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Monitoring soil salinity in irrigation schemes by the use of remote sensing and GIS

Study case : Fordwah irrigation scheme - Pakistan

A brief synthesis of the final version in French

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Introduction

1. Salinity monitoring in irrigation schemes

Soil salinity is nowadays a serious problem that concerns the majority of irrigation schemes in arid zones. It seems very important to detect this problem in order to come through the appropriate solutions before further soil degradation.

Salinity dynamic depends on the context : Whenever salinity is linked to natural phenomena, it comes very slowly through time. But it comes very quickly when man interferes : soil salinity appears in some irrigation schemes 10 to 50 years following their installation.

The utility of soil salinity monitoring in time and space depends upon the objective of the demander of this study. Our study is done as part of a research program of irrigation schemes management. But salinity evaluation is done through salinity indicators at time of observation.

2. Framework of this study

IIMI-Pakistan and CEMAGREF are working on a collaborative research program about the management of irrigation schemes. The impact of irrigation on soil salinity is one part of this program. Its objective is to identify possible improvements in irrigation management that could lead to prevention of further deterioration. So IIMI confines its research to areas where salinity and sodicity levels are still relatively low.

One of the research areas of this program deals with monitoring soil salinity through the use of GIS and remote sensing. GIS is a powerful tool that can be used to process large data bases and to visualise processed information. Then it can be coupled with scientific models to be used as a decision support tool. The sources of the data that supply a GIS system are field data, physical measurements, laboratory analyses and remote sensing images.

3. Objective of this study and methodology applied

The purpose of our research is to test the usefulness of remote sensing data on one of IIMI's research areas, in the Indus Plain of Pakistan, near the Sutlej river : Chistian Subdivision, Fordwah irrigation system. The study is carried out at the watercourse scale (tertiary level). We have selected eight watercourses : four from Azim and four from Fordwah distributaries (azim 20, azim 43, azim 63, azim 111, fordwah 14, fordwah 46, fordwah 62 and fordwah 130), where IIMI has collected data since 1991.

The final report (French version) contains three parts :

- In the first part, we have presented a literature review of past studies made to identify soil salinity through chemical indicators, salinity indications on soils and plants and studies made to characterise spatial soil salinity through GIS and remote sensing. We have also presented Fordwah system, the problem of soil salinity and sodicity in Fordwah as well as in Pakistan in general and actual field methodology used in Pakistan to characterise spatially salinity.
- The second part deals with three approaches established to describe soil salinity in Fordwah system through the use of SPOT satellite images. The results obtained are discussed in this part.
- Finally, the third part shows the perspectives of the subject in general.

This document is a brief summary of the final report written in French, some references are relative to figures in that report.

Part I : Literature review and presentation of the study case

1. Literature review

1.1. Characterisation of soil salinity

Soil salinity is a frequent problem in irrigation schemes. It represents three kinds of problems :
- toxicity : presence of particular ions in sufficient quantities to be considered toxic for plants,
- salinity : presence of excessive quantities of salt in soils, which causes hydric stress on plants and inhibits their development
- sodicity : presence of sodium quantities in excess comparing to calcium quantities.

Our study deals essentially with the last two types of salinity.

These problems are characterised by quantitative chemical indicators. The concentration of salts or of specific ions in the soil water characterises the presence of these salts so it can be compared to toxicity threshold values. The electrical conductivity (EC) is an indicator of soil salinity. The ESP (Exchangeable Sodium Percentage), as well as the SAR (Sodium Adsorption Ratio) are indicators of soil sodicity.

Visual indications could be detected on soil and on plants. Soils could be covered by salt crust or black crust in the case of high sodicity (black salinity). The development of the plants, their height, their density could be modified in the presence of salts. Specific symptoms to soil salinity, such as foliar burns, could affect specific plants. In general, these indicators appears at a certain period of the plant life.

