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Participation and cooperation
for development programmes

Nubian sandstone aquifer modelling and groundwater resources planning for new valley

by Nguyen Quang Trac

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A R A B R E P U B L I C O F E G Y P T

NUBIAN SANDSTONE AQUIFER MODELLING
AND GROUNDWATER RESOURCES PLANNING
FOR NEW VALLEY

by Nguyen Quang Trac

Report prepared for the Government of
the Arab Republic of Egypt by the
United Nations Educational, Scientific
and Cultural Organization (Unesco)

U N E S C O

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I. INTRODUCTION

1. Within the framework of Unesco's Participation Programme for 1981-1983, the Government of the Arab Republic of Egypt requested Unesco for assistance in making a study of the Nubian sandstone aquifer in Egypt. The General Authority for Reclamation Projects and Agricultural Development (GARPAD) of the Ministry of Development and the Ministry of State for Housing and Land Reclamation plan to conduct the study over a period of 12 months, in three phases. Unesco has been requested to provide a 4 m/m consultancy in hydrogeology and systems analysis. The present mission corresponds to the first mission to be carried out by the hydrogeologist.

2. This mission was carried out from 5 October to 4 November 1983, with the following terms of reference :

"The consultant will analyse the possibility of realizing a multi-layer model of the Nubian sandstone aquifer system in the Western Desert of Egypt on the basis of an inventory of existing hydrological data and their interpretation".

3. While he was in Egypt, the consultant had numerous meetings with the technical staff of GARPAD's Groundwater Department and of the Groundwater Research Institute, Ministry of Irrigation. These staff members are listed in Appendix 1. In addition, the consultant also met with the Unesco Representative in Egypt for debriefing on the mission results.

4. Although the mission was dedicated mainly to the work carried out or under development on the Nubian sandstone aquifer, at the request of the Groundwater Research Institute, the consultant also had the opportunity to discuss at length, with members of the Institute, different questions related to

the Nile Delta aquifer and the management of groundwater resources in the Nile Valley.

5. In the first section of the report, the consultant reviews the present situation and previous modelling works of the Nubian sandstone aquifer. The following section analyses the recent study of the Regional Plan for New Valley based on water resources exploitation of this aquifer, and proposes additional works to be realized eventually by GARPAD to progress from the regional planning stage towards an efficient resources management on a local scale.

6. Finally, the current Transnational Project of the Major Regional Aquifer in North-East Africa is briefly reviewed followed by the consultant's recommendations.

II. PRESENT SITUATION

Hydrogeological knowledge

7. The Egyptian Western Desert corresponds to the eastern part of a very large sedimentary basin (about 1.800.000 km²) which underlies extensive areas of Egypt, Libya, Sudan and Chad. This basin is filled in with a thick succession of sandstone and shales of Palozoic to Mesozoic age, and is known as the Nubian sandstone complex which constitutes the Nubian sandstone multi-layer aquifer system.

8. The groundwater resources of the Nubian aquifer system in the Western Desert of Egypt have attracted the interest of investigators since the end of the 19th century. Methodical studies of the aquifer in the Kharga and Dakhla oases date from 1956 when the Government of Egypt initiated the New Valley Development Project.

9. Since that date, a series of exploratory and production well-drilling programmes have been undertaken, and some 500 wells

have been completed to various depths in the Kharga and Dakhla oases, and also the two northern oases of Fafafra and Bahariya, as well as their environs. A great number of these wells have electrical logs and pumping tests.

10. In 1960, regional piezometric mapping, water level monitoring, and annual extractions estimation were initiated.

11. On the same lines, various regional geophysical studies, using airborne magnetic, ground magnetic and gravity techniques, have been carried out to define the geometry of the Nubian sandstone aquifer system. Isopachous maps of the aquifer and the upper confining bed have been prepared.

12. There is thus a considerable volume of basic hydro-geological data (aquifer geometry, hydraulic characteristics, water level evolution during the last 15 or 20 years, historic of extractions) concentrated mainly in and around the oases which are areas of population settlement and potential development zones. Data are more sparse in remote areas of the Western desert.

13. Simultaneously with the field investigation effort, simulation techniques have been implemented and up to now seven models of different sizes covering partially or totally the Western Desert have been developed to analyze the Nubian sandstone aquifer system. The main characteristics and principal results of these models are summarized in the following paragraph.

