infiltrating volume feeding the NSQ groundwater, in order to reduce losses and enhance water availability. These measurements would allow to mitigate the current climate crisis and urbanization related constraints. This strategy is supported by the following hydrodynamic indicators 1/ the groundwater static level annual balance and 2/ the rainwater infiltrating rate variabilities. These parameters are calculated according to three pluviometric models -average, low and excess rainfall- representing the 80 last years rainfall variability.

INTRODUCTION

The site of this study, Dakar area, is located in the western central part of Senegal (figure 1a), between 17° 33' / 17° 05' West and 14° 55' / 14° 35 North coordinates. Climate is sahalian and pluviometric average is around 500mm. The term “niayes” is the local designation of the agricultural bottom-lands. These lands are depressions located in the sand dunes system where the top-table of quaternary sand groundwater

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(Nappe des Sables Quaternaires or NSQ) reaches or overflows the soil surface. These wetlands occupy a large surface in the area (figure 1a-1b). They are often exploited by traditional farming practices using irrigation, the production supplying the city of Dakar in fruits and vegetables. Farms in the "niayes" are specialized in market vegetable gardening [cabbages, carrots, salads, onions and tomatoes (figure 1c)], and fruit production [mainly mangos, papaws, oranges, mandarins (figure 1d)]. Urban and peri-urban agriculture has been on the rise and is now estimated to provide 60% -some 39.000 tons annually- of Dakar's consumption of vegetables.

Nowadays, the bottom-lands groundwater depletion, related to rainfall insufficiency, causes more and more constraints on irrigation and threatens traditional agriculture on the long time. The ecosystem of the "niayes" are relicts formed during quaternary wet climate, and it is in dephasing with the current pluviometric conditions, their preservation is an important issue in the region. The goal of this paper is to propose, in an urban and peri-urban context, an innovating approach and technical measurements enhancing groundwater availability in order to mitigate related water problems.

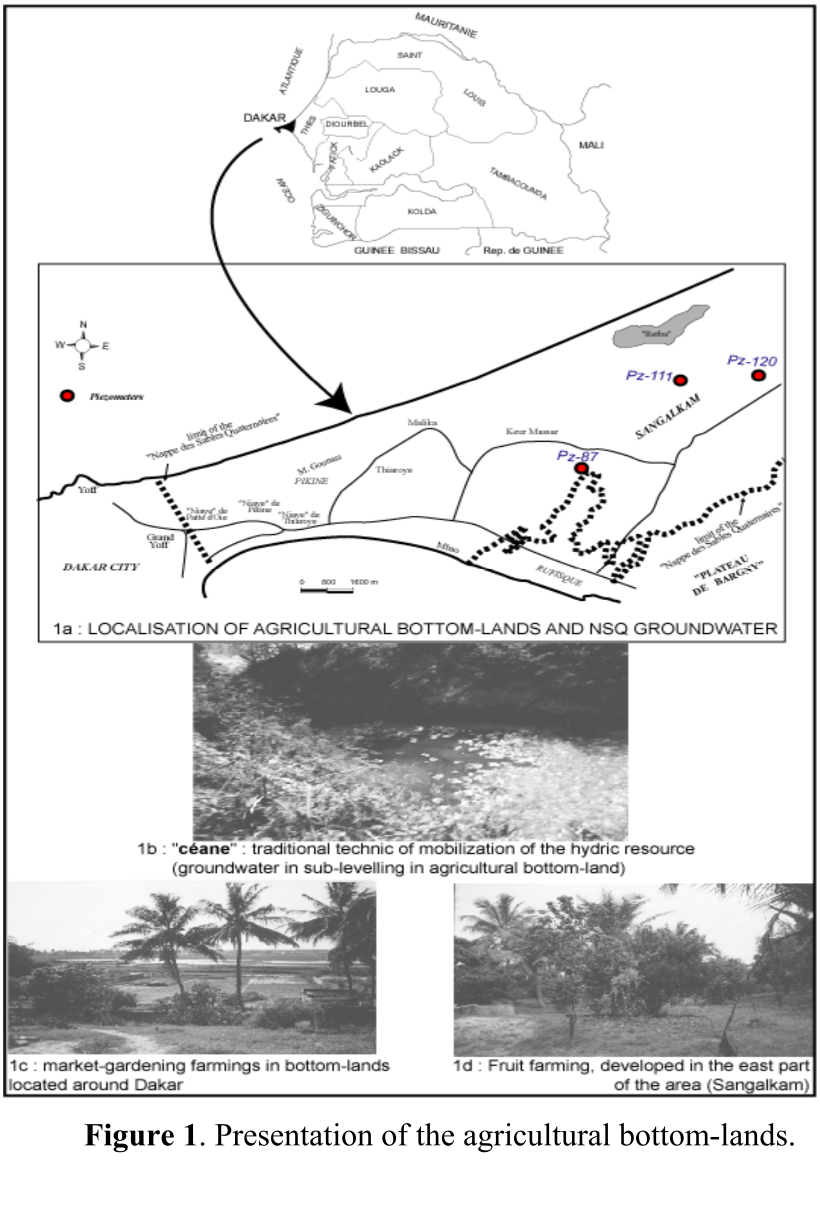


Figure 1. Presentation of the agricultural bottom-lands.