1.2. Past experiments in remote sensing

Laboratory experiments focused on the sensitivity of sensors to the presence of salts in soil samples. Aeroplanes experiments dealt with optical and radar sensors on experimental fields while satellite images dealt essentially with studies on irrigation schemes with optical sensors : the American satellite Landsat , the French satellite SPOT and the Indian satellite IRS[1].
Bands in the visible spectrum give information about the soil reflectance while the NIR (near infrared) band informs about the health of the crop. The MIR (mid infra red) and the TRI (thermal infra red) inform about moisture in soil and in plants and the surface temperature so the stress hydric for example. The radar waves are sensitive to soils surface permittivity which is sensitive to salt presence.

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[1]Specific characteristics of these sensors :

	size (km^2)	repetitivity (days)	resolution (m)	bands
IRS			72.5 - 36.26	4 (B, G, R, NIR)
LANDSAT Landsat TM	185 *185 same	16 same	80 30 and 120 (IRT)	4 7 (B, G, R, NIR, MIR, TIR, MIR)
SPOT XS SPOT Panchromatic	60 * 60	26	20 10	3 (B, G, R) 1 (Pan)

B = Blue, G = Green, R = Red, NIR = Near Infra Red, MIR = Mean Infra Red, TIR = Thermal Infra Red

Detection of salinity problems is possible through the detection of its direct effects on soils and plants and through its indirect effects such as the appearance of halophytes, soil moisture... Combination of data from different bands is interesting to obtain information on soils as well as on crops. Multitemporal studies are interesting to monitor the dynamic of salinity and to detect salinity in the best conditions (best solar reflections or the period when maximum of salinity appears on top surface). There has been a little use of GIS in past experiments.

2. Study case

2.1. Location

The Chistian subdivision is located in South East Punjab, at a distance of 350 km South West of Lahore and is bounded by the Sutlej River in North West and the Cholistan Desert in the South. IIMI, International Irrigation Management Institute, has selected 8 watercourses to do researches on irrigation management and soil salinization. Four watercourses have been selected from Azim distributary at the Reduced Distance[2] 20610-L, 43260-L, 63620-L, 111770-L and four are from Fordwah distributary at RD 14320-R, 46725-R, 62085-R, 130100-R.
Both distributaries are on the left bank of the Sutlej River, running more or less parallel to the river. Azim is the nearest to the river. Azim and Fordwah distributaries are located in two different administrative Districts : Bahawalpur District and Bahawalnagar District.

2.2. Soil salinity in the study area

The comparison of the visual salinity classification maps of 1960 (WASID) and 1976 (WAPDA) shows that salinity has globally decreased. However, it seems that since canal water is supplemented by the use of groundwater of bad quality, salinity and sodicity are increasing in the area.
In general, salinity in this area is encountered in coarse textured soils and sodicity in medium and coarse textured soils. The soil salinity level is not important : it is a characteristic area where salinity appears in small patches and at low levels that farmers manage to control till now.

[2]Reduced Distance designates the distance from the head of the distributary till the outlet of the watercourse. Its unit is equivalent to 2000 feet (3218 km). The letters L (Left) or R (Right) that follows it designates the side river of the outlet.

Part II : Application on the study case

1. Data

For this study, we have used data collected by IIMI on the 8 watercourses mentioned before and SPOT satellite images.

1.1. Field data

The salinity data mainly used in this study are the salinity classification made in February 1995, by 4 field assistants of IIMI Hasilpur station, who visited all the acres of the sample watercourses. The fields were classified into 4 classes :

- S0 for non saline fields.
- S1 for slightly saline fields : small salinity patches are present in the field, crop stand is uneven, the salt patches do not cover more than 25% of the field as a whole.
- S2 for moderately saline fields : large salinity patches are present in the field (about 50% of the field). Crop stand is in patches.
- S3 for strongly saline fields : totally bare area without any crop. Some salt tolerant bushes may be present.

