INTELLIGENT CONDITION MONITORING OF ROTATING MACHINERY

P. Akangah[1] and K. Wang[2]
[1]Department of Mechanical Engineering, KNUST, Kumasi, Ghana
[2]Department of Production and Quality Engineering, NTNU, Trondheim, Norway

ABSTRACT
This study investigated the use of pattern recognition techniques in intelligent diagnosis of rotating machinery. Existing literature on machine fault diagnosis suggested many approaches to machine diagnosis: notable among them are pattern recognition technique, data mining and Hidden Markov Modelling. A method using MLP neural network classifier for pattern recognition of fault in a centrifugal pump-rig has been developed. The study was primarily experimental and involved the simulation of six types of faults on a centrifugal pump, one at a time. These were bearing failure, seal-ring wear, misalignment, unbalance on impeller, cavitation, and unbalance on coupling. Data were collected using a portable data acquisition system: SKF Microlog. Data were collected when the pump was in no-fault condition. Each fault was trained on a separate neural network, giving a total of six types of networks with different number of inputs and only one output. The results obtained from the simulation work confirmed previous studies that pattern recognition technique is effective in recognising and classifying machine faults. Using the seal-ring wear as an example, the distribution of weight vectors showed low weight values distributed around zero. This is a sign of a healthy network. The distribution was also slightly skewed to the left, indicating the presence of large weight values, and subsequently, the network may have slightly over-fitted the data. The error associated with a decision made by the network was evaluated. After 240 epochs, an average error of 0.004070 was obtained. The validation set error obtained was 0.0%.

Keywords: *Intelligent Diagnosis, Neural Network, Condition Monitoring, Pattern recognition, Fault Diagnosis*

INTRODUCTION
This study seeks to develop a neural network that has the ability to recognise faults in a centrifugal pump test rig. Detection, location and analysis of faults play a vital role in the field of rotating machinery because of the requirement of high reliability imposed on these systems, and the need to operate for longer periods (Edwards, *et al.*, 2005).

The application of neural computing technique in machine condition monitoring has been of interest to many scientists and engineers since the 1980s; neural computing techniques are very good at pattern recognition, manipulating noisy data and generalising. These properties are ideal in the field of machine condition monitoring (Harris, 1996).

Edwards, *et al* (2005) presented a very comprehensible review of the state of the art techniques in rotating machinery fault diagnosis, citing fault detection and isolation (FDI) techniques: vibration condition monitoring; fuzzy logic and neural networks, as some of the current techniques. Fault detection and isolation using fuzzy logic and neural networks are becoming more popular, because of the complexity of modern rotating machinery. This complexity hampers the operator's ability to diagnose and eliminate equipment failures before their occurrence (Chen and Mo, 2004).

Other researchers have also used other methods to automate machine fault diagnosis. Jiang, *et al.*, (2002) investigated the use of data mining technique to machine fault diagnosis; Sun, *et al.*, (2004) carried out a study using pattern recognition ability of neural network in machine fault diagnosis; Ocak and Lopora (2005) developed a new bearing fault detection and diagnosis scheme that was based on the Hidden Markov Modelling (HMM) of vibrational signals.

Using experimental method, this study developed an intelligent diagnostic system based on pattern recognition that used data from vibration signals, flow leakage, and cavitation on a centrifugal pump-rig.

MATERIALS AND METHODS

The Experimental Set-up

The experimental pump-rig consists of a centrifugal pump designed for a pressure increase of 6.6 bars at flow-rate of 90 m^3/h with the pump operating at a speed of 3000 rpm. The drive unit is a three phase induction motor with power output of 26 kw. The pump-rig is mounted on rigid foundation and housed in a relatively noise-free environment. It is designed to lift and circulate water. The experimental pump-rig is shown in Figure 1. Both the motor and the pump are equipped with ball bearings.

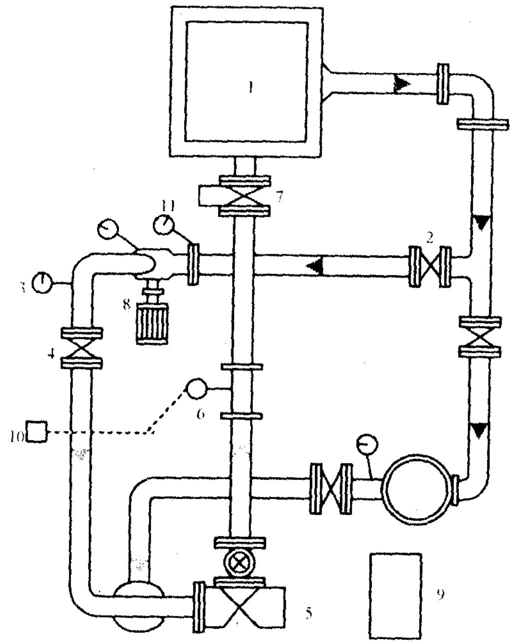

Fig. 1: Experimental Set-up as seen from above

1. Water reservoir.
2. Suction valve.
3. Pressure gauge.
4. Pressure valve.
5. 3-way valve.
6. Venturi-meter with differential pressure meter.
7. 3-way valve.
8. Centrifugal pump with electric motor.
9. Control unit, containing speed controller, start button, current, voltage and frequency meters etc.
10. Measuring bridge.
11. Pressure gauge, suction side.