RELATED ISSUES AT THE WATER RESOURCE IN THE AGRICULTURAL BOTTOM-LANDS

THE CURRENT CLIMATIC CRISIS AS A MAIN CONSTRAINT

For a better evaluating of the climatic threats upon the hydric resources, the relative share of components of NSQ groundwater annual hydric balance will be specified. Reference data are the annual average hydric balance (from 1972 to 1984) calculated by Béture Sétame (1988). On figure 2, results (originally in m^3 j^{-1}) are converted into precipitation equivalent by the formula: 1 litter / m^2 = 1 mm.

It is interesting to note that rains are the only “inputs”, and hence precipitation variability has determining impacts on the recharge, i.e. on the “natural” evolution of the resource. Concerning “outputs”, referring to Béture Sétame assessment, the relative shares of following factors are:

- natural outputs (Etr + losses to the sea) = 72,3%,
- anthropic withdrawals (Agriculture + Urban water supply) = 27,7%.

The NSQ level piezometric variation equation is:

$$\Delta_r = P - (Q_{sea} + Et + Q_a)$$

with: Δ_r = Reserve variation (= Piezometric level evolution or Resource evolution); P = Precipitations; Q_{sea} = losses to the sea; Et = Evapotranspiration; Q_a = Anthropic withdrawals

Given that rainfall as the only “input”, its variability of the last 80 years focuses our attention. The evolution trend of annual precipitations shows a net difference since 1969. Before this date, the annual precipitation amount of Dakar area was relatively abundant, with an average close to 574 mm. Since 1969, a persistent rainfall crisis occurs in the area (Dasylva, 2001): the interannual average dropping down to 342 mm

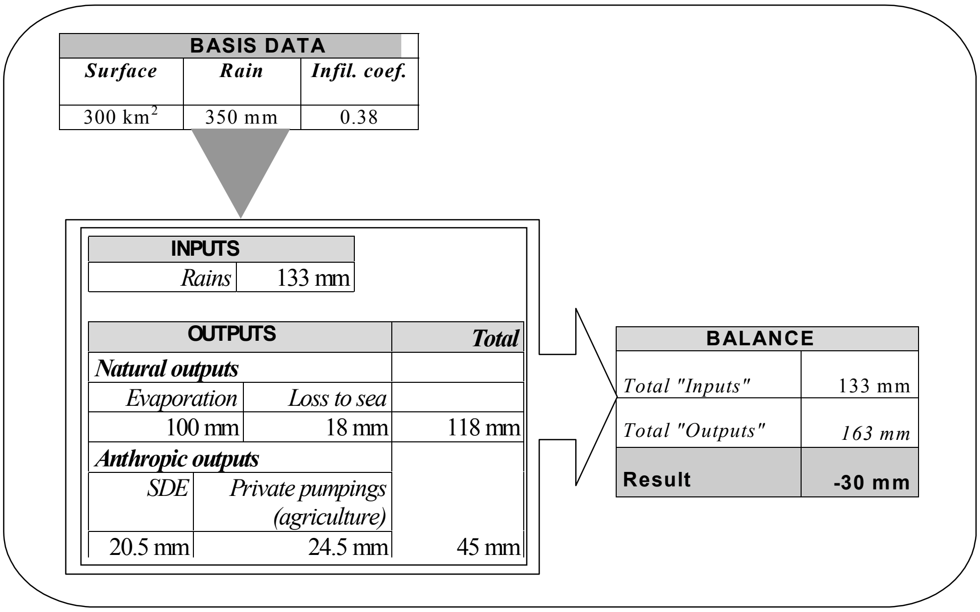


Figure 2. The annual average values of the NSQ groundwater hydric balance, from 1972 to 1984 (Béture Sétame, 1988)

(figure 3). The annual average rainfall deficit of this post-1969 dry phase is 231 mm (i.e. 40% of the previous average amount). If we refer to the drought threshold defined by Durand (1988), i.e. 20% deficit, the climatic crisis prevailing in the area is very severe and has negative consequences on the groundwater recharge (figure 4). In relationship at this water shortage context, it is important, 1/ to specify the impacts on the hydric resources in the region, and 2/ to promote technical measurements involving a better management of rainwater. It is a challenge to improve water availabilities for irrigation and water drinking activities, by enhancing groundwater recharge. The evolution of the SdE pumping volumes is a supplementary proof element of the water shortage context. SdE –Sénégalaise des Eaux- is a private company in charge of exploitation of the resources and the distribution of the drinking water. In relationship of hydrodynamical condition variations, in part related to climate change (Dasylva & Cosandey, 2006), the pumping volumes drop continuously: the maximum threshold passed from 15000 m^3j^{-1} in 1952 to 8000 m^3j^{-1} currently.