1.2. Satellite data

SPOT, Systeme Probatoire Observation de Terre, is a French satellite which has four bands in the optical spectrum : one panchromatic band (0.51-0.73 micron), three multispectral bands : one in the near-infrared (0.79-0.89 micron), one in the red (0.61-0.68 micron) and one in the green (0.50-0.59 micron). The panchromatic resolution is 10m while the multispectral ones are 20m. The panchromatic image is usually used for location, the multispectral bands are richer in information. SPOT images are often used for land classification.
The images were acquired over the study area in October 1994 and in March 1995. No rain has been registered at these periods.

1.3. Additional data

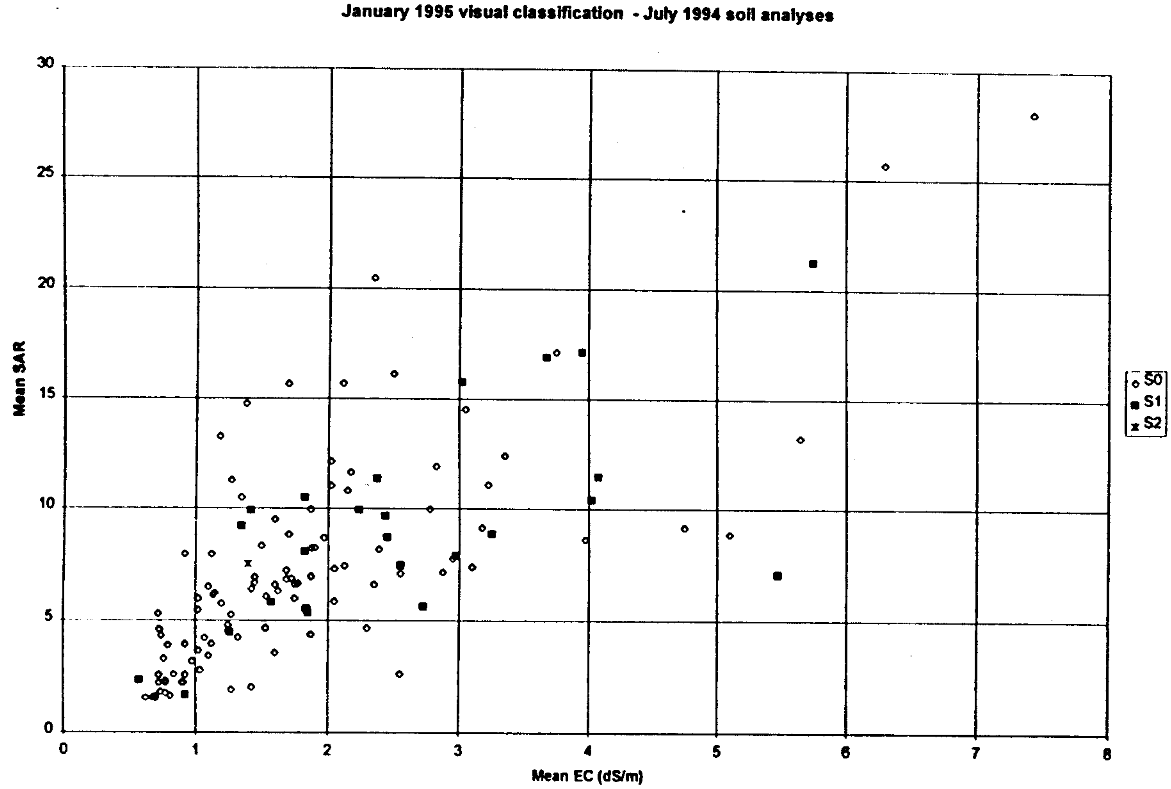
We have obtained from IIMI extra information about topography, water market and farms organisation, as well as soil salinity and sodicity analyses of 120 fields from 1991, 1992, and July 1994.

2. Data critical analysis

2.4.1. Data field and satellite data

The field data and satellite data were not registered at the same time, that is why we have limited the study to March image and visual soil salinity classification of January 1995.
A second problem is related to the size of the sampling fields. Each field is about 10 pixels, which is a problem for statistical processing. In addition, field crop coverage is frequently heterogeneous, especially in Fordwah, where farms are smaller than farms in Azim so farmers have to diversify in order to get through all their agricultural needs. When more than one crop is grown in a field, field data show the area of each crop but not their spatial distribution.