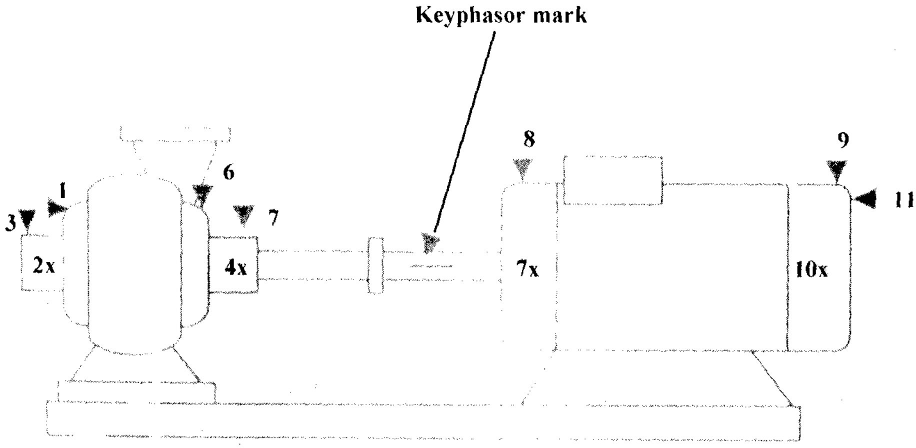

Fig. 2: Vibration measurement point

The various types of vibration measurements that were taken on the test-rig are shown in Table 1. Vibration measurements were taken in the axial direction at the free-ends of both the motor and the pump. Measurements were also taken at the vertical and the horizontal directions on the bearing housing at both the pump-drive and –free ends; the motor-drive and –free ends. Along the vertical direction on the pump casing, another measurement was taken close to the impeller. These measurement points are shown in Figure 2.

An optical Keyphasor™ was used to measure the speed of rotation and to give the reference for vibration measurement. Situated on the high pressure side of the circuit, pressure valve 4 was used to regulate the pump's capacity. The capacity was read using the measuring-bridge. The pressure difference over the venturi at full range corresponds to 1 bar. The delivery capacity, which is a function of the pressure difference, was estimated from the characteristic curve of the pump. The inlet and outlet pressures were estimated using pressure gauges 3 and 11, respectively.

Sixteen operational points were defined for the test-rig, and measurements were taken at these points for each fault. Four different speeds i.e. about 1880, 2200, 2700 and 3000 rpm were chosen. These were then matched with four different volume flows i.e. about 0, 30, 61 and 74 m^3/h. These combinations created 16 different operational points. Measurements were also taken at 7x7 operational points from 1880 to 3000 rpm and from 0 to 74 m^3/h. These operational points were taken without any faults, to give the reference points.

Each fault was simulated one at a time. Each operational point was set by regulating the flow valve 4 and the speed controller 9. For each operational point thus set, the Microlog data acquisition instrument was used to take vibration measurements at the 11 physical locations that were situated on the pump-rig as shown in Figure 2. The rotational speed was automatically keyed in, using the optical keyphasor™ reference mark, which is the fifth physical location. Using the dial gauges located on the test-ring, suction and outlet pressures were read and manually keyed in. Data that were collected by the Microlog were transferred to a dedicated computer and analysed using PRISM4 software. Prism4 provides a variety of pre-defined application functions, and stores equipment logging and test information in an embedded database within the software (Plant Maintenance Resource Centre, 2005).

Measurement Procedure

On the Pump-rig, the following faults were simulated:

- leakage from worn wearing-ring
- unbalance on impeller
- unbalance on coupling
- misalignment between motor
- pump, bearing damage and cavitation faults.

Wearing-ring fault: This fault was implemented by exchanging one of the two rings with another that had a clearance of 1.0 mm, instead of the recommended 0.25 mm. clearance is measured as the maximum distance between the inner side of the ring and the impeller in the radial direction.

Unbalance on impeller fault: This was implemented by exchanging the impeller with another which has a steel weight of 0.114 kg mounted on the suction side, at a radius of 100 mm. The shape of the weight was designed to give minimum disturbance to the flow around the impeller.

Unbalance on coupling fault: This fault was simulated by mounting a weight of 0.102 kg on the periphery of the coupling at a radius of 80 mm.

Misalignment fault: This fault was simulated by moving the motor in both vertical and horizontal directions. This movement created a combination of parallel and angular misalignment.

Bearing damage fault: This fault was implemented by exchanging the ball bearing at the pump's free-end with another bearing which has a small cavity on the inner ring.

Cavitation fault: This is unfavourable operational state because of pressure losses at the suction side at high flow rates. Valve 2 was used to regulate flow on the suction side to a pressure below the pump's net positive suction head (NPSH).

Selection of Features for Each Fault Category

A fault category is described by a set of features, which were selected according to a chart in Sawyer's Turbo-machinery (Sawyer and Hallberg,

Table 1: Measuring points and their corresponding vibration types

Equipment	Measuring Points	Type of Vibration Measurements
Pump	Free-end axial (1) Free-end horizontal (2) Drive-end horizontal (4)	Low Frequency Spectrum
	Free-end vertical (3)	High Frequency Domain Low Frequency Spectrum
	Free-end vertical (5)	High Frequency Spectrum
	Pump Casing (6)	High Frequency Domain High Frequency Spectrum
Motor	Drive-end horizontal (7) Free-end horizontal (10) Free-end axial (11)	Low Frequency Spectrum
	Drive-end vertical (8)	High Frequency Domain Low Frequency Spectrum
	Free-end vertical (9)	High Frequency Spectrum

1980). Features that were selected to describe the faults under investigation are shown in Table 2, and are related to vibration symptoms and distress manifestations. These features were selected because they offer high predictive power in the diagnosis of centrifugal pump condition.

For seal ring wear fault, the set of features that readily diagnosed this condition were decreased pump head at the corresponding flow rate and speed.

DESIGNING THE NEURAL NETWORK

A Multi-layered Perception (MLP) neural network was chosen. MLP uses back error propagation training algorithm. This classifier was selected because it is a powerful tool for condition monitoring: it is good at pattern recognition in noisy data and generalisation; it has the ability to correctly classify inputs not seen during the training process; it has other desirable properties such as speed and compactness (Roa, 1996).