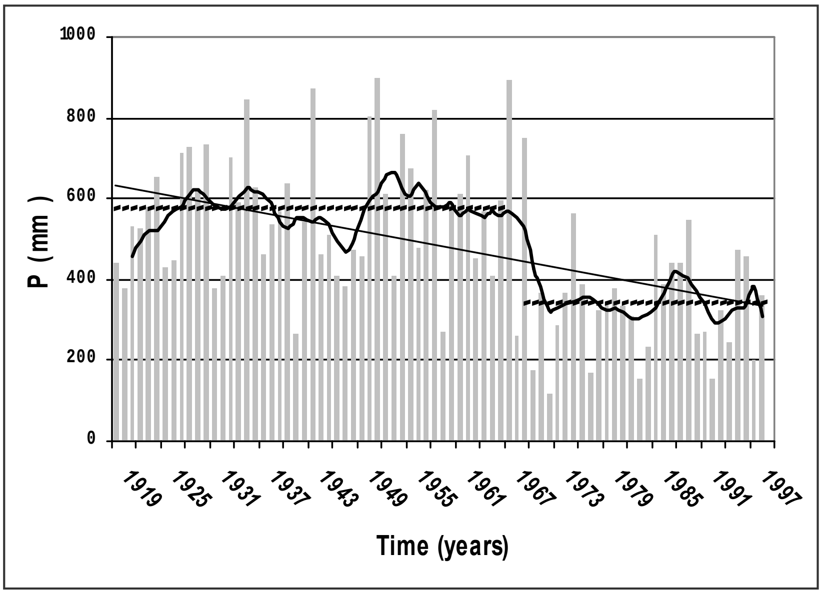


Figure 3. Rainfall evolution trends at “Dakar-Yoff” station, from 1919 to 1998.

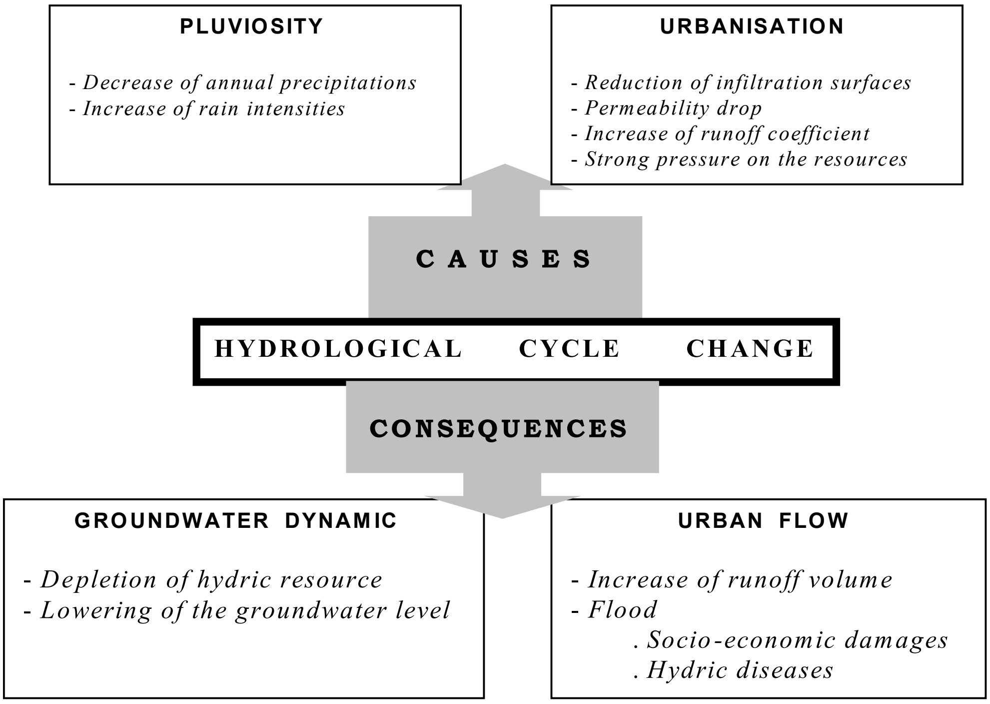


Figure 4. Factors and impacts of the hydrological cycle change.

IMPACTS OF THE URBANISATION ON THE HYDRODYNAMICAL CONDITIONS

Dakar area is characterized by a dramatic social pressure on the environment due to high population number (2.9 million in 2001) on a reduced surface (550 km^2). Moreover, land occupation without official authorization complicates the situation: lands are urbanized out of any control by official town-planning, mainly by poor populations. As a consequence, related constraints at the urbanisation are triple: 1/ strong pressure on the lands and the hydric resources, 2/ infiltration surfaces reduction and 3/ permeability drop of soil superior horizon (figure 4). The two last factors are leading to a decrease of infiltrating rainwater volume feeding the groundwater and an increase of runoff. Our previous studies showed that the infiltrating rate is higher in sectors the least urbanized -the eastern part of the region (Sangalkam)- compared to the sectors with strong urban pressure -zones located around Dakar- (Dasylva *et al*, 2004). However, in the perspective for promoting a participative rainwater management policy, it is necessary to find infrastructures adapted at this urban environment, and which could be appropriated by populations and local authorities. In this way, alternative technologies of rainwater management are the focal point of investigations; they are rarely used in Africa.