Finally, the visual classification has been done according to the visual manifestations of salinity on plants and on soil surface which are not always good indicators of salinity. In fact, we have compared, soil analysis of July 1994 with the visual classification of 1995 and obtained the following results :



Classification of non saline fields (EC < 4 dS/m and SAR < 13) as S1 or S2 could be related to confusions of salinity characteristics with some farming practises (for example hydric stress induced by insufficient irrigation).

This could be also related to the fact that field soil samples have been taken from different places in the field so they are representative of the mean field salinity status and do not focus on the presence of these isolated salinity patches.

Classification of saline fields into S0 class could be explained by the fact that we are in salinity ranges corresponding to a tangent domain where salinity could have an effect or not (see for example figure 2, the theoretical wheat yield curve : the wheat yield starts to be affected by salinity whenever EC is over 6 dS/m).

Finally, the visual classification has been done in beginning 1995 while soil analyses are relative to July 1994, the discordance between visual classification and soil analyses could be related to the evolution of salinity in time (see figure 29 showing the evolution of EC and SAR values of the sampling fields of Azim 63 in time).

2.4.2. Spatial data

Some problems have been encountered to use IIMI data in a GIS. Some data has not been collected for that purpose. This was the case of data collected about the use of tubewells : data are collected at the farm level but farms pattern changes every season and no clear reference

exists about the boundaries of these farms. Data collected on salinity since 1991 do not correspond to the same fields every year.
An other type of problems is due to a lack of precise data on soil and topography (at watercourses scale). We had to refer to our own analysis on the field through transects along watercourses.

3. Methodology

The location of the study area on the satellite images has been done by the use of a regular grid generated on all Chistian subdivision representing the fields pattern : the plain is divided in squared blocks, each block is divided into 16 squares (4*4) and each square is divided into 25 fields (5*5), all the fields have the same size (60*67 m). The boundaries of each watercourse have been digitised according to IIMI field maps.

3.1. Preliminary diagnostic of soil salinity status

If we only take into account the water management variable, there are at least three types of watercourses : watercourses which never receive canal water and use only tubewells water (Azim 111-L), watercourses which receive canal water during the summer season only (Azim 63), watercourses which receive canal water during all the year but farmers use tubewells water because canal water is insufficient (Fordwah 62). We have taken these three examples for our study.

We have compared the visual salinity map (per field) with other information layers, about :
- Space permanent characteristics : such as characteristics related to soil and topography, these information have been collected on the field along a transect made in each watercourse (see figures 30).
- Characteristics related to agricultural practises : proximity to tubewells of bad quality, position of the field in the watercourses, the farms pattern (see figures 31, 32).

3.2. Use of SPOT satellite images

3.2.1. Generation of two indices

The green and the red bands are significantly correlated. The red and the NIR layers have been replaced by two indices layers : the vegetation index (NDVI) and the brilliance index (BI). These classical indices have the advantage to show better dynamic than the raw bands.

$$NDVI = \frac{NIR - R}{NIR + R}$$

$$BI = \sqrt{R^2 + NIR^2}$$

3.2.2. Three approaches of the problem

a) Estimation of the indices mean value per field

The objective of this approach is to compare the mean radiometry/indices value of saline fields and that of non saline fields. Each field (killa) covers about 10 pixels of an XS SPOT image. The mean value has been extracted for the group of pixels contained in each killa. This operation is possible by the use of grid and statistical GIS functions : the killa grid has been cut into pixels of a resolution equivalent to SPOT resolution. The killa pixels grid has been superposed to the image. Indices values has been attributed to each killa pixels by the method of the nearest neighbour. Statistical function allows to get the mean and extreme values of the pixels indices inside a killa.