Training Procedure

Two training modes, normal training and cross-validation, were used. In normal training mode, the number of hidden layers was initialised to the smallest number possible and for each trial, number of hidden neurons weights were initialised to small random numbers. The network was trained until further improvement was negligible. If the training set error was not acceptable, the number of hidden layer was increased by one and the network trained again. If the training error was acceptable, the network was validated, using a validation set. If the validation error was not acceptable, the weights were initialised to another set of small random numbers and training carried out again.

In the cross-validation mode, two separate and independent sets of training data were used. One was used to train the network in the normal way, and the other set was used at regular intervals to investigate the generalisation ability of the network.

Proposed Solution

In the MLP architecture chosen, each fault was assigned to a dedicated network. This is therefore a binary decision, i.e. a choice between two classes - a fault or no-fault condition, and therefore only one neuron was specified for each network as shown in Figure 3. An arbitrary activation level of 0.5 was selected. This means that, an activation of less than 0.5 is interpreted to mean no-fault condition, and an activation level of equal or greater than 0.5 implies the presence of a fault.

A classifier of configuration 6:3:1, implies 6 nodes in the input layer, 3 nodes in the hidden layer and 1 node in the output layer. Each fault classifier was trained using the appropriate set of features for that fault. Except for speed and flow rate, all the input data were given as decibels above their respective reference of no-fault condition value. These were scaled to an approximate range of 0 to 1.

Four training sets were built, each with different 25% of the data removed, which was used as the validation set. For each fault, four networks were built, trained and validated. The network

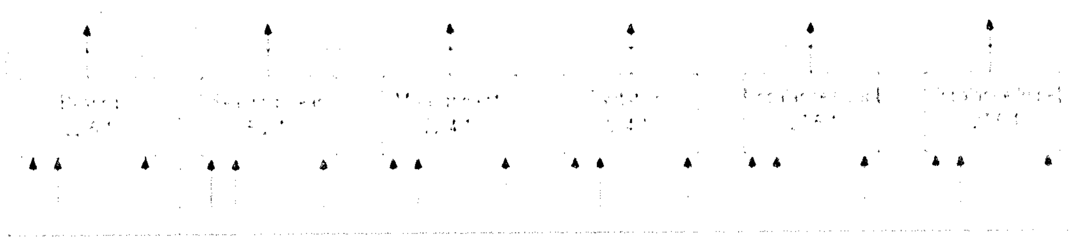

Fig. 3: Classifier Configuration

Table 2: Selection of Features

Feature	Predominant Frequencies	Direction and Location of Predominant Amplitude
Misalignment	1. Rotor frequency (speed) 2. 1x, 2x and higher multiples 3. High frequency spectra 4. Other data include flat shape orbit and a phase angle of 180° between the two bearings.	These frequency amplitudes are located at the vertical, axial and horizontal directions on the pump and motor's free- and drive-ends. These frequencies are also found on the pump's casing.
Bearing fault	1. Rotor frequency (speed) 2. 1x and 2x frequencies 3. High frequency spectra 4. High frequency domain	These are located at the vertical, axial and horizontal directions at the pump and motor free- and drive-ends. The pump's casing is also of interest.
Cavitation	1. Rotor frequency (speed) 2. 1x, 2x and higher multiples 3. High frequency spectra 4. High frequency domain 5. Sub-synchronous orders	The high frequency spectra and the HFD, that are of interest are located at the pump's casing. Others are at the vertical, axial and horizontal directions on the pump's free and drive-ends.
Unbalance	1. Rotor frequency (speed) 2. 1x, 2x and higher multiples 3. High frequency spectra Other data include: 1. High current consumption at high rpm and flow 2. Low efficiency 3. A phase difference of about 90° between the 1x vibration in the vertical and in the horizontal directions; and 0° between the 1x vibration at the pump's free- and drive-end bearings.	The locations of interest are the vertical, axial and horizontal directions on the pump and motor free- and drive-ends bearings.

that worked equivalently on both the train- and validation-data was selected.

RESULTS AND DISCUSSION

Bearing fault

The networks for the bearing fault were trained using the cross-validation mode. Each of the four nets performed equally well at their respective validation set. The configuration which gives the best result is 22:5:1. The simulation results are shown in Table 3.

Seal-ring fault

The networks for the seal-ring fault were trained using the cross-validation mode. There were some variations in performance of the various

Table 3: Bearing fault simulation results

Network	No. of Epochs	Average Error	Validation Error	Remarks
Bear1.ncs	330	0.045544	0.0%	
Bear2.ncs	110	0.030427	0.0%	Any of the nets can be selected
Bear3.ncs	1830	0.035357	0.0%	
Bear4.ncs	1040	0.029914	0.0%	

nets on their respective validation set. The configuration that gives the best result was 22:4:1. The simulation results are shown in Table 4.

Table 4: Seal-ring fault simulation results

Network	No. of Epochs	Average Error	Validation Error	Remarks
Srwear1.ncs	1050	0.182047	6.45%	
Srwear2.ncs	610	0.153230	6.45%	Net no. 4 was chosen
Srwear3.ncs	420	0.303390	16.13%	
Srwear4.ncs	1004	0.355809	3.13%	

Cavitation fault

These were trained using the normal training procedure. There were some variations in the results obtained. The configuration that gave the best result was 22:4:1. The simulation results are shown in Table 5.

