Vingtièmes journées techniques du Comité Français d'Hydrogéologie
de l'Association Internationale des Hydrogéologues.
« Aquifères de socle : le point sur les concepts et les applications opérationnelles » La Roche-sur-Yon, juin 2015

Contrôles structuraux à grande échelle des propriétés hydrogéologiques et modélisation des eaux souterraines du bassin de socle de la haute vallée de l'Ouémé (Bénin, Afrique de l'Ouest)

Large-scale structural controls on hydrogeological properties and groundwater modelling in the Upper Ouémé basement basin (Benin, West Africa)

Neil Dickson(1), Jean-Christophe Comte(1,2), Jean-Michel Vouillamoz(3), Youssouf Koussoube(4), Ulrich Ofterdinger(1)

(1) Queen's University Belfast, School of Planning, Architecture and Civil Engineering, Northern Ireland (UK), (2) University of Aberdeen, School of Geosciences, Scotland (UK), (3) Institut de Recherche pour le Développement, Laboratoire d'Etude des Transferts en Hydrologie et Environnement (France), (4) Université de Ouagadougou (Burkina Faso)

Basin scale groundwater modelling is challenging in basement rocks due to the high spatial variability of aquifer hydrogeological properties typically controlled by weathering, fracturing and lithological diversity. The metamorphic basement units of the Upper Ouémé watershed (14,500 km^2) in Benin have been investigated to identify the structural controls on aquifer hydraulic properties, groundwater flow and water balance at large scale. Spatial analysis of borehole, remote sensing and hydrogeophysical data suggest poor correlation between bedrock lithological types, lineaments, and geomorphological features with weathering profiles and hydraulic properties. Instead, large scale weathered zone geometry, aquifer transmissivity and storage properties appear better correlated to a palaeo-weathering surface identified through mapping of the residual lateritic iron crust surface. Based on a number of alternative aquifer conceptual models developed, nine transient numerical groundwater models were applied. Assessment of models against observations, including groundwater heads, river flow rate and catchment water balance, suggest that the best conceptual models are those were hydraulic properties are distributed according to (i) the geometry of the weathered zone based on the interpolation of borehole and geophysical data and (ii) the lineaments density within both weathered and fresh basement. Modelled groundwater balance suggests that the combined borehole abstraction in the basin is less than 1% of the average groundwater discharge to surface drainage network (~100 m^3/s) and that about 90% of this localized discharge is lost to evapotranspiration, leaving the remaining 10% to contribute to streamflow.

I. INTRODUCTION

West Africa has been experiencing a drought for the past 40 years or so with the height in 1970s and 80s (Descroix et al., 2009; Lebel and Ali, 2009). Due to the drought impact and social implications of water, the Upper Oueme region has been subject to investigations by various research projects (e.g. GLOWA, IMPETUS, AMMA-Catch), allowing for an extrapolation of findings to assist water resources development and management in other West African countries.

Developing groundwater is unreliable in basement environments as is usually limited to selected geological units or areas of preferential flow which are often poorly connected (Krasny and Sharp, 2007; El-Fahem, 2008) e.g. permeability and storage are limited to the weathered zone and fractures in the vicinity of major faults (Barthel et al., 2009). Investigations dedicated to groundwater in the Benin basement are relatively scarce with most concentrating on geological or governing hydrology, while a few studies (Boukari et al., 1995, 1996; Fass, 2004; El-Fahem, 2008) focus on the hydrogeological aspects.

The Groundwater Resources In Basement rocks of Africa (GRIBA) project was successful through the 10th European Development Fund and was organised to contribute to improve science and technology research in basement regions of Africa for securing and sustaining access to water. The outputs are projected to be a collection of quantified hydrogeological properties of the basement aquifers of the Upper Oueme basin in Benin (Fig. 1) allowing for scenarios of sustainable use of groundwater in the target areas at both borehole and catchment scale. This work aims at setting-up large-scale numerical groundwater models based on the information coming from traditional hydrogeological investigation as well as advanced geophysical methods (Dickson, 2015). The groundwater models will be used to quantify current groundwater reserve and to estimate its sustainable use according to several scenarios of both abstraction and recharge rate changes.