b) Reproduction of the visual classification principle

The second approach aims to reproduce the logic of the visual classification. Fields are divided into two categories : cultivated fields and non cultivated fields. For the first category, if the crop on cultivated field is in good health, the field is classified C0, otherwise if the soil is brilliant, the field is classified C2 otherwise it is classified C1. For the second category, if the field is covered for more than 50% by salt crust : it is classified C3 if the salt crust is very thick otherwise C2. If the salt crust is not very important, the field is classified C1 otherwise C0.
This classification has been translated in a algorithm taking into account the percentage of pixels below or beyond threshold values deduced by a study on 60% of the fields (of the 8 watercourses studied). These fields correspond to all fields that had homogeneous crop cover on their total surface.

c) Research of exogen information to help the imagery processing

The third approach aims to combine satellite images with exogen information and with the results of the preliminary salinity diagnostic. Two applications were identified :
- the use of October image : we can consider that the probability that a field is saline increases whenever it was not cultivated in the summer season
- the second application is to link pixels that have values in the same range in order to show up any salinity gradients linked to spatial distribution of salinity.

4. Computer software used

The digitising and processing operations : in CEMAGREF-ENGREF remote sensing laboratory, Montpellier France. The work has been done on :
- ERDAS-IMAGINE (IMAGINE station version) for the processing of satellite images
- the GIS ARC/INFO (station version)
- and the spreadsheet EXCEL.

5. Results

The distribution of pixels in the diagram BI-NDVI shows that the pixels position moves from high VI to low VI and from low BI to high BI whenever the salinity level increases. This could be easily seen whenever we compare S0 and S3 fields, the phenomena is less evident whenever we compare S0 and S1 fields (see figures 42 : representing the distribution of the pixels of non cultivated soils (barren and fallow) of S0 (figure 42.a), S1 (42.b), S2 (42.c) and S3 (42.d) categories and see figure 43 : representing the distribution of pixels of wheat fields of S0 (43.a) and S1 (43.b) categories).

The same results are found whenever we consider the mean value of the indices per field. S3 fields are apart from the rest of the fields (see figure 41). The third of the envelop[3] of S1 fields overlap the envelop of S0 fields (see figure 37 : example of S0 and S1 wheat fields), its second

[3] Envelop of a group of points : limit of the area containig the points of this group.

third correspond to low VI and BI values (domain I) and the rest of the envelop area correspond to low VI and high BI values (domain III).

The algorithm classification gives the following confusion matrix showing in columns the number of fields in the 4 visual salinity classes and in lines the 4 classes of the algorithm :

number of fields	S0	S1	S2	S3	TOTAL
C0	1766	365	59	7	2197
C1	307	130	45	21	503
C2	99	37	36	18	190
C3	7	10	22	76	115
TOTAL	2179	542	162	122	3005

%	S0	S1	S2	S3
C0	81	68	35	5
C1+C2+C3	19	32	65	95

Globally 72% of the fields are well classified in the grouped classes (C0 and C1+C2+C3).

The classification details per crop are as given in the following table :

crop	wheat	sugarcane	fodder	fallow	barren
% well classified	91	80	80	85	81

Whenever we take into account the cropping pattern of the previous season (on October image), the results are globally improved of 10%.