THREATS ON THE TRADITIONAL WATER RESOURCE MOBILIZATION TECHNIQUES

Agricultural bottom-lands are mainly located in the eastern part of the peninsula head (suburbs of Dakar city) in zones where urban density is very high. Near the city, the strong urban pressure on the environment implies that the size of farms is rather small. Farmers often use traditional techniques, designated by the vernacular term of "*céanes*" (excavations in the ground, reaching sometimes 2 meters depth, with an access path) for mobilizing the groundwater resource (figure 1b). An essential performance parameter of this traditional technique is that the top-level of the groundwater should not be far from the soil surface. However, recent climate evolution involves a continuous decrease of groundwaters top-table (figure 4), increasingly compromising the traditional agricultural activity performance. To preserve this activity, new technical measurements are necessary for mitigating the groundwater dropping process, and for maintaining its depth on an acceptable level. Eastward from Dakar city, in peri-urban zones where urban pressure is less heavy, the farm size becomes larger. Modern infrastructures of water resource mobilization (drillings and wells) are used to face anthropic water request. In the context of groundwater level drop, these infrastructures are a possible alternative to the traditional "*céanes*". But, the financial sizable cost is a limiting factor for farmers having low income.

The underlined issues in these paragraphs are as many parameters justifying the urgency of developing a sustainable water management policy in the region. Technological solutions should integrate both "resource/risk" dimensions of rainwater. That means they should have a double goal: enhance groundwater availabilities by increasing the rainwater infiltrating volumes and mitigate the flood problems. Two hydrodynamical variables of the NSQ groundwater -"recharge" and "rainwater infiltrating rate"- will be studied to illustrate possibility of improving the management of rainwater. Their evolution according to pluviosity variability provides responses elements of the groundwater reaction at the change of hydrodynamic conditions. Thereby, they are key elements for the understanding and the solution of the groundwater depletion problems.

DETERMINATION OF INDICATORS SUPPORTING A SUSTAINABLE GROUNDWATER MANAGEMENT: "*recharge" and "rainwater infiltrating rate" variabilities*

METHODODOLOGY

The "recharge" and the "rainwater infiltrating rate" are analyzed through the volume of infiltrating rainwater reaching the groundwater, symbolized by the variation of the groundwater altitude level. In our previous studies (Dasylva, 2001), piezometric data concerning the NSQ groundwater -from 1953 to 1992- were used to study the groundwater behaviour. However, available data are monthly, corresponding at the measurements of one day or a few consecutive days. Consequently, the groundwater behaviour can be studied only on a monthly scale. In this paper, piezometers Pz 87 (or n° 87), Pz 111 (or n° 111) and Pz 120 (or n° 120) are selected for measuring rainwater volume feeding the groundwater. They are localised in the eastern part of the area (*cf.*

figure 1) and they are representative of groundwater behaviour variability in this zone. Their functioning is considered as "natural" because it responds to rainfall variability and not to SdE pumping and saline water intrusions (Dasylva *et al*, 2003).

For measuring the variation of groundwater top-level, in order to determinate the volume of infiltrating rainwater feeding the groundwater, our method uses the MVSL - monthly variation of the static level- (table 1) or the net values of the groundwater altitude (GA) change between two consecutive months. This variation is positive or negative in relationship with the interactions between the hydric balance components. The method allows us to determine the characteristics of the hydrological year, i.e. to identify its duration and both recharge and discharge periods (figure 5a). The recurrence of monthly volumes of infiltrating rainwater are represented by the positive variation of the static level. The cumul of all MVSL values is carried out on the CMVSL (cumulated monthly variation of static level) column (table 1): the results gives directly the net values of variation of the hydric resource in the time (figure 5b). The maximum level of the variation represents the net values of "recharge" generated by infiltrating rainwater. The minimum level indicates the final budget of the stock during the hydrological year. The balance is positive when the final budget is above zero and is negative when the final budget is below zero.

This method is a mean to solve the problems of groundwater altitude heterogeneities and to be able to compare all sites on similar bases: the hydrological year starting is fixed at zero for all piezometers (red line). In irrigation, the CMVSL method provides data on the hydric resource temporal variation (figure 5b), more precisely the starting (1), height (2), duration (3) and end (4) of the rainwater inputs, and the final budget (5).

The approach is original in comparison to most of the previous researches in this zone, realized by hydrogeologists which were only focused on the hydrogeological characteristics, delivering results in volume -m^3- [(Anonyme, 1963); (Béture-Sétame, 1988); (Fohlen & Melka, 1989); (Gaye *et al*, 1977 and 1998); (Géohydraulique, 1972); (Henri, 1921 & 1922); (Martin, 1969 & 1970); (OMS, 1972); (Tandia, 1993 & 1997)]. These researches do not take into consideration the hydrological relations between the groundwater and the "niayes" or agricultural bottom-lands.

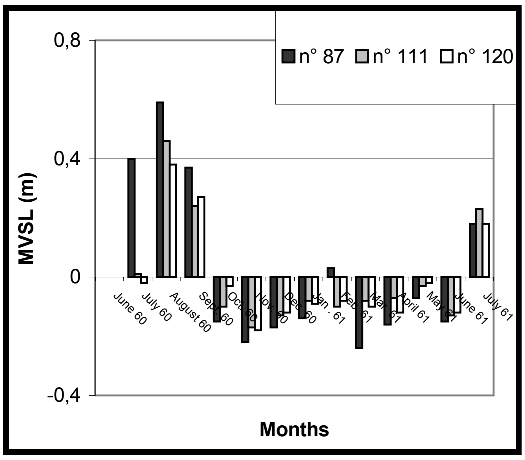


Figure 5a. Representation of the monthly variation of the static level (MVSL).