II. SITE DESCRIPTION

The Upper Ouémé Basin (Haute Vallee de l'Ouémé, HVO) covers an area between 14,000 and 15,000 km^2 (Bormann et al., 2005; El-Fahem, 2008; Giertz et al., 2006; Hector et al., 2013), which constitutes approximately 43% of the area of Benin (Fig. 1). Portions of the basin extend into neighbouring Togo and Nigeria however the majority (89%) are located in Central / Northern Benin (Barthel et al., 2009). The Ouémé Basin is required to sustain the growing population of 30 inhabitants per km^2 with a growth rate of 3.48% (1992-2002, Hector et al., 2013). The region has an extensive drainage network throughout the regional catchment with the Ouémé River being the main river (510km). There are several sub-catchments within the lager basin (Donga, Terou-Igbomakoro and Beterou) (Ollivier et al., 2014).

Figure 1 – Location of the Upper Oueme basin (HVO) as part of the Oueme River basin in Benin, West Africa

The basin is characteristic of sub-humid/semi-arid Savannah zones (Sudian) with rainfall ranging from 1100–1300 mm/yr and average temperature of 27 °C (Barthel et al., 2009; El-Fahem, 2008; Hector et al., 2013; Kamgaté et al., 2007; Ollivier et al., 2014). The topography is relatively homogeneous with flat pedeplains (Giertz et al., 2006) and isolated inselbergs throughout the region and upland mountain range to the West. Groundwater recharge and evapotranspiration are estimated to be 18.8% and 73-90% of rainfall respectively (Hector et al., 2013; Ollivier et al., 2014) and runoff is approx. 7.8%. (Awoye, 2007; Bossa, 2007). The total annual abstraction from wells and boreholes is estimated at 0.34 mm/yr, i.e. 13,500 m^3/d (Vouillamoz et al., 2015). The geology is composed of Precambrian metamorphic basement rocks (Giertz et al., 2006) and separated between the Donga compartment to the West (predominantly micashists, gneiss and quartzites) and the Borgou compartment to the East (predominantly migmatitic gneisses) by a major crustal fault, the Kandi fault (El-Fahem, 2008). Transmissivity (T), permeability (hydraulic conductivity K) and storage (porosity n) of the solid, unweathered crystalline rocks is low. However, despite this, a large number of boreholes have been commissioned with a large percentage being successful. This is related to the shallow weathered zone conditions which increase K and n. The region has a highly variable fractured basement aquifer which transitions towards a quasi-porous aquifer in the overlying weathered zone (Bormann et al., 2005). Weathered bedrock varies in average from 0-25m below ground level (Barthel et al., 2009; Kamgaté et al., 2007). This is characterised with saprolithic weathering above the migmatitic basement followed by a lateritic strengthened horizon overlying the highly permeable sandy topsoil. It is partially saturated due to high water table variability. No regional distribution of *T*, *K*, *n* or *Sy* (specific yield) values exists despite local testing and existing point data (Barthel et al., 2009). Yet, due to the dedicated investigations that focused on the Upper Oueme, there is an abundance of data and information available for the country and basin (Fig. 2). These range from Satellite imagery, Shuttle Radar Tomography Mission (SRTM) Digital elevation model (DEM), geological maps (available as a generalised and more detailed interpretation) and borehole database. Climatic data (rainfall, evapotranspiration, river flow rates) and maps are available from various literature sources alongside dedicated weather station scattered throughout the region. Drainage networks (Fig. 2) and total discharge values are available at selected locations.