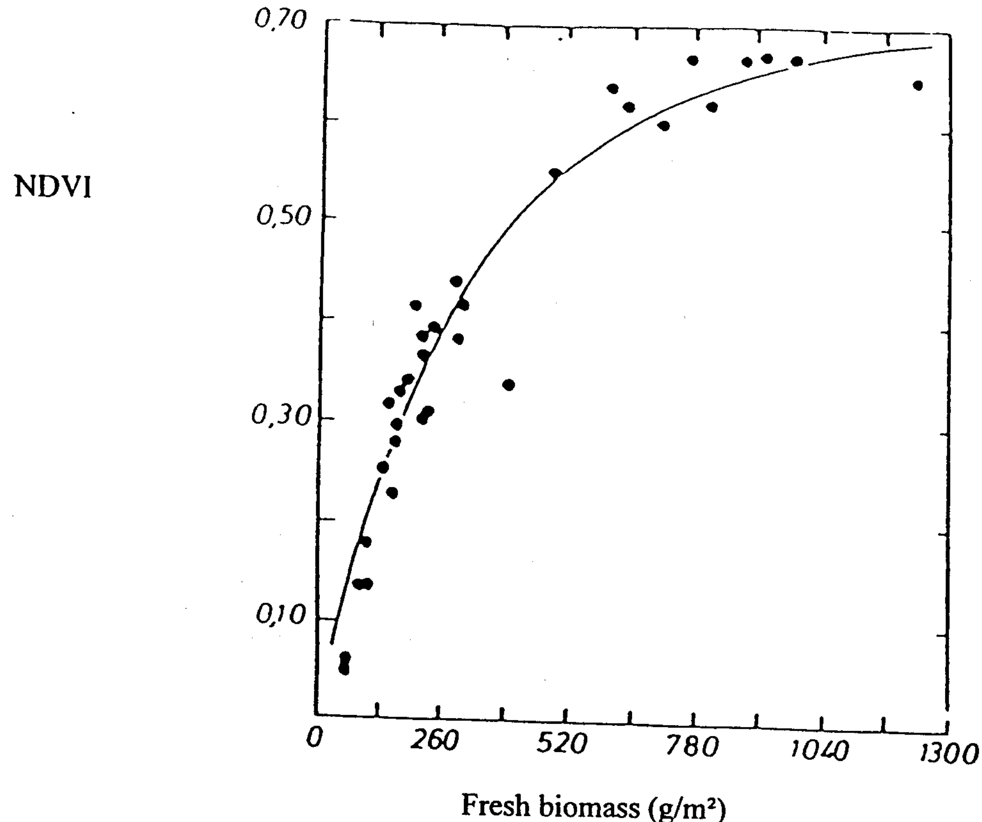
Finally, the isobrilliance method showed concentric gradients of brilliance in very saline areas : see figures of Azim 111 (figure 47), of Azim 20 (figure 48) and of Fordwah scheme (figure 49).

6. Interpretation

Soil salinity induce the apparition of salt crust and the decrease of crop density : this induces a decrease in vegetation index and an increase of soil brightness. These physical changes are detected by the type of sensors used in this study. The envelops curves is the best example : in the case of wheat, the domains I and III show that fields reflects less in a saline environment, as wheat is less dense, soils have an important weight in the brilliance index value : soils participation is not important whenever soils are dark or wet (domain I) but it is important whenever these soils are dry or brilliant (domain III).

However, some limits of detection are relative to the sensor resolution which has already been mentioned before (the size of salinity patches) and to sensor sensitivity to crop biomass variation : the sensitivity curve of sensors has a saturated part. For low salinity levels, we stay in this saturated area[4] (see Tucker curve).

[4] according to biomass measurements made in April 1995 for radar images.



Relation between the NDVI and biomass (in Tucker, C.J, 1979, Red and Photographic infrared linear combinations for monitoring vegetation, Remote Sensing Env.,8 : 127-150.)

The second point is linked to the methodologies applied. For example, the mean values method do not take into account the presence of local salinity patches. The algorithm method is limited by the problem of resolution (number of pixels per field), the threshold values which were deduced from a study taking into account the presence or the absence of crop and not crops types : wheat fields represents the majority of cropped fields so threshold values are well adapted for this crop, that is why wheat fields have been well classified.

[5] Wheat biomass of S1 fields varies between 600 and 1200 g/m²

Part III : Conclusions

1. Salinity in Fordwah

Salinity in Fordwah seems to be very patchy and the majority of the fields are concerned by low salinity. High salinity areas are found to be associated with abandoned river beds and old ox-bow lakes.