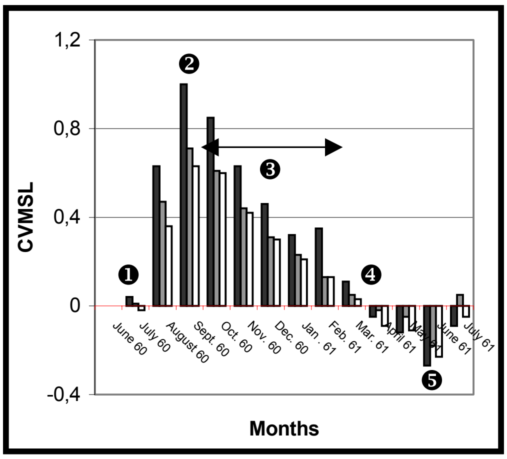


Figure 5b. Representation of the cumulated monthly variation of the static level (CMVSL).

G MOIS	n° 87			n° 111			n° 120		
	GA (in m)	MVSL (in m)	CMVSL (in m)	GA (in m)	MVSL (in m)	CMVSL (in m)	GA (in m)	MVSL (in m)	CMVSL (in m)
June 60	10,57	0	0	2,97	0	0	4,62	0	0
July 60	10,61	+0,04	0,04	2,98	+0,01	0,01	4,6	-0,02	-0,02
August 60	11,2	+0,59	0,63	3,44	+0,46	0,47	4,98	+0,38	0,36
Sept. 60	11,57	+0,37	1	3,68	+0,24	0,71	5,25	+0,27	0,63
Oct. -60	11,42	-0,15	0,85	3,58	-0,1	0,61	5,22	-0,03	0,6
Nov. 60	11,2	-0,22	0,63	3,41	-0,17	0,44	5,04	-0,18	0,42
Dec. 60	11,03	-0,17	0,46	3,28	-0,13	0,31	4,92	-0,12	0,3
Jan. 61	10,89	-0,14	0,32	3,2	-0,08	0,23	4,83	-0,09	0,21
Feb. 61	10,92	+0,03	0,35	3,1	-0,1	0,13	4,75	-0,08	0,13
Marsh 61	10,68	-0,24	0,11	3,02	-0,08	0,05	4,65	-0,1	0,03
April 61	10,52	-0,16	-0,05	2,95	-0,07	-0,02	4,53	-0,12	-0,09
May 61	10,45	-0,07	-0,12	2,92	-0,03	-0,05	4,51	-0,02	-0,11
June 61	10,3	-0,15	-0,27	2,79	-0,13	-0,18	4,39	-0,12	-0,23
July 61	10,48	0,18	-0,09	3,02	0,23	0,05	4,57	0,18	-0,05

A = groundwater altitude
MVSL = monthly variation of the static level
CMVSL = cumulated monthly variation of the static level

Table 1. Method for calculating the groundwater reaction under the impulse of infiltrating rainwater.

The CMVSL method used in this paper makes it possible to determine the relationship with the bottom-lands functioning. It presents one disadvantage: results apply to monthly average and not to daily value.

In relation to the characteristics of precipitations, infiltrating rainwater volume reaching the groundwater is calculated according to three annual pluviometric models : 1) annual rainfall (529 mm) close to the regional average (484 mm) ; 2) annual rainfall on excess (10 years recurrence : 712 mm) ; and 3) insufficient annual rainfall (20 years recurrence : 220 mm). These precipitation data are the annual values recorded respectively in 1960, 1969 and 1970. They are representative of interannual pluviosity variability of the last 80 years and they have monthly piezometric data available.

RESULTS

RECHARGE AND INFILTRATING RAINWATER RATE

The recharge corresponds at the maximum level of the CMVSL (figure 6). Results are indicated in table 2: values in meters (m) represent the height variation of the groundwater static level in the aquifer, and values in millimeters represent this variation in equivalent precipitation height. This latter calculation is based on 0.15 porosity value in sand dunes (Béture-Sétame, 1988). The initiation of the recharge shows that the groundwater responds rapidly at pluviometric impulses because the level is near from the soil surface in the bottom-lands and the soil permeability is strong (Dasylva *et al*, 2003). The main information shown by theses results is that the evolution of both recharge and pluviosity phenomena is quantitatively dependent: the average height of the recharge is in direct dependence of rainfall variability (table 2).

The infiltrating rainwater rate (or share of precipitation volumes reaching the groundwater) is the ratio 'Volume of the recharge'/'Annual precipitation amount'. The results also illustrate a variability dependent on the sites location and on the annual precipitation amounts. The estimated averages values are 9, 22.5 and 30.5 %, respectively for low, normal and excess years (table 3). Like for the recharge, it is logical to observe a link between variabilities of infiltrating rainwater rate and precipitation amount. More the infiltrating water potential (precipitation amount) is high, better is the groundwater recharge (infiltrating rate). This indicator is a fundamental element of the rainwater management strategy proposed in this paper.