Groundwater models

14. Regional resistor - capacity model
(A. Salem, 1962)

- Area covered : Western desert of the Arab Republic of Egypt, an eastern strip of the Libyan Arab Jamahariya and the northern zone of the Democratic Republic of Sudan
(total area : more than 1.000,000 km²) ;

- A one-layer model simulating the aquifer artesian condition ;
- A one-layer model simulating the water table condition ;
- Two pumping programmes to simulate drawdowns ;
- Principal results : the model had the extraordinary merit of introducing simulation techniques in Egypt. Although the simulated pumping programmes were far from realistic (withdrawals of about 4,500 MCM/year* to irrigate 600,000 feddans**, provoking drawdowns ranging from 50 m to 110 m), they probably were the first assessment of the enormous potential of the Nubian sandstone aquifer.

15. Kharga-Dakhla resistor - capacity model

(Borelli, 1968)

- The systems analysis work included, in fact, three analogue models :

a) A regional one-layer model (1.000.000 km², 1,000 nodes) for boundaries condition analysis.

b) A two-layer model for the Kharga-Dakhla area (43.000 km², 2,600 nodes) ;

c) A pilot model for solving the inverse problem.

- Simulation of the pre-1960 steady-state situation and the 1960-1967 transient regime ;

- Simulation of a 985 MCM/year withdrawal for the irrigation of 88,000 feddans of land in the two oases. Predicted drawdowns range from 65 m to 110 m after 50 years of pumping ;

- Principal results of the models ; first simulation work with the two-layer approach ; inverse problem solving ever tested for this aquifer ; prediction results seem to be in the correct order of magnitude.

* MCM/year : million cubic meters per year

** 1 feddan: 0.425 hectare

16. Kharga-Dakhla ECAP analogue model

(Ezzat, 1975)

- The study consisted of two models ;

a) a regional model with 26 polygons covering an area of about 360.000 km² ;

b) a semi-detailed model concentrated in the Kharga Dakhla area (10.000 km²) with 28 nodes to analyse the possibility of securing the groundwater supply (30 MCM/year) of the Phosphate project of Abu Tatur.

- The regional model, calibrated under steady-state regime with a total recharge along the feeding border of 660 MCM/year, will be partially confirmed later by the results of a more sophisticated digital model in 1980 whilst losses to Quattara Depression in the north seem to be over-estimated.

17. South Quattara ECAP analogue model

(Ezzat, et al, 1977)

- A one-layer model covering the northern part of the Western Desert with a very careful preparation of basic hydrogeological input data ;

- Detailed analyses of changes in regional storage coefficients in relation with the pumping effects showed substantial differences in predicted drawdowns produced by simulated withdrawals in Fafafra, Bahariya and Siwa oases.

18. Dakhla-Kharga mathematical model

(FAO, 1976)

- A digital two-layer model covering an area of about 86.000 km² with 222 x 2 polygons. Relatively small polygons (with size ranging from 30 km² to 300 km²) were designed for the two oases of Dakhla and Kharga.

- A steady-state calibration reached after 22 runs with uniformed hydraulic characteristics applied to the whole system (horizontal permeability for both upper and lower aquifer : 3.5 m/day ; confined aquifer storage coefficient : 10^{-3} ; specific yield : 10^{-1} ; leakage coefficient of conceptual confining bed separating the two aquifers : 2.5×10^{-6} , day⁻¹).

- As a result of the test of different extraction patterns, the following development programme was proposed : additional exploitation of 696 MCM/year to irrigated 58.000 feddans in the Dakhla, Kharga oases and 30 MCM/year for the Abu Tatur Phosphate project. Average drawdowns, after a 50 year pumping, would be less than 20 m and depths to water table would range from 13 m to 85 m in the oases and would exceed 120 m in Abu Tatur.

- The model provided a credible forecast of the Nubian aquifer system behaviour for the probable ranges of development in the foreseeable future. However, the critical issue of relationship between the upper and lower aquifers which depends mainly on the leakage coefficient, and the corresponding exploitation alternatives (shallow and/or deep wells development) with their economic impact on water cost was insufficiently analysed.