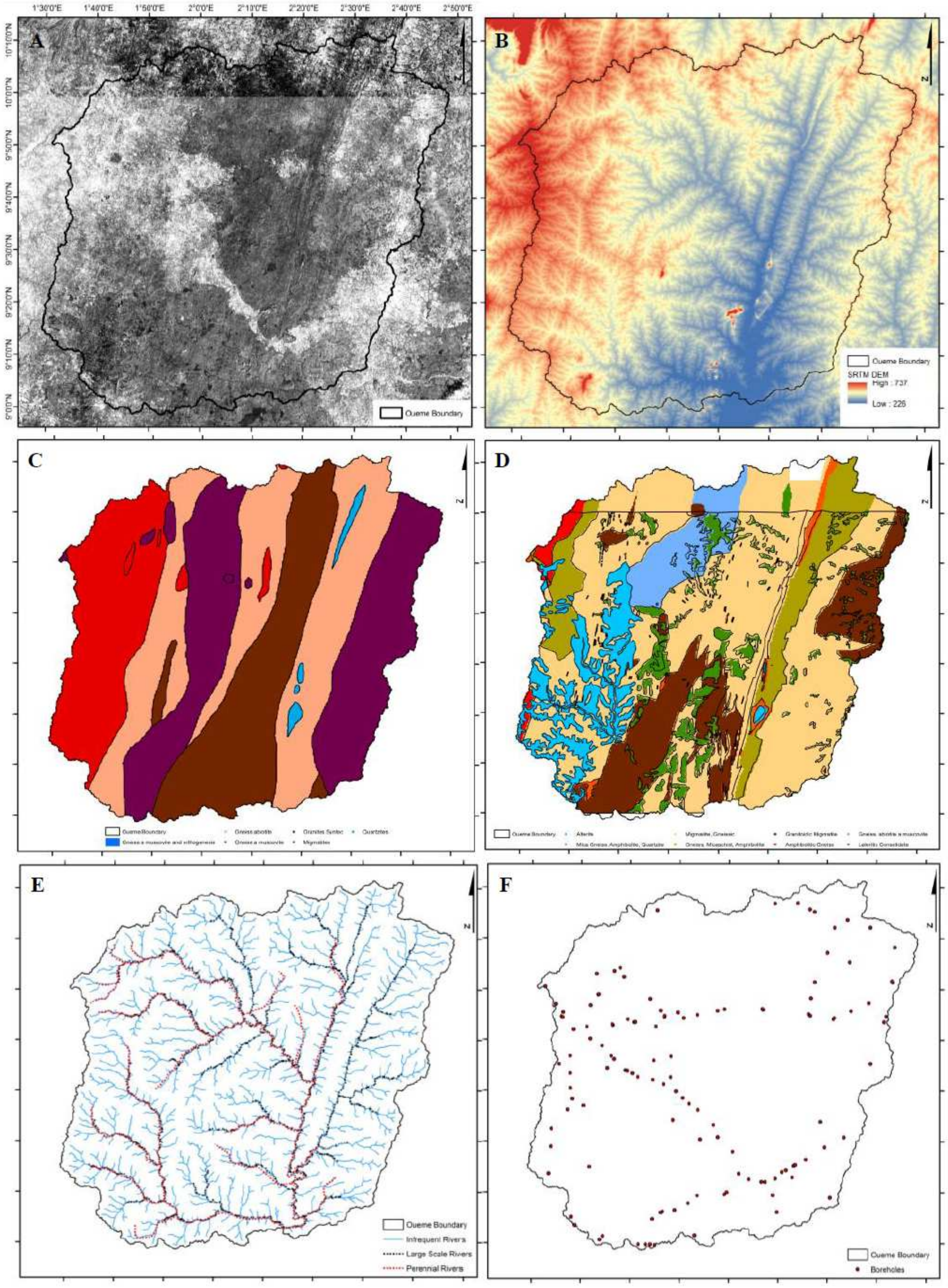

Figure 2 – Images depicting : (a) satellite imagery ; (b) SRTM DEM ; (c) generalised geology map ; (d) detailled geology map ; (e) drainage network ; and (f) abstraction borehole locations

III. METHODS

Spatial analysis of existing geological, structural, hydrogeological and geophysical data was carried out to establish groundwater conceptual models of the Upper Ouémé catchment. This analysis focussed on exploring the structural controls on groundwater flow. First the base of the weathered zone was mapped from existing borehole log datasets (Fig. 3) and second, a lineament analysis was performed based on DEM and satellite image using different processing and interpretation techniques, followed by spatial quantification of fracture densities (Fig. 4). Finally, the role of different physical features on both the structure of the weathered zone and the aquifer hydrodynamic properties (*T*, *K*, *Sy*) were analysed through spatial correlations, this included:

- The current topography using DEM data;
- The palaeo-weathering surface, obtained through interpolation of existing maps of exposed weathering surface;
- The hydrological network (distance to drainage network);
- The lineament distance and density.