RELATION INFILTRATING RAINWATER VOLUME CHANGES / FINAL BUDGET OF GROUNDWATER LEVEL BALANCE

First, it is important to note on figure 6a and 6c, in spite of variability of the recharge, the budget at the end of the hydrological year is almost identical for all piezometers. This phenomenon is caused by the static level rebalancing process: this parallelism between responses indicates that the piezometers selected are representative of the global groundwater behaviour in this zone.

Impacts of infiltrating rainwater volume changes on the final budget of the static level balance are indicated by the CMVSL level variability at the end of the hydrologic year. By referring on figure 6, results give negative values in two annual pluviometric scenarios: dry and average years (figure 6a, 6b). This means that infiltrating rainwater are insufficient to ensure an effective recharge of the groundwater, which would allow facing at the climatic and anthropic requests. Reversely, the budget is positive when the annual precipitation amount reaches 700 mm: thus, a wet pluviosity of decennial recurrence is necessary to recharge positively the groundwater (figure 6c).

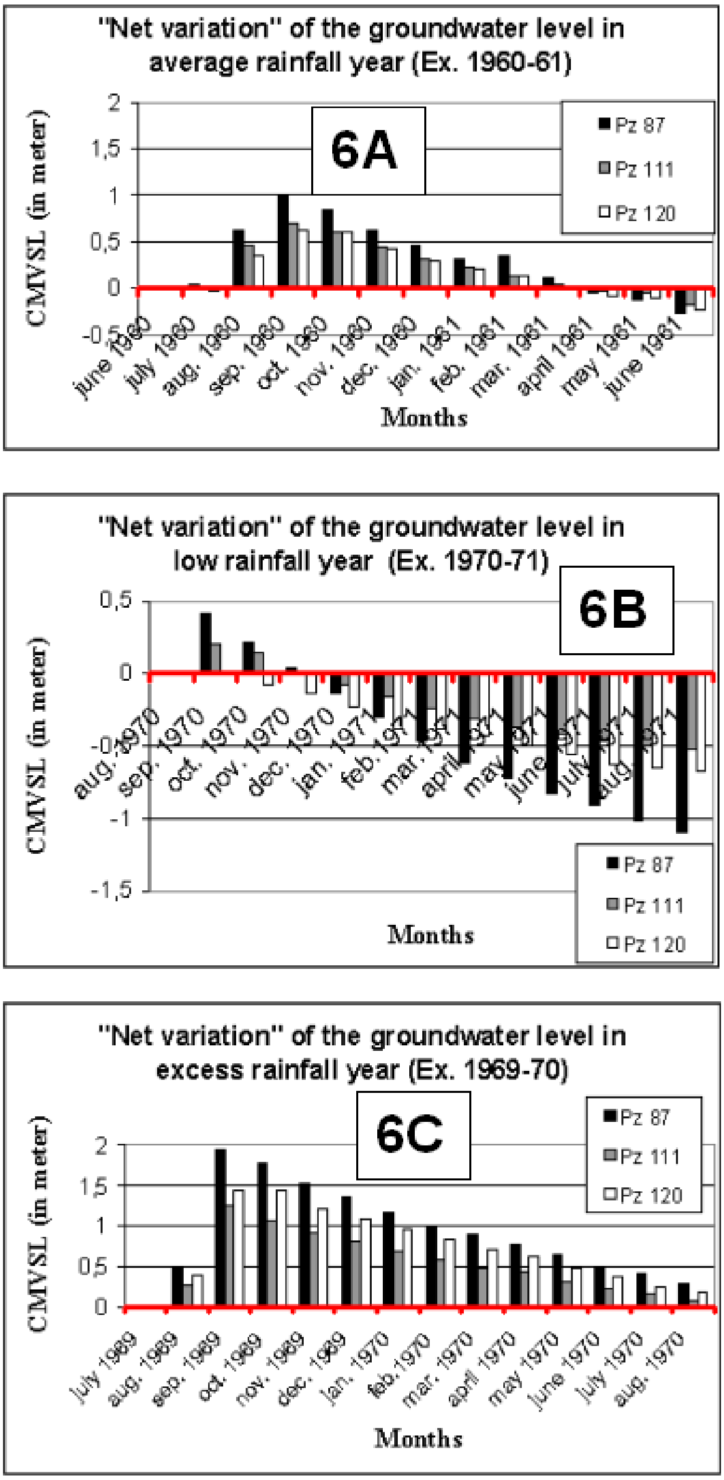


Figure 6. The net values of hydric resource variation according to annual precipitation amount variabilities.

Rainfall values	*n° 87*		*n° 111*		*n° 120*		*Average*	
	m*	mm**	m	mm	m	mm	m	mm
P = 529mm	1	150	0.71	106	0.63	94	0.78	116
P = 712mm	1.93	290	1.25	187	1.44	216	1.54	231
P = 220mm	0.41	61.5	0.21	31.5	0	0	0.2	31

*= net values of cumulated monthly variation of static level in the aquifer during the recharging phase
**= height equivalent of the variation by comparison to precipitations

Table 2. Estimate of recharge net values in three rainfall scenarios.

Rainfall values	*n° 87*	*n° 111*	*n° 120*	*Average*
P = 529 mm	29,4%	19,6%	18,4%	22,5%
P = 712 mm	38,4%	24,8%	28,3%	30,5%
P = 220 mm	18%	10%	0%	9%

Table 3. Estimate of the infiltrating rainwater rate reaching the groundwater according to rainfall variability.