2. Perspectives of the subject

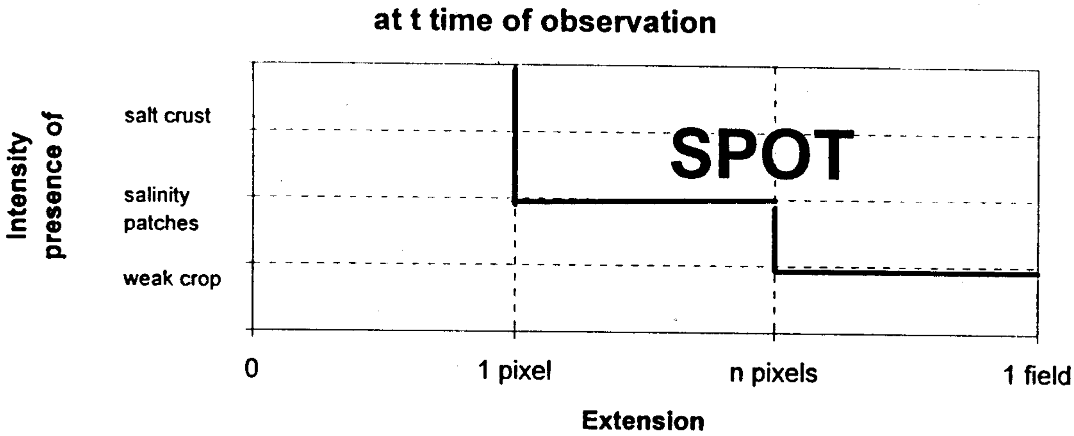
This study shows that soil salinity monitoring has three dimensions :

1. Salinity extension and space resolution :
Two types of salinity could occur. The first could be local and related to farmers practises on one field, this case of salinity is difficult to be detected. That is why we have developed the algorithm method. But whenever salinity is massively present on the field, it is easier to detect it. Our choice to work at the field level gives results in terms of fields affected by salinity and the level of this salinity. These results do not determine the area affected by salinity.
The second type of salinity has its own space pattern : salinity related to topography and drainage pattern, the problem is to find the best way to show the logic of this phenomena.

2. Time dimension :
Salinity affects the development of plants after germination. However this influence could be seen during plant development. So there is no necessity to acquire images just after germination, images could be taken at the end of the season when plants are at the same stage of development. But soil salinity crust appear only during hivernal seasons, so the most appropriate period to detect salinity on barren and fallow fields is winter season. These results have been proved by the comparison of October and March images.
For future multisensors studies, images should be acquired during the same periods. Multitemporal studies should be used with caution as salinity classes must refer to the corresponding cropping pattern.

3. Salinity intensity :
Salinity affects physical space properties (soil and plants). Sensors are sensitive to radiometric modifications (for optic sensors) and electrical modifications (radar sensors) of soils and plants, that depend on hydric stress, salinity, photosynthetic activities of plants. Each type of sensor is sensitive to a certain type of salinity effects.
However, low levels of salinity are controlled by farmers practises so salinity effects are not guaranteed. For example, farmers can increase the quantity of sowing to compensate the yield deficit in quality, so wheat biomass, that is detected by sensors, is not modified by salinity.

Spot limits are represented in the following scheme :



Microwave sensors such as ERS-1 could bring more information about soil salinity if all soils are wet, more information about crop density (no problems of saturation such as for SPOT) but its resolution is not better than SPOT. Landsat bands in the infra-red give information about surface temperature so detect crop hydric stress and dunes of sand. But its resolution is of 120m.

This study showed us that a lot of work is still to be done to characterise salinity pattern through salinity field analyses and to improve field data collection.

Appendix 1 : Table of contents of the final version of the report in French

CHAPTER II : SPATIO-TEMPORAL SALINITY CHARACTERISATION IN FORDWAH 87

CHAPTER III : CONCLUSIONS : SALINITY STUDY BY REMOTE SENSING : MULTITUDE OF TIME, PLACE AND ACTIONS - FORDWAH STUDY CASE- 153

REFERENCES 161

APPENDIXES