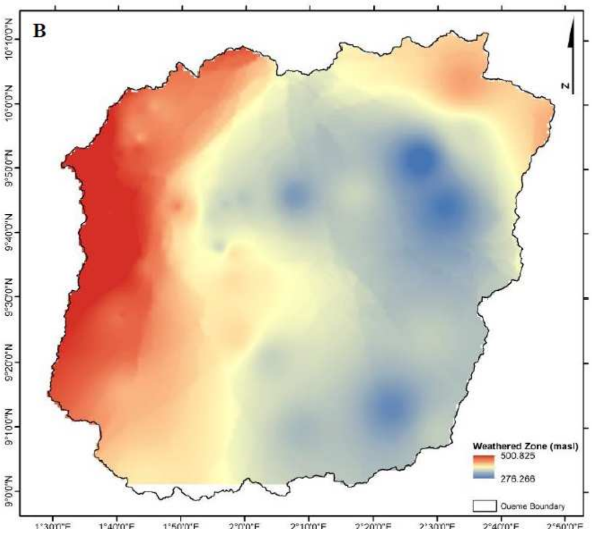

Figure 3 – Interpolated (IDW) surface of the base of the weathered zone from borehole and geophysical data

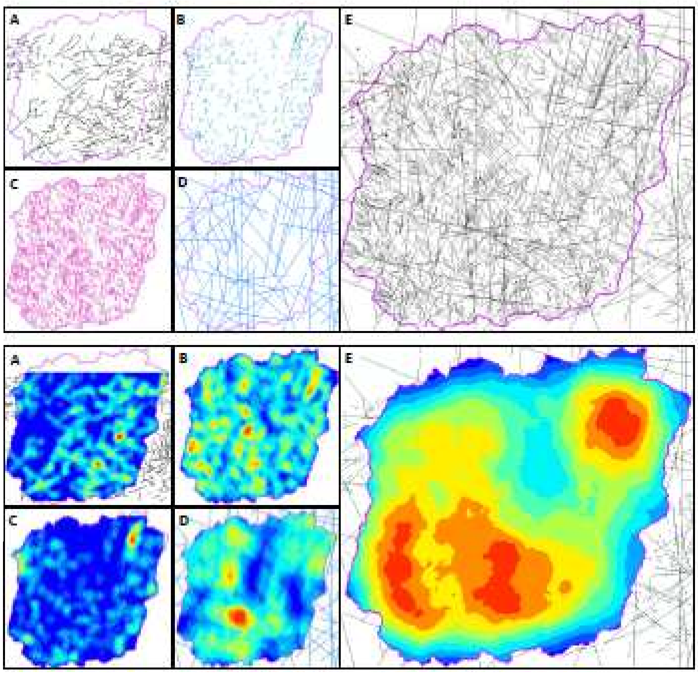

Figure 4 – Fracture occurrence (top) and density (bottom) as determined from (a) geological map interpretation ; (b) slope analysis ; (c) geomatica shade analysis ; (d) aerial imagery interpretation ; (e) combined analysis

Numerical groundwater flow models (using FEFLOW code) based on the alternative conceptual models obtained (including the geometry of the weathered zone and the spatial distribution of hydrodynamic parameters) were implemented. Model results were assessed against observed groundwater heads, observed drainage flow rate at the basin outlet and spatial distribution of river drainage. Model boundary conditions included (i) the spatial distribution of the recharge according the map of GIZ, 2012 (Carte hydrogéologique du Bénin), (ii) a seepage face applied on the entire model topographic surface and (iii) well/boreholes abstraction. Models were initially run in steady state using average annual recharge and ultimately in transient state using monthly recharge.