19. Finite element model of the Nubian aquifer system in Egypt (Amer et al, 1980)

- One-layer model simulating steady-state pre-1960 condition of the system and covering an area of 570,000 km² with 377 elements and 211 nodes.

- The study has concentrated on the sensitivity analysis of the system to boundaries condition and space variations of horizontal permeability. Calibration was achieved in 8 runs.

- The model constituted an interesting simulation exercise as it applied for the first time in Egypt the finite element techniques for groundwater modelling. However, its practical results for resources planning or management were rather limited.

III. THE REGIONAL DEVELOPMENT PLAN FOR NEW VALLEY

20. This study*, realized in 1982, represents a major contribution to the development planning of the New Valley region which comprises four main oases in the Western Desert : Kharga, Dakhla, Farafra and Bahariya.

21. Applying an integrated approach, it deals with the principal socio-economic and physical factors and constraints of the region, using various planning tools for decision-making and aiming at explicit regional and specific objectives.

22. The study has established a future water use optimization strategy using three planning tools for the agricultural sector which is the main user of groundwater resources :

- a two-layer digital groundwater model ;
- an optimum well design programme ;
- a linear programming model which uses optimization techniques to determine the optimum combination of agricultural production factors.

23. The model and programme directly related to groundwater resources exploitation are discussed hereinafter.

Groundwater model for regional planning

24. The model encompasses the four oases and part of the Western Desert covering a total area of 220.000 km² with a

* Ministry of Development. Euroconsult/pacer Consultants' draft final reports - January 1983.

polygonal network consisting of 449 x 2 nodes. Relatively small polygons with areas ranging from 30 km² to 200 km² were used in the oases whilst large polygons, up to 4,000 km², were designed for the desert area.

25. This model was basically an extension of the FAO model (1976) with a few minor differences in hydraulic characteristics of the aquifers used as input data ; instead of using a universal value for horizontal permeability (3.5 m/day) a slightly higher permeability (4.5 m/day) was applied to the southern area ; the same leakage coefficient ($2.5 \times 10^{-6} \text{ day}^{-1}$) was used, with the exception of the Bahariya depression which was given a higher value ($7.5 \times 10^{-6} \text{ day}^{-1}$).

26. As no additional field data have been collected, only the simulated regional piezometry in steady-state pre-1960 condition for the deep aquifer could be considered as reasonably satisfactory. In relation to the shallow aquifer, a piezometric contour map was not available, and it is rather difficult to assess the calibration achievement.

27. For the transient regime corresponding to the 1960-1980 period, the study estimated that the generated hydrographs fit fairly well with those observed at 28 different locations of the nodal network although the examples presented in the report (Annex B) to illustrate calibration in characteristic nodal points of Kharga, Zayah and Farafra (nodes 26, 104 and 302) do not show any perceptible progress in comparison with the FAO model.

28. On the other hand, the model sensitivity analysis of the boundaries condition confirms the importance of extending the model limits to the actual system limits or as far as possible from the interested areas (the oases in the present case) even when there is an acute lack of data.

29. It could be considered that the model qualified by the study as a regional model has achieved the assigned planning objective one can expect from such a tool, that was designed for groundwater resources assessment at regional scale, and for predictions at the same scale of effects derived from different exploitation alternatives. But the critical relationship between the deep and shallow aquifers with the corresponding exploitation and management alternatives was not deeply analysed. Field investigation of the shallow aquifer piezometry, a more detailed simulation addressing specifically the confining bed geometry and its hydraulic characteristics would be essential to any pre-feasibility or feasibility study of agricultural development in the oases based on groundwater pumping from the shallow and/or deep aquifers.

Optimum well field design programme

30. It corresponds to a computer programme which gives automatically the standard well design for each area of development taking into account the aquifer characteristics of the zone, the annual and peak water requirements, the number of operating hours, the investment, operation, maintenance and reparation costs of water at well head and at the farmer's field. One of the principal constraints explicitly used in the programme is water table drawdowns and consequently the pumping depths at the end of the planning horizon (100 years).

31. The programme is highly valuable for future exercises of planning or analyses of management alternatives, as it allows rapid evaluation or computation of water cost with various hypotheses on physical and economic influencing factors (aquifer and well construction characteristics, formation loss, well loss, energy cost, discount rate...). However, the programme actually is not an optimization model

with an explicit optimization function either at the well scale or the well field scale. Its title is rather misleading. Future users of the programme should be aware of its limitations. Moving from the regional planning scale to actual well design for localized development areas, actual detailed field data for more realistic prevision could be as important as pseudo optimization techniques.