Table 5: Cavitation fault simulation results

Network	No. of Epochs	Average Error	Validation Error	Remarks
Cavit1.ncs	251	0.027196	13.00%	
Cavit2.ncs	37	0.087640	9.70%	Cavit3.ncs was selected
Cavit3.ncs	45	0.090112	6.45%	
Cavit4.ncs	49	0.090689	9.70%	

Impeller fault

The nets were trained using the normal training procedure. There were significant variations in the results obtained. The simulation results are shown in Table 6.

Table 6: Impeller fault simulation results

Network	No. of Epochs	Average Error	Validation Error	Remarks
Impell1.ncs	13	0.099701	0.00%	
Impell2.ncs	281	0.020357	3.60%	The first net showed the best results
Impell3.ncs	290	0.035221	100.00%	
Impell4.ncs	18	0.092731	13.33%	

Misalignment fault

The first net was trained using the cross-validation method, whiles the remaining three were trained using normal training method. Both results compare very favourably. The configuration obtained was 22:4:1. The results are shown in Table 7.

Table 7: Misalignment fault simulation results

Network	No. of Epochs	Average Errors	Validation Error	Remarks
Misalig 1.ncs	280	0.107763	0.00%	The first net which was trained using cross validation, gave the best result
Misalig 2.ncs	960	0.255470	3.33%	
Misalig 3.ncs	9	0.093412	16.13%	

Coupling fault

This was trained using the normal training method. The results obtained vary significantly. The configuration that gave the best result is 27:5:1. The results are shown in Table 8.

Table 8: Coupling fault simulation results

Network	No. of Epochs	Average Error	Validation Error	Remarks
Couplg1.ncs	293	0.023210	0.00%	The first two nets are comparable and either could be chosen
Couplg2.ncs	291	0.023771	0.00%	
Couplg3.ncs	912	0.009627	43.33%	
Couplg4.ncs	540	0.009782	14.81%	

Measuring the Health Index of the Network

As an example, the seal-ring wear network was analysed. This can easily be extended to other networks.

The ability of a network to generalise can be determined from the distribution of its weight vectors. The weights connecting the input to the hidden layer were examined.

A weight histogram was built by calculating the range over which the weights in the network vary. This range was split into arbitrary number of 10 sub-ranges. A histogram with weight size along the bottom axis, with the vertical axis showing the frequencies of the weights of each size was developed as shown in Figure 4.

The results revealed low weight values that were distributed around zero. These are some of the attributes of a healthy network. The distribution was also slightly skewed to the left, indicating the presence of large weight values, and subsequently, the network may have slightly over-fitted the data.

Network Output and Error Analysis

The error associated with a decision made by the network was evaluated. A single error over the 32 output units, taken from the validation set, residual chlorine at the sources (Owabi and Barekese), initial residual chlorine concentration in the network, and the chlorine decay coefficients.

The residual chlorine concentration of the treated water from the treatment works was determined by the ortho-tolidine method. The chlorine residual of the water entering the network, just after the treatment process at Owabi was found to be 0.4 mg/l on the average, whilst that of the Barikese headwork was 0.3mg/l. After post chlorination in the reservoirs at the Suame distribution centre the residual chlorine concentration for the water leaving the ground water reservoirs was 0.2mg/l. On the average the residual chlorine concentration within the network was less than 0.1 mg/l.

For the simulation, the residual chlorine concentration throughout the network except the sources at Barikese, Owabi and the ground reservoirs were set at 0.1 mg/l at the start of the simulation.

The decay rate in the bulk water was determined by the bottle point analysis and was found to be 0.85 day^{-1} (Figure 5). Pipe wall decay coefficient "K_w" for the transmission mains and distribution mains could not be measured during the fieldwork because of the lack of equipment.

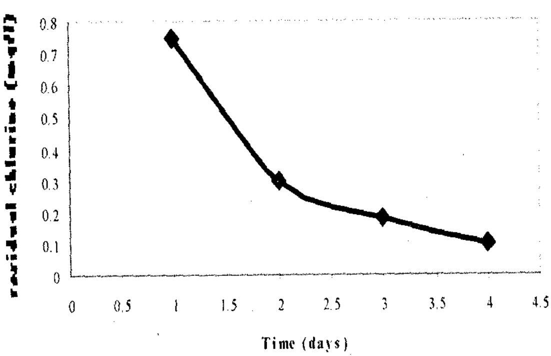

Fig. 5: Chlorine Demand curve

Tables 2 and 3 summarise the decay coefficients from the work of other authors. Therefore, pipe wall decay coefficient was initially estimated based on previous work by others (Clark, 1994; Clark *et al.*, 1994) after which the values were adjusted until the field measurement and model results converged.

Table 2: Summary of decay coefficients from the Saltonstall study

Area	Decay coefficient (day^{-1})
"Off main" locations	5.01
Reservoir	0.60
Reservoir line	4.7

Source: Clark, 1994

Table 3: Decay coefficient for chlorine demand from the Fort Monmouth study

Type of pipe	Diameter (cm)	Length (m)	Flow rate (m^3/s)	Decay coef. (day^{-1})
Unlined cast iron	15.3	537	0.0015	7.78
Unlined cast iron	30.6	1080	0.0090	5.76
PVC	30.6	531	0.0060	4.89

Source: Clark, 1994

The values of "K_w" were adjusted till the predicted value of the residual chlorine was the same as the measured. The pipe wall decay coefficients used in the network varied between 1.4 and 6 day^{-1} depending on size and age of the pipe.

RESULTS AND DISCUSSION

The water quality model was used for the following:

- Extended simulation of residual chlorine concentrations was performed for different operating conditions in the system. Four nodes were selected for studying the water quality variation in the network. Two nodes, namely, Kejetia and Georgia were selected from the low-level zone while Yenyawoso and Prempeh were selected from the high level zone. These were selected because of the following reasons: the nodes cover both pressure zones, easily accessible for sampling and are designated sampling points for Ghana Water Company Limited and as a result past records on water quality are available.