IV. RESULTS

Results of spatial analyses suggested very poor correlation between lineaments/drainage network and both the structure of the weathered zone and hydrodynamic parameters. In contrast, strong correlations were found between the structure of the weathered zone and both the topography and the palaeo-weathering surface (Fig. 5). No clear spatial controls were found for the aquifer hydrodynamic properties which would suggest smooth or possibly stochastic spatial variations from site to site, thus permitting the use of interpolated distributions (Fig. 6).

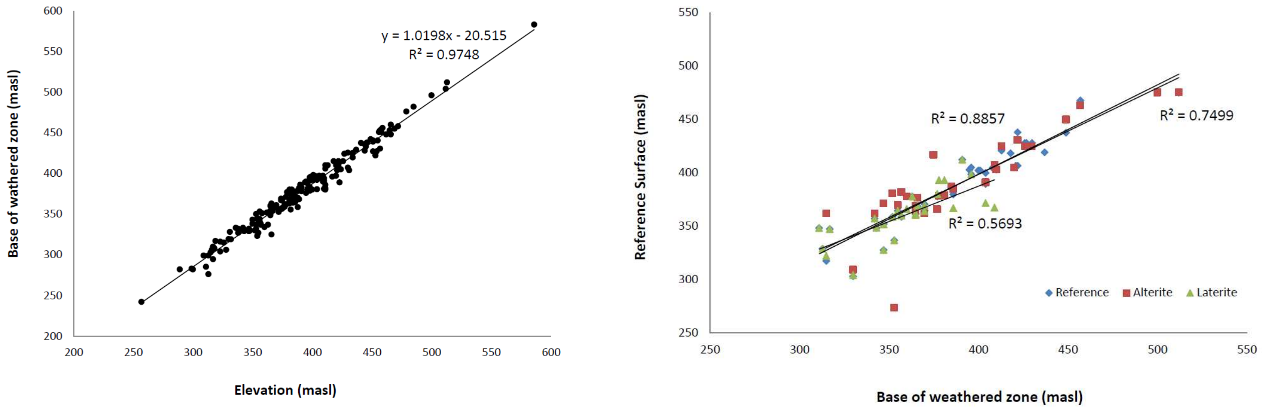

Figure 5 – Correlation between the base of the weathered zone in boreholes and geophysical sounding with : Left, the topographical surface; Right, 3 versions of the interpretated palaeo-weathering surface

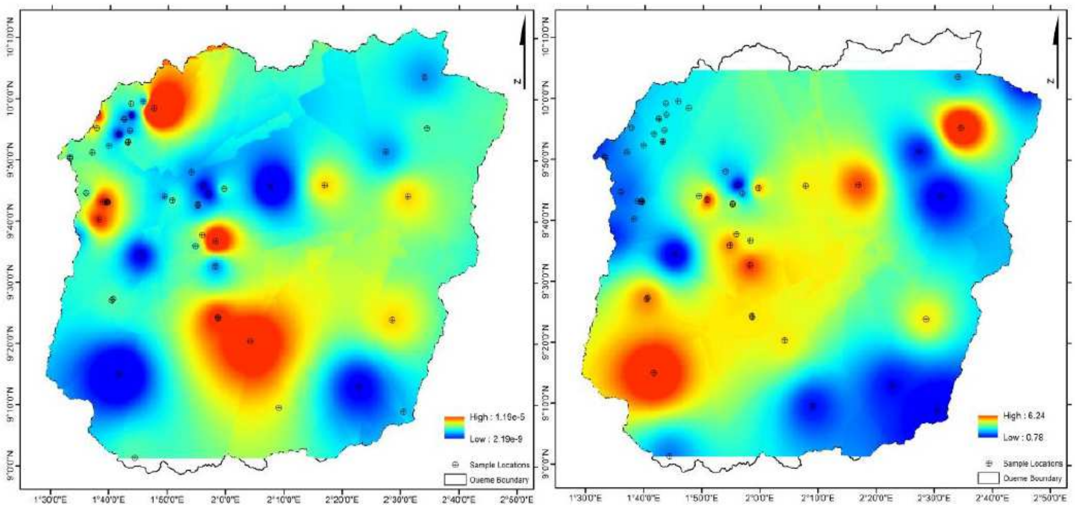

Figure 6 – Maps depicting interpolated (IDW) distributions of (a) K *and (b)* Sy *from borehole testing data and geophysical surveys (Vouillamoz et al., 2014)*