Currently, pluviometric context is characterized by annual precipitation amounts close in best cases to the regional average; consequently the NSQ groundwater is not being refilled sufficiently. This unfavourable context is leading to processes of declining of NSQ water table and drying of the agricultural bottom-lands. Coastal zones are not concerned by the lowering of the groundwater table, since groundwater table level is about the same as that of the sea (Dasylva *et al*, 2003).

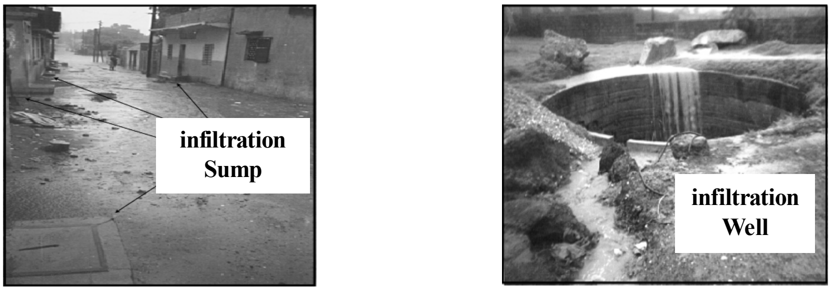
DISCUSSION: RAINWATER EFFICIENT MANAGEMENT / GROUNDWATER AVAILABILITIES INCREASE

As outlined above, any rainfall increase seems nowadays hypothetical, given the low rainfall recorded for the last 30 years. Therefore the "efficient" recharge is not and probably will not be occurring in the near future. Then, alternative solutions may emerge to improve runoff management. However, a sustainable rainwater management policy implies to implement actions will have positive impacts on both groundwater behaviour and rainwater drainage network performance. Furthermore the runoff volume increase, the inefficiency of solutions is also due to the reduction of the transfer capacity of drainage network. This dysfunction is caused by the decantation of the solid load contained in the flows. Concerning strategies used to solve the surface water problems, some management practices existing in the African cities (more precisely in Sahalian zone) are matter of debate (Dasylva *et al*, 2002). In the case of Dakar, rainwater management "classical" systems evacuate drained waters (more and more important) toward the sea and/or evaporation basins; in a rainwater scarcity context, and with the possibility of storing water in the sand dunes, this strategy leads to a loss of resource (Dasylva *et al*, 2004a). Rainwater must not be considered as a harmful element but a resource. In an international context where researchers are increasingly determined to find adaptive solutions to the climatic change, a sustainable management of water resources constitutes a strong recommendation.

A better management of runoff is necessary and possible. This viewpoint is showed by the groundwater dynamic changing according to rainfall variability and the water management technique and policy problems. In relationship with the problematic of this paper, the challenge is to find alternative solutions to improve water availabilities (i.e. the groundwater recharge)- exploited by the irrigation and other activities. Technological measurements will have the objective of maximizing the infiltrating water volume in the dune sands. By transferring water from risk zones (urbanized area) toward milieus allowing a positive use (groundwater aquifer), this prospect is a mean to produce safe supplementary (or unpolluted) hydric resource for irrigation. Then, rainwater harvesting policy are interesting perspectives. Research in Africa showed that runoff can constitute a complementary hydric resource [(Valet & Sarr 1999); (Lamachère & Serpantié 1990)]. In the case of Dakar agricultural bottom-lands, the increasing of the infiltrating rainwater rate by artificial means is the most evident factor that would

a better replenishment of the NSQ groundwater. The groundwater level decrease in the "niayes" in an average pluviosity context, could be stopped by increasing the infiltrating rate of the rainfall to 50% (Dasylva *et al*, 2004b). An efficient management of surface water requires an intervention in the upstream zones by using rainwater harvesting technologies allowing an infiltration and storage of water in the dune sands reservoir. Goals are to decrease the runoff volume (for mitigating the flood problems) and enhance the groundwater recharge (for reducing the losses due both by direct evaporation and the diverting of rainwater to the sea). Being in urban and peri-urban contexts, "habitats" and "streets" would be the prime spatial reference units, i.e. the firsts level of intervention. Technical issue is to find the infrastructures adapted at these sites. By referring at local practices, sumps and wells -only intended to rainwater- are technologies selected to increase the infiltrating rainwater rate, respectively installed in the concessions and the streets (figure 7). To strengthen the rainwater drainage network, a massive use of these techniques -classified in the alternative technologies of rainwater management (S.T.U., 1989; Chaïb J., 1997) is suggested. The local population knowledge is an advantage to facilitate the appropriation. Feed backs on water management show that the success and the duration of solutions needs to imply local communities in the process. Moreover, in relationship with the limits of the rainwater drainage network functioning and the insufficiency of means mobilized by official services, a correction of the current system in a participative way, integrating various stakeholders, is necessary. Today, it is a challenge of increasing numerically the infrastructures and implying the population in the maintenance.

However, this artificial recharging must be "controlled" in order to limit the contamination of the groundwater by infiltrating water from polluted zones, for example the household refuse discharges [(Tandia *et al*, 1997); (Tandia, 1993); (Collin & Salem, 1989); (Gaye *et al*, 1977)].