- Simulation of water age, which is the time spent by a parcel of water in the network was performed. The water age concept is based on the principle that new water entering the network from the source nodes enters with age of zero.

The water quality parameters used for the study, residual chlorine concentration and water age, were analysed for two different scenarios. Figure 6 depicts the variation of residual chlorine concentration with time for the existing situation and the two options proposed. It is interesting to note that at the four nodes considered in this case, the two scenarios give reasonable results.

Residual Chlorine

As mentioned already, the existing situation of residual chlorine concentration of 0.3mg/l at Barikese, 0.4mg/l at Owabi and 0.2mg/l at the Suame distribution centre produced undesirable residual chlorine concentration predominantly less than 0.1 mg/l in the network: few show trace or detectable residual chlorine whilst most were nil. Generally the acceptable residual chlorine levels in the distribution networks vary from country to country. In the United States, it is required that post chlorination should have a minimum of 0.2 mg/l entering the network and that a detectable residual must be maintained throughout the system (Grayman *et al.*, 2000). The Ghana Standards Board requirement for residual chlorine concentration should be in the range of 0.2mg/l – 0.5 mg/l within the network (GSB, 1998). Given the poor state of residual chlorine levels in the network, two scenarios that improve residual chlorination concentration in the network were considered and are discussed. The minimum residual chlorine concentration within the network considered to be satisfactory was 0.1mg/l for this study.

Scenario A was considered as the case where the water entering the network (from both sources) have residual chlorine concentration of 1.0mg/l and post chlorination done to achieve a residual chlorine concentration of 0.5 mg/l at the Suame distribution centre. This scenario looks at increasing the dosage of disinfectant because the

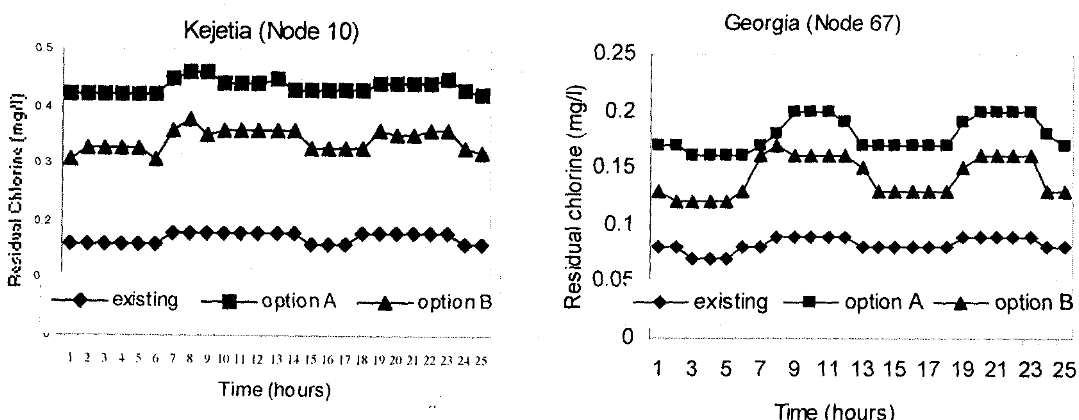

Fig. 6: Residual Chlorine variation at four selected nodes

existing situation is inadequate and utilises the available or existing facilities to improve the situation. The results depicted in Figure 6 show that the residual chlorine concentrations generally vary within the range of 0.1-0.4 mg/l in the network, which implies that this scenario could be an acceptable option.

A second option considered, Scenario B, where the water entering the network (from both sources) will have residual chlorine of 0.6 mg/l and chlorination is further boosted in the reservoirs at the distribution centre in Suame to achieve residual chlorine concentration of 0.4 mg/l for water leaving the distribution centre to the low pressure zone. In addition the chlorine concentration at node 22 (Suame round about) near the distribution centre at Suame is also boosted to 0.4 mg/l to feed the high-pressure zone.

This option calls for additional investment for a booster chlorine station. In this case the results are also acceptable with residual chlorine levels primarily between 0.1-0.3 mg/l in the network.
Both scenarios give acceptable results. However, option "B" reveals the following advantages:

- Optimising the quantity of chemicals used for the disinfection
- The reduction of the primary chlorine dose prevents consumers close to the source taking excessive amounts of chemicals (disinfectants)
- The introduction of the booster chlorinator at node 22 (Suame roundabout) near the distribution centre improves residual chlorine levels in the high-pressure zone. This is useful for the present situation and for future extension of the network.

The residual chlorine map such as Fig. 7 depicts residual chlorine levels throughout the network in the form of contour map for the scenario B condition at the minimum consumption hour at 02:00 hrs. This kind of model is useful for providing information to help in the planning to ensure acceptable residual chlorine in the network. As indicated on the contour map, the few areas most susceptible to water quality deterioration is found in areas around Santasi and east of the Airport (Yenyewaso) with residual chlorine levels less than 0.1mg/l. These areas should be sampled more frequently and water quality improvement measures such as flushing should be done more frequently.

Water Age

Water age is the time spent by a parcel of water in the network. New water entering the network from the source nodes enters with age of zero. Water age provides a simple, non-specific measure of the overall quality of delivered drinking water. When the model is run under constant hydraulic conditions, the age of water at any node in the network can also be interpreted as the time of travel to the node.

Fig. 8 shows the results for water age for the same set of operation conditions as the residual chlorine concentration presented in Figure 7 for option B. The results show that the water age ranges from 0 to 20 hours as depicted in Figure 8. The water in the southern part of the network is generally older (age 10-15 hours) than the other areas. This confirms that the southern part of the network is within the low-pressure zone and receives water from the ground reservoirs. The areas with water age ranging from 5-10 hours are predominantly the high-level zones and low-level zones closer to the ground reservoirs. Specifically, the areas such as stadium, Ahinsan, Georgia and Mangodown were found to have water ages above 16 hours. As such, these areas with high water ages of more than 16 hours should be monitored and flushed more frequently than the other areas. Areas like Santasi, Bantama, and Yenyewoso had water ages within the range of 8 – 12 hours.