IV. PROPOSED STUDIES

32. The Regional Development Plan for New Valley, briefly analysed in the previous section, constitutes an excellent plan resulting from a comprehensive approach and realized with limited time and means. However, it should be considered as a framework plan only, which provides basic guidelines and strategies for the development of the region based mainly on the Nubian sandstone aquifer exploitation. Some results such as those derived from the optimum well field programme (Annex C - Appendix V) should not be considered as actual design criteria in spite of their apparent precision, which is a pure product of computational process.

33. Strong discrepancy in the economic evaluation of land rehabilitation and land reclamation between the Regional Plan and the FAO-AfDB preparation mission report^{*}, deriving from different cost estimation mainly for water development, calls for detailed studies at pre-feasibility or feasibility level prior to any implementation of the agricultural development programme proposed by the Regional Plan. According to the Plan, the estimated economic rate of return would be 38,2% for rehabilitation land, and 17,1% for reclamation land whilst FAO estimation results in 0% for virgin land reclamation, 14% for land already reclaimed, and 12% for rehabilitation.

* FAO - Investment Center - New Valley rehabilitation project - Egypt - Preparation report - 12/82 DDC EGY/22 - March 1982

34. The studies proposed hereinafter will only deal with the hydrogeological and economic aspects of water resources development of the Nubian sandstone aquifer in the oases, with a pre-feasibility and feasibility orientation.

Field investigation of the shallow aquifer
of the Nubian sandstone system

35. The importance of the relationship between the shallow and deep aquifers of the Nubian sandstone system has been mentioned. To simulate correctly the two subsystems, the piezometry of the shallow aquifer, which has been neglected by previous studies, must be investigated carefully. Field investigation would be based exclusively on measurements of numerous existing wells in the oases. The duration of the investigation is estimated at four months, including potentiometric map and report preparation.

Nubian sandstone aquifers management model
for New Valley

36. The model would have a precise and explicit objective : to analyse different alternatives of groundwater resources management, i.e. the development of these resources through various possible combinations of exploitation of the shallow and/or deep aquifers according to local hydrogeological conditions of each oasis in view of minimizing water cost.

37. Although the study would be centred on the oases, the model would cover the entire Western Desert to minimize any boundary condition effects. It is proposed to use the USGS-Peter Trescot finite difference programme, the flexibility and versatility of which are well known. Node areas would range from 25 km² to 100 km² in the oases, and could reach 25.000 km² in the desert zone.

38. The model would simulate an actual confining bed separating the two aquifers instead of a conceptual one adopted by the two previous models (1976, 1982). The simulation would require a detailed input data preparation for the aquitard top level (= bottom of shallow aquifer) and bottom level (= top of deep aquifer).

39. For calibration and analysis of the leakage coefficient or vertical permeability of the confining bed, it is suggested to operate first with the shallow aquifer kept artificially inactive.

Well field optimization

40. This study would develop an optimization model for well field design with an explicit objective function such as minimization of water cost at the well head and in the farmer's field. Working at the design scale, the model would require input data actually collected and compiled specifically for each area of potential development.

41. It would also work interactively with the agricultural linear programme and the groundwater model.

Implementation of studies

42. The New Valley Development Authority (NVDA) of the Ministry of Development is the principal agency responsible for project development and implementation. Actually, the main task of NVDA is to implement projects and monitor their progress until completion, and then to hand over to the civil administration. Under the mounting pressure of project implementation with concern for schedules and deadlines, NVDA has rather neglected the importance of comprehensive economic planning and basic studies. There is an acute lack of adequately trained and skilled professionals for these activities.

43. To realize the proposed studies it would be more advantageous for the NVDA and Ministry of Development to sub-contract them to the General Authority for Reclamation Projects and Agricultural Development (GARPAD) which has an extensive experience of groundwater investigation and management in the Western Desert and a multidisciplinary staff of civil engineers, geologists, hydrogeologists, soil experts, agronomists, economists, well superintendents ... On the other hand, as resource planning and management are conceived as a dynamic system with continuous efforts of adjustment, updating the system analysis tools would be better developed and maintained by a governmental organization in close relation with NVDA, the implementing agency.