Sumps: used on this photo –"Grand Yoff" district- to infiltrate domestic waters
Well: used on this photo –"Technopole" site- to infiltrate runoff

Figure 7. Local practices as regard wastewater and rainwater management techniques.

CONCLUSION

For coping with the sensitive problem of the water scarcity in Sahalian zones, an alternative solution is to manage better the runoff for improving water resource availability, in addition to benefits which would be produced by a rational use. For this purpose, our paper suggests to implement a new strategy based on rainwater harvesting systems for storing water in the dune sands reservoir. By taking in consideration urban and peri-urban contexts and in accordance with water management practices used in Dakar, rainwater infiltrating technologies leading to a participative management are suggested; elsewhere they should be selected by referring to the local techniques. Beyond technical measurements, the benefit to consolidate and to promote is the scientific approach used to determine issues and solutions for improving the rainwater management efficiency. The strategy –increasing rainwater infiltration rate toward sand dunes reservoir by proximity water absorbing infrastructures- derives from a four "step-study", illustrated on figure 8. In the three first steps, salient issues of the region are defined by taking into consideration the interactions between physical and social environments and the water management practices. The underground storage choice is determined by 1) the possibility of reusing infiltrated waters, and 2) the necessity to preserve water resources from climatic request or evapotranspiration.

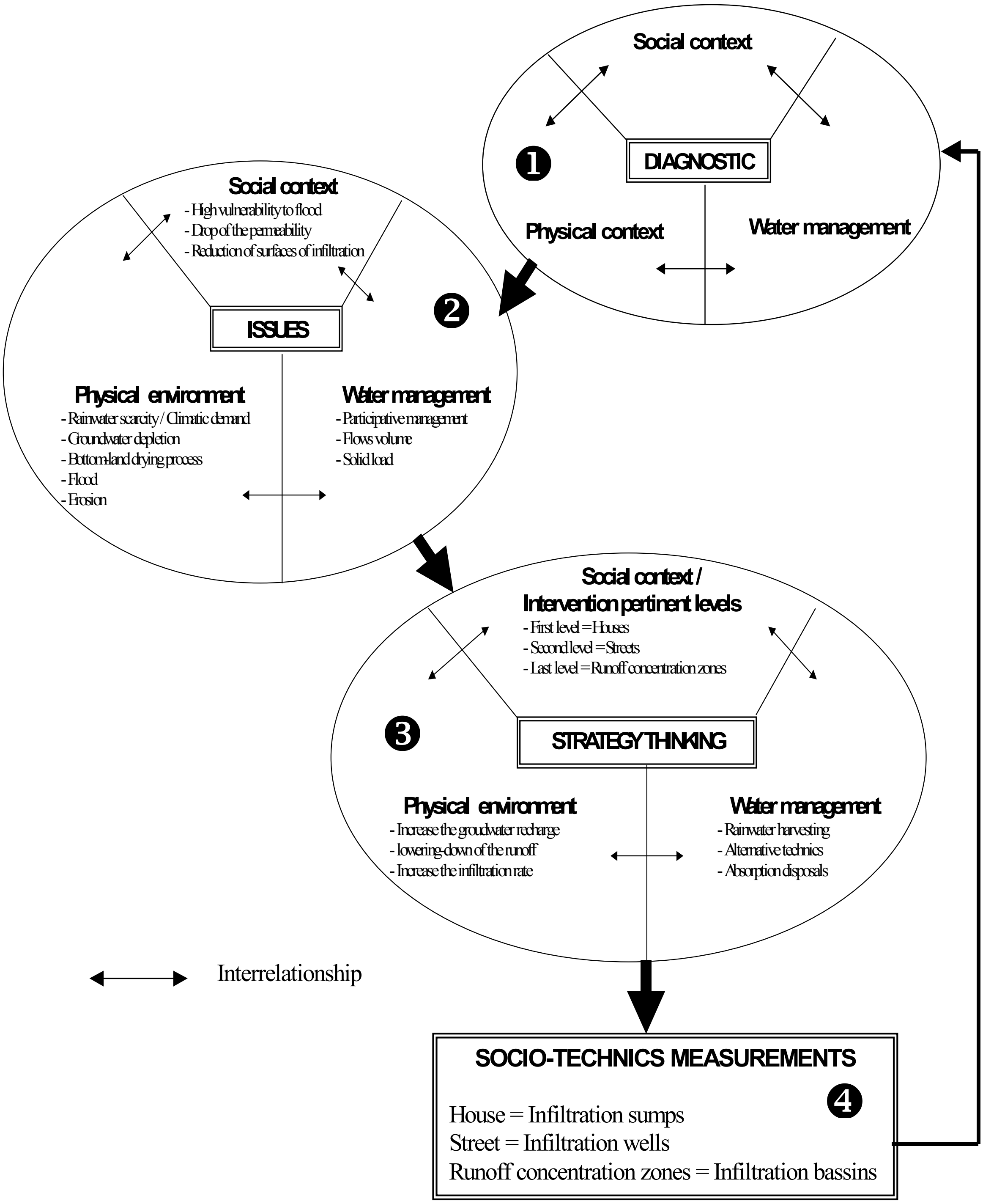


Figure 8. Strategy building process of a sustainable rainwater management applied to Dakar region.

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