The four nodes selected had two in the high-pressure zone and two in the low-pressure zone. Simulation revealed that, using scenario B im-

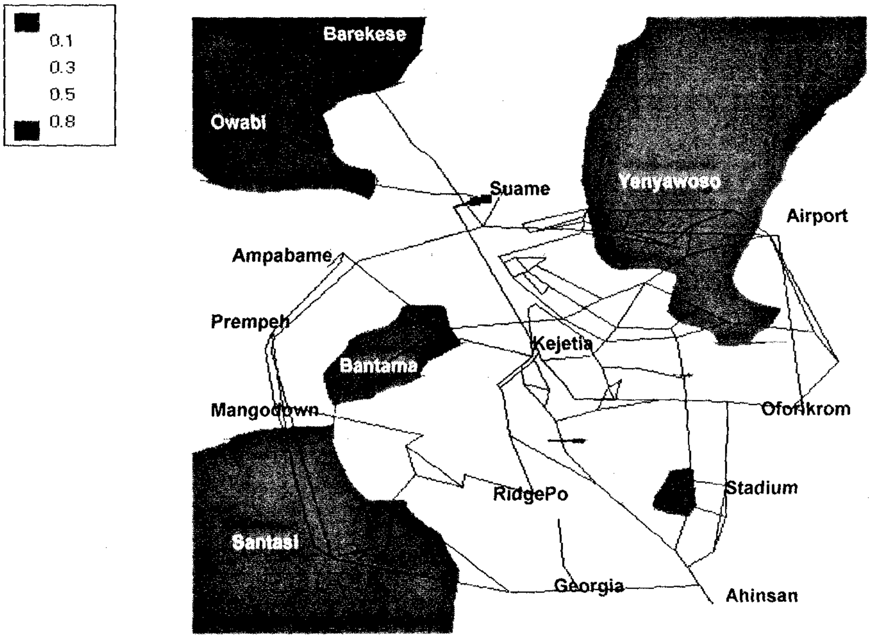

Fig. 7: Contour Map for Residual Chlorine (mg/l)

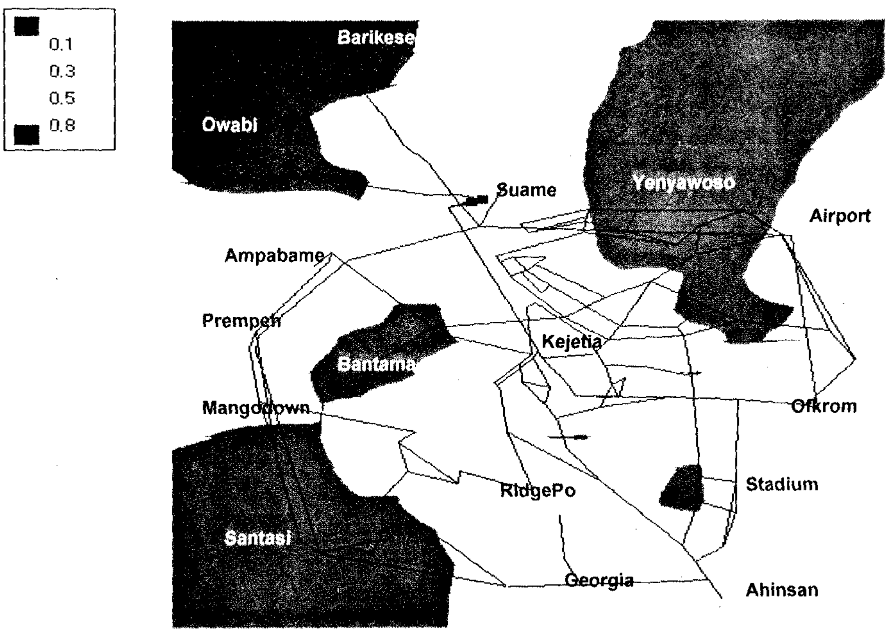

Fig. 8: Contour Map for Water Age in hours

proved the residual chlorine concentration at Prempeh and the corresponding water age also within acceptable range. The situation at Kejetia was also within acceptable range. At Georgia, although the water age was above 16 hours, the residual chlorine concentration was within acceptable range and hence water supply from this node will not pose any hygienic threat to users. The only node with unacceptable condition is the Yenyanwaso node where although the water age is between 8 and 12 hours the residual chlorine concentration was below 0.1 mg/l. As such areas around this node should be flushed more frequently.

CONCLUSION

An EPANET-based model capable of predicting residual chlorine concentrations and water age in a distribution system has been developed. The model was successfully used to create water quality zones of the Kumasi distribution network. Based on the zoning, effective monitoring and flushing programs can be carried out to improve management of water quality in the system. The critical area identified by the model is the area around Yenyawoso with residual chlorine less than 0.1 mg/l. This area should have a higher water quality monitoring frequency. The pipes located in these areas should be flushed frequently, at least once in three months. The model is good and may be a useful tool for monitoring and evaluating water quality programs.

REFERENCES

Chun, D. G., and Selznick, H. L. (1985). Computer modelling of Distribution system water quality. Proc, ASCE Spec Conf on Comp Applications in Water Resources, ASCE, New York, N. Y.

Clark, R. M. (1994). Modelling water quality changes and contaminant propagation in drinking water distribution systems: A US perspective. *J Water SRT – Aqua* Vol 43, No 3: 133-143.