44. The total duration of the proposed studies would be 12 months, with 4 months for field investigation and 8 months for system analysis. The total budget would amount to 138,600 L.E. (A tentative detailed budget is presented in Appendix 2). It may be mentioned here that the average cost of an exploration or exploitation of a deep well in the Western Desert is about 250,000 L.E.

V. GROUNDWATER RESEARCH INSTITUTE ACTIVITIES

The Transnational Project on the Major Regional Aquifer in North-East Africa

45. The Groundwater Research Institute has participated in this project since 1982, as the Egyptian counterpart.

46. The project includes an Egyptian national component of 5 years' duration, a Sudanese national component of 9 years' duration and a United Nations (UN/DTCD and UNEP) co-ordination component of 1 year's duration.

47. A United Nations extension of 3 years with possible financial participation of the United Nations Development Programme is under negotiation.

48. The main objective of the project is to arrive at a rational, economical and sustained use of the Nubian sandstone aquifer which extends over great areas of both countries.

49. The two national component activities include the classical methods of aquifer investigation with Landsat mapping, aerial and ground mapping, subsurface investigation in selected areas, pilot experimental projects for water use, wells inventory, topographic survey, geophysical survey. The Sudanese counterpart has programmed a mathematical model to be implemented during the final phase of the project.

50. The U.N. component includes co-ordinator and consultants' services, an information and data system, training of technical personnel, and organization of seminars.

51. The workplans of both Egyptian and Sudanese components incorporate the use of well accepted methodology for preliminary groundwater resources assessment, and also the establishment of projects for immediate water resources use in agricultural development. However, the brief review of existing hydrogeological data during this mission would suggest that groundwater resources to be tapped from the Nubian sandstone aquifer may not represent the major constraint to economic development of the areas under consideration in both Egypt and the Sudan. In the workplans little attention had been given to numerous other socio-economic factors which are crucial for any sound and comprehensive design of agricultural development strategy. Even if the project is primarily an hydrogeological investigation, its water resources evaluation

efforts should be placed into the socio-economic framework of the region, as groundwater is but one subsystem in hydrology, and hydrology only one subsystem in the larger realm of land and water planning and management. Planning and decision-making on water resources development constitute a series of exercises in alternative allocations and trade-offs in a setting of physical, economic, social and policy constraints. In systemic approach terms, a groundwater resources subsystem, even in an early phase of investigation, would be better conceived and analysed if it were integrated into a larger system of water demand for socio-economic development.

52. This approach also applies to optimization of investigation efforts under time and budget constraints. During the first operational year, the project teams have compiled almost all geologic and hydrologic data readily available. They are sufficient to define the basic features of the groundwater reservoir. A global evaluation should be undertaken in order to clarify the main hydrologic elements of the problems and the most promising approaches to solutions. A first-cut mathematical model is the tool proposed for such global evaluation. Though based on limited available data, it would be highly helpful to perceive clearly the hydrogeologic problems for which the groundwater investigation is programmed, and to ensure that the data to be collected will have full bearing on those problems.

53. It is recommended that the project (i) implements as early as the beginning of 1984 a first-cut mathematical model to simulate the Nubian sandstone aquifer system in both areas of investigation in Egypt and the Sudan (ii) prepares a framework study of socio-economic environment for agricultural development in the considered areas of both countries, which would provide the guidelines for future

groundwater resources exploitation. These two activities are essential to optimize the investigation efforts of the project.

Groundwater studies in the Nile Delta and Valley

54. The consultant had the opportunity briefly to review various on-going hydrogeological studies with the G.R.I. staff members.

55. A study of the groundwater resources of the Nile Delta using finite element models for reservoir simulation and salt water/fresh water interface analysis entitled "Systems Analysis of the Nile Delta Aquifer" by Samir Farid, is almost completed. The study could be used for a next step analysis of conjunctive use of surface and groundwater resources in the Nile Delta.

56. In the same investigation line, the G.R.I. is carrying out pilot projects of irrigation with groundwater in the Nile Valley, of water balance analysis for vertical drainage alternatives (Miria Governorate) and of groundwater reservoir conservation for Greater Cairo water supply.