Overall, the different results (including good and bad correlations) created 9 catchment-scale hydrogeological conceptual models to be tested numerically. Those 9 models account for 3 possible structural geometries X 3 possible distribution of hydraulic properties. Structural types were defined based on the geometry of the weathered zone which is assumed to be a function of either (i) the topography; (ii) the palaeo-weathering surface or (iii) simple interpolation of the weathered zone as observed in boreholes and geophysical soundings. Distributions of hydrodynamic properties were defined as (i) simple interpolation of borehole/geophysical point measurement; (ii) function of fracture density (poor observed correlation) and (iii) average *K* and *Sy* values applied to mapped geological units creating distinct boundaries between values.

FEFLOW model results includes the simulation of water heads and seepage flow rates over the whole Ouémé catchment for the 9 conceptual models. All 9 models show good agreements between observed and calculated groundwater heads in steady-state (Fig. 7). The best agreement is obtained with the model using the weathered zone geometry defined from the palaeo-weathering surface and *K*, *Sy* distributed as a function of fracture density. In transient state, the best agreement is obtained with the model using a geometry of the weathered zone interpolated from borehole and geophysical data and *K*, *Sy* distributed as a function of fracture density. However, no one model produced satisfactorily match for all observations (Fig. 8), in particular in low elevation areas. The mismatch in those areas is probably due to not directly applying the groundwater uptake by evaporation occuring in valleys, which results in water table fluctuations being constrained by the ground elevation instead of seasonal variations in evapotranspiration.

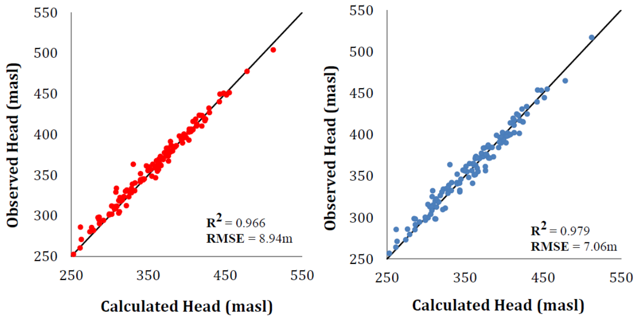

Figure 7 – Steady state comparison between observed and calculated groundwater heads (left, best model ; right worst model)

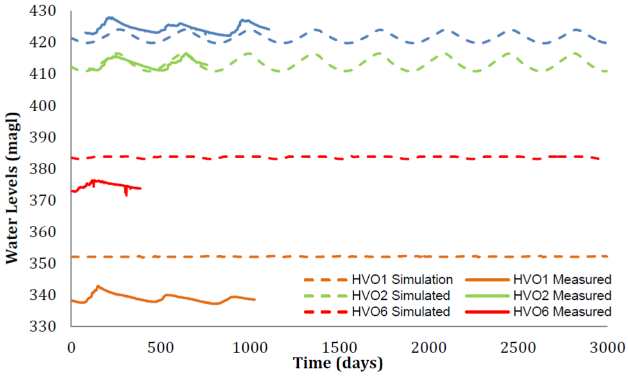

Figure 8 – Transient-state comparison between observed and calculated groundwater heads for selected wells (best model)

The total groundwater discharges simulated by the different models were assessed by comparing qualitatively the location of simulated discharge zones with the existing drainage network of 'perennial' rivers. Again, the model made of interpolated weathered zone geometry from borehole logs and *K*, *Sy* distributed as a function of fracture density shows the best agreement for both dry and rainy season (Fig. 9).