Clark, R. M., Smalley, G., Goodrich, J., Tull, R., Rossman, L.A., Vasconcelos, J.J., and Boulos, P. F. (1994). Managing water quality in distribution systems: Simulating TTHM and chlorine residual propagation. *Journal Water S. R. T. Aqua* Vol 43, No. 4: 182-191.

Cohen, J. (1991). Further development of a dynamic calculation and simulation model for water distribution. Proc AWWARF/EPA Conf on water quality modelling in Distribution Systems, AWWA Research Foundation, Denver, Ohio.

GSB (1998). Ghana Standards 175, Ghana Standards Board, Accra, Ghana.

Grayman W. M., Rossman, L. A, and Geldreich. E.E. (2000). Water quality. In Mays, L.W. (ed) Water Distribution Systems Handbook. McGraw Hill, 9.3-9.15.

Harding, B.L., and Walski, T. M,. (2000). Long time-series simulation of water quality in Distribution systems. *ASCE Journal of Water Resources Planning and Management* Vol. 126, No 4: 199-209.

KMA (1996). Development Plan for Kumasi Metropolitan Area (1995-2000), Kumasi Metropolitan Assembly.

Mau, R. E., Boulos, P.F., Clark, R. M., Grayman, W. M., Tekippe, R. J., and Trussell, R. R. (1995). Explicit mathematical models of distribution storage water quality. *ASCE. Journal of Hydraulic Engineering*, ASCE 121(10): 699-709.

Nyarko, K. B., and Odai, S. N. (2002). Predicting Residual Chlorine propagation in the Kumasi Water Distribution System. Proceedings of the Fifth International Conference on Structural Engineering Analysis and Modeling, February 26–28, Accra: 8-11–8-20.

Rossman, L. A., and Boulos, P. F. (1996). Numerical Methods for modelling Water Quality in Distribution System: A comparison.

ASCE Journal of Water Resources Planning and Management Vol. 122, No 2: 137-146.

Tryby, M. E., Boccelli, D. L., Uber, J.G., and Rossman, L. A. (2002). Facility location model for booster Disinfection of water Networks. *ASCE Journal of Water Resources Planning and Management* Vol. 128, No 5.

Journal of Science and Technology

ADVERTISEMENT

As from January 2006, two pages of each issue of JUST has been reserved for institutions (local and international), manufacturing and commercial organizations to advertise their products and place announcements. Appropriate fee will be charged for the space that will be made available.

BRIEF ON THE AUTHORS

B. ADU-AMANKWA

He is a Senior Lecturer in Chemical Engineering and consultant in project engineering and financial analyst. He is a member of Ghana Institution of Engineers (GIE). His research and professional interest span into areas of reaction engineering, mass transfer, extractive and biotechnology, process design, business plan formulation, investment analysis of projects. He was a former director of an Investment Bank and involved in analysis, financing, implementation and supervision of industrial projects. E-mail: aduamankwa@yahoo.com; baamankwa.soe@knust.edu.gh.

C. AGYARE

Lecturer at the Department of Pharmaceutics, Faculty of Pharmacy and Pharmaceutical Sciences, College of Health Sciences, Kwame Nkrumah University of Science and Technology (KNUST).
He holds a BPharm and MPharm from Kwame Nkrumah University of Science and Technology (KNUST). His area of interest is in natural products research with emphasis on antimicrobial principles from medicinal plants. E-mail: chrisagyare@yahoo.com.

R. AKROMAH

He holds a PhD from The University of Reading, UK. He is a lecturer in plant breeding and biotechnology at the Department of Crop Science, KNUST, Kumasi. E-mail: rakromah@yahoo.com.

S.K. AMPONSAH

He holds a PhD (Mathematics and Statistics) from Birkingham, UK, an MSc, BSc. (Maths) from KNUST and he a lecturer in the Department of Mathematics, College of Science, KNUST.
Dr. Amponsah is a member of the African Operations Research Society (OPRA) and the Mathematical Association of Ghana (MAG).
He has eight books and several publications to his credit and his research interests are in the Heuristics, Routing, Location, waste Management and Probability.
He is currently the Chairman of The Board of Governors of the Angel Educational Complex, Kumasi.

C. ANSAH

Lecturer, Department of Pharmacology, College of Health Sciences, KNUST, Kumasi, Ghana. He holds a B.Pharm degree from the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, and an MSc., DIC and a PhD in Molecular Toxicology from Imperial College London. His research interest is in the safety assessment of medications from botanical sources. E-mail: cansah.pharm@knust.edu.gh.

M. D. ASANTE
He is a rice breeder with the CSIR-Crop Research Institute. He holds an MSc Agronomy (Plant breeding) degree from Kwame Nkrumah University of Science and Technology. His current research interest is studying quality traits of rice in order to develop rice varieties with characteristics that are acceptable to Ghanaian consumers. He is presently doing a molecular mapping study of the gene controls aroma in NERICA rice at Cornell University, NY, USA. E-mail: mdasante@yahoo.com.

P.K. BAIDOO
Lecturer at the Department of Theoretical and Applied Biology, Kwame Nkrumah University of Science and Technology, Kumasi. He holds B.Sc. (Dip. Ed.), MPhil and Ph.D. from the University of Cape Coast. His current research interests are fungal pathogens that cause mortality in maize stem borers. E-mail: pkbaidoo2002@yahoo.com

M.A. BOTCHEY
Associate Professional of Entomology of the University of Cape Coast. She holds B.Sc. General Ed. (Cape Coast), Ph.D. (Entomology) University of Ghana, Legon. She is currently the Head of the Department of Human Biology, University of Cape Coast. Her research interests include studies of stem borers of maize and their parasitoids. She is also working on the genetic diversity of bees.