57. These studies constitute a highly valuable basis for a future comprehensive integrated management of surface and water resources in the country. The staff members should be encouraged to progress in the field of analysis of complex water systems and economics of land and water development.

VI. CONCLUSION AND RECOMMENDATIONS

58. The Regional Development Plan for New Valley carried out recently by the Ministry of Development constitutes a sound and comprehensive framework plan for the four principal

oases of the Western Desert. For the following pre-feasibility and feasibility analysis step, complementary field investigation, groundwater management models and optimized well field design are proposed. With a view to ensuring a continuous effort in groundwater resources management and monitoring, it is suggested that the proposed studies be carried out with the close co-operation of GARPAD under NVDA responsibility.

59. In relation with the Transnational Project on the Major Regional Aquifer in North East Africa, it should be recalled that, since 1962, Unesco has promoted regional co-operation for Nubian sandstone aquifer investigation, organized numerous meetings and seminars on regional aquifers, and executed groundwater projects on a regional scale. Therefore, the Groundwater Research Institute as participating agency in the project has expressed strong interest in having Unesco co-operation for the next project extension, as well as for other activities of the Institute, mainly in the systems analysis field and the training of technical personnel.

60. It is recommended that a mission go to Egypt and the Sudan as soon as possible and explore the possibility of EXTERNAL participation in the project while its extension is still under negotiation.

61. With a view to making a more effective impact, and subject to a formal request from the Government, a consultant mission should be programmed for the beginning of 1984 to assist the Groundwater Research Institute and its Sudanese counterpart in structuring the proposed first-cut mathematical model of the Nubian sandstone aquifer covering the project areas of both countries. This should lead to future extensive co-operation in the ample field of systems analysis for conjunctive use of ground and surface water, water resources management and protection.

PERSONALITIES MET

EGYPTIAN NATIONAL COMMITTEE FOR THE INTERNATIONAL
HYDROLOGICAL PROGRAMME

Dr. Ahmad Ali Kamal - Chairman

GENERAL AUTHORITY FOR RECLAMATION PROJECTS AND AGRICULTURAL
DEVELOPMENT - Groundwater Department

- Dr. Mohamed Aly Ezzat - Director
- Eng. Salah Nour - Deputy Director
- Eng. Rafai Shaker - Drilling Section
- Eng. Magdi Mishriki - Reservoir Section
- Mr. Hamed Shaker - Geologist

GROUNDWATER RESEARCH INSTITUTE (Ministry of Irrigation)

- Dr. Kamal Hefny - Director
- Dr. Abdelsalam Moursy - Deputy Director, Team Leader of the Transnational Project on the Major Regional Aquifer of North-East Africa
- Eng. Samir Farid - Team leader of the hydrogeological training project
- Eng. Awad El Meligy
- Dr. Mayhawvy Diab - Consultant
- Mr. Ali Abdala
- Ms. Nadra Ibrahim
- Ms. Soad Hassan
- Ms. Samira Nancy
- Ms. Fatma A. Rahman
- Ms. Maha Abdel Salam
- Ms. Nahed El arabi

UNESCO

Mr. Vernon L. Mendis - Unesco representative
Ms. Rageh - Administrative Officer.

BUDGET FOR INVESTIGATION AND ANALYSIS
OF THE NUBIAN SANDSTONE AQUIFER SYSTEM
IN THE WESTERN DESERT OASES

| | <u>m/m</u> | <u>L.E.</u> |
|---|------------|-------------|
| <u>1. Field investigation</u> | | |
| - Team leader* | 4 | 3.200 |
| - Hydrogeologists* | 16 | 9.000 |
| - Transport facilities | - | 21.600 |
| - Reports | - | 5.000 |
| Subtotal 1 | | 38.800 |
| <u>2. Aquifers management model and well field optimization study</u> | | |
| - Team leader* | 9 | 4.800 |
| - Engineers, hydrogeologists, analysts, economists* | 64 | 25.600 |
| - Consultants . national | 4 | 4.800 |
| . international | 2 | 16.000 |
| - Micro computer facilities | - | 30.000 |
| - Reports | | 6.000 |
| Subtotal 2 | | 87.200 |
| Total 1 + 2 | | 126.000 |
| Contingencies | | 12.600 |
| GRAND TOTAL | | 138.600 |

* Fees calculated at the overtime rate.