In terms of mass balance, the groundwater discharge calculated by the different models ranges between 50 and 150 m^3/s in average over the year (the best model above giving a value of 96 m^3/s). This is generally higher than the average flow rate of 54 m^3/s recorded at the outlet of the basin. Given that previous studies (e.g. Awoye, 2007; Bossa, 2007) suggest that this recorded value break down to about 44 m^3/s of runoff and 10 m^3/s of groundwater contribution, we can conclude that between 40 m^3/s (80%) and 140 m^3/s (93%) of ground-water discharge is lost to evapotranspiration in seepage areas, only

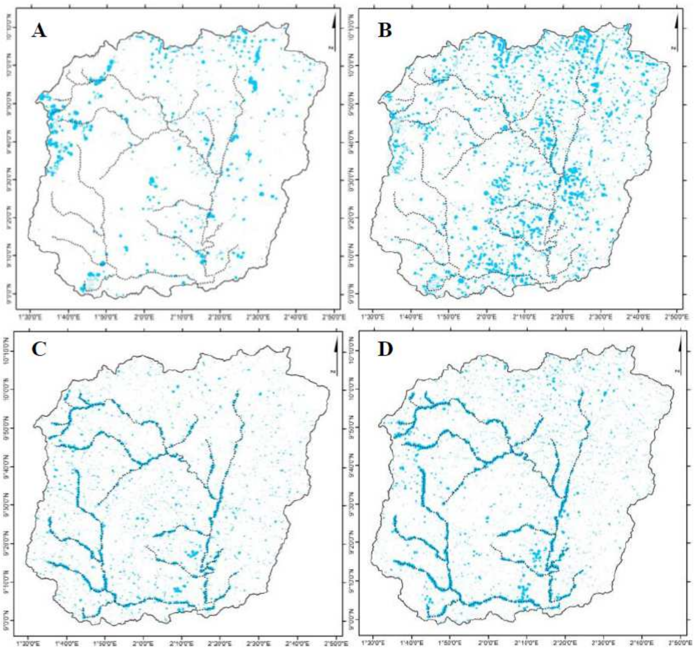

Figure 9 – Spatial distribution of modelled discharge throughout the Oueme basin (size of blue symbols indicates discharge magnitude). Top maps (a,b) and bottom maps (c,d) are results of the worst and best model, resp. Left maps (a,c) represent the dry season and right maps (b,d) the rainy season

leaving between 7 and 20% to contribute to the basin river flow at its outlet. Groundwater abstraction within those figures represents a negligible part of groundwater discharge of less than 0.1%.

V. CONCLUSIONS

By combining basin-scale spatial analysis with numerical models, which represent groundwater flow in the basement rocks in the Upper Oueme in Benin, different hydrogeological conceptual models were tested which are all geologically constrained. The various model produced a range of results that were assessed against observation data, including groundwater heads and river discharge. Overall, the conceptual models that show the best agreement with observations are those that are defined by a geometry of the weathered zone either correlated to the palaeo-weathering surface of the region or simply interpolated from borehole log and geophysical data and by a distribution of hydrodynamic parameters (*K*, *Sy*) as a function of the regional lineament density. Distributing hydrodynamic parameters as a function of geological litho-types often produced the worst fit and distributing them as interpolation of borehole and geophysical data generally produced intermediate good fit. This modelling study highlights the difficulty of selecting appropriate conceptual models for groundwater flow in basement rocks at the regional scale while accounting for local observations. It confirms previous water balance estimates, which suggested that a large quantity of groundwater flow is available for well abstraction, yet largely underexploitated. It also confirms the major role of groundwater evapotranspiration in low-lying seepage areas of the regional drainage network, which needs to be accounted for in further modelling works.

VI. REFERENCES

Awoyé, H. (2007), Modélisation du bilan hydrologique dans le bassin du Klou au Centre-Bénin : contribution a l‟utilisation durable des ressources en eau. Unpublished Dissertation, University of Abomey- Calavi.

Barthel., R., Soneveld, B. G. J. S., Götzinger, J., Keyzer, M. A., Pande, S., Printz, A. and Gaiser, T. (2009), Integrated assessment of groundwater resources in the Ouémé basin, Benin, West Africa, *Physics and Chemistry of the Earth*, 34:236-250.

Bormann, H., Faβ, T., Giertz, S., Junge, B., Diekkrüger, Reichert, B. and Skowronek, A. (2005), From local hydrological process analysis to regional hydrological model application in Benin: Concept, results and perspectives, *Physics and Chemistry of the Earth*, 30: 347-356.

Bossa, Y. A. (2007), Modélisation du bilan hydrologique dans le bassin du zou à l'exutoire d'Atchérigbé: contribution à l'utilisation durable des ressources en eau. Unpublished Dissertation, University of Abomey- Calavi.

Boukari, M., Alidou, S., Oyede, L. M., Gaye, C. B. and Maliki, R. (1995), Identification des aquiferes de la zone littorale du Benin (Afrique de l'Ouest) : hydrodynamique, hydrochimie et problemes d'alimentation en eau de la ville de Cotonou, *African Geoscience Review*, 12:139-157.

Boukari, M., Gaye, C. B. and Fae, S. (1996), The impact of uban development on coastal aquifers near Cotonou, Benin, *Journal of Afican Earth Sciences*, 22(4): 03-08

Descroix, L., Mahé, G., Lebel, T., Favreau, G., Galle, S., Gautier, E., Olivry, J.-C., Albergel, J., Amogu, O., Cappelaere, B., Dessouassi, R., Diedhiou, A., Le Breton, E., Mamadou, I. and Sighomnou, D. (2009), Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa : A synthesis, *Journal of Hydrology*, 375:90-102.

Dickson, N. E. M. (2015), The integration of multi-scale hydrogeophysical data into numerical groundwater flow models, Unpublished PhD Thesis Queen's University of Belfast.

El-Fahem, T. (2008), Hydrogeological conceptualization of a tropical river catchment in a crystalline basement area and transfer into a numerical groundwater flow model: case study for the Upper Ouémé catchment in Benin. Unpublished Ph.D. Thesis Universitat Bonn.

Fass, T. (2004), Hydrogeologie im Aguima Einzugsgebiet in Benin / Westafrika, Mathematisch–Naturwissenschaftliche Fakultät. Rheinische Friedrich-Wilhelms-Universität. Dissertation, 161 p., Bonn, Germany.

Giertz, S., Diekkrüger, B., Jaeger, A. and Schopp, M. (2006), An interdisciplinary scenario analysis to assess the water availability and water consumption in the Upper Ouémé catchment in Benin, *Advances in Geoscience*, 9:3-13.

Hector, B., Séguis, L., Hinderer, J., Descloitres, M., Vouillamoz, J.-M., Wubda, M., Boy, J.-P., Luck, B. and le Moigne, N. (2013), Gravity effect of water storage changes in a weathered hard-rock aquifer in West Africa: results from joint absolute gravity, hydrological monitoring and geophysical prospection, *Geophysical Journal International*, 194(2):737-750.

Kamgaté, B., Séguis, L., Favreau, G., Seidel, J.-L., Descloitres, M. and Affaton, P. (2007), Hydrological processes and water balance of a tropical crystalline bedrock catchment in Benin (Donga, upper Ouémé River), *Comptes Rendus Geoscience*, 339(6):418-429.

Krasny, J., and Sharp, J.M., eds. (2007), *Groundwater in Fractured Rocks*: Selected Papers 9, International Association of Hydrogeologists: London, Taylor & Francis, 646p.

Lebel, T. and Ali, A. (2009), Recent trends in the Central and Western Sahel rainfall regime (1990–2007). *Journal of Hydrology*, 375:52–64.

Ollivier, S. L., Barnabé, Z., Maurice, A. D., Expédit, V. W. and Euloge, A. K. (2014), Modelling the water balance of Ouémé catchment at the Savé outlet in Benin: contribution to the sustainable water resource management, *International Journal of AgriScience*, 4(1): 74-88

Vouillamoz, J. M., Lawson, F. M. A., Yalo, N., Descloitres, M. (2014), The use of magnetic resonance sounding for quantifying specific yield and transmissivity in hard rock aquifers: The example of Benin, *Journal of Applied Geophysics*, 107:16-24.

Vouillamoz, J. M., Lawson, F. M. A., Yalo, N., Descloitres, M. (2015), Groundwater in hard rocks of Benin: Regional storage and buffer capacity in the face of change, *Journal of Hydrology*, 520:379-386.