P. K.A. DARTEY
He holds a PhD from the University of Liverpool, UK. He is currently working as a rice breeder with the CSIR-CRI. E-mail: pkadartey@yahoo.co.uk.

M. DUWIEJUA
Associate Professor, Department of Clinical and Social Pharmacy, College of Health Sciences, KNUST, Kumasi, Ghana. E-mail: mduwiejua.pharm@knust.edu,gh

D. K. DJOKOTO
BSc. Food Science & Nutrition, Legon; MSc. Food Science & Technology, KNUST. Chemistry Teacher, Ejisu Secondary Technical School, Ejisu Ashanti.

V.P. DZOGBEFIA
Associate Professor of Biochemistry and current Dean, Faculty of Biosciences. She holds B.Sc.; Ph.D. Biochemistry in KNUST and Oregon State University, USA, respectively. She holds Certificate in Introduction to Industrial Biotechnology from Biotechnology Research Centre, Brauschweig, Germany. Her area of specialization and research interest is in Enzymology and Enzyme Biotechnology, Application of enzymes of industrial processes, application of fungi as enzymes sources for bioprocessing of agricultural wastes into food and feed. E-mail: vicdzogbefia@yahoo.com

K. EDUSEI
Holds the B.A. (Art) degree in Painting, M.A. (African Art), P.G. DAE (Art Education) and Ph.D (Art Education). He is a Senior Lecturer in Art Education with areas of specialization as Painting, Sculpture, Educational Foundations - Philosophy, Sociology and History of Education. E-mail: kodwoedusei05@yahoo.com.

T.C. FLEISCHER

Senior Lecturer and Head of Department of Herbal Medicine, Faculty of Pharmacy and Pharmaceutical Sciences, College of Health Sciences, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi.

Holds a BPharm and MPharm (Pharmacognosy) from KNUST, Kumasi; PhD from Strathclyde, University of Glasgow, UK. Member of the Pharmaceutical Society of Ghana. His area of interest is in Medicinal Plants with antimicrobial, antiasthmatic and antidiabetic activities, composition and mosquito repellant properties of essential oils, Phytochemistry. E-mail: tc_fleischer@yahoo.com.

J. M. FRIMPONG

Frimpong is a Lecturer in Economics and Finance as well as a Business Consultant. He holds a Teachers' Diploma in Mathematics (Winneba), BA Economics/Law (KNUST), MSc. Project Analysis, Finance and Investment (York, England) and Advanced Diploma in ProfessioOnal Studies (London). He also holds a Qualified Overseas Teachers' Status, England (DES Number: 9042992) and has taught in and researched from a number of academic institutions in London. At KNUST he has successfully supervised numerous MA and MBA graduate thesis in Economics, Financial Management and Entrepreneurship. His wide international experience and in-depth knowledge in Mathematics, Economics, Finance, Econometrics, Research and Business Consultant has enabled him to serve as distinguished resource person and consultant for several institutions including CIAMC, CBUD, EMPRETECH - Ghana Foundation, and Barclays Bank. E-mail: jf_magnus@yahoo.com.

D. K.B. INKOOM

Lecturer, Department of Planning, College of Architecture and Planning, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. He holds a BSc. (Hons) Planning degree from KNUST, and a doctorate degree in Resource and Environmental Management from the University of Dortmund, Germany. He also has qualifications in Organisations and Systems Development from the Gestalt Institute of Cleveland, Ohio, USA, Forest Policy Analysis from the European Forest Institute in Joensuu, Finland, and International Development Studies from the University of Oslo, Norway. A member of the Ghana Institute of Planners, his research interests include urban environmental management and evaluation. E-mail: dinkoom2002@yahoo.co.uk. or dinkoom.feds@knust.edu.gh.

A. Y. MENSAH

Senior Lecturer and Head of Department of Pharmacognosy, Faculty of Pharmacy and Pharmaceutical Sciences, College of Health Sciences, Kwame Nkrumah University of Sciences and Technology (KNUST), Kumasi.

He holds a BPharm degree in Pharmacy from KNUST, Kumasi; PhD degree from King's College, London (University of London). His area of specialization and research interest is in Ethnorpharmacological studies in Natural Products. E-mail: aymensah.pharm@knust.edu.gh.

M.L.K. MENSAH

Associate Professor of Pharmacognosy in the Faculty of Pharmacy and Pharmaceutical Sciences, College of Health Science, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi.

He holds the BPharm (Hons) and PhD (Phytochemistry and Botany) from the KNUST and University of Norringham, UK respectively. Member of the Pharmaceutical Society of Ghana, and Fellow of the

West African College of Pharmacist (FPCPharm). His area of interest is in Traditional/herbal medicine, Medicinal plants, Essential oils and Standardization of Herbal Medicines.

K. B. NYARKO
Lecturer in the Department of Civil Engineering of the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. He holds a BSc Degree from the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana and MSc from UNESCO-IHE, Delft, the Netherlands. He is a member of the Ghana Institution of Engineers. His research interests are water distribution modeling and water services management. E-mail: nyark10@yahoo.com.

K. NSIAH
Senior Lecturer, Department of Biochemistry and Biotechnology, KNUST. Had his BSc. and MSc. Degrees from the Department of Biochemistry, KNUST. His Research interests are in clinical biochemistry, ethnopharmacology and biochemical education. He is the coordinator of the Clinical Analysis Laboratory, a semi-commercial set-up in his Department. E-mail: knsiah2002@yahoo.com

D. D. OBIRI
Lecturer, Department of Pharmacology, College of Health Science, KNUST. He holds B.Pharm, M.Pharm (Pharmacology) (Ksi). Research interest is in Natural Products Pharmacology.
E-mail: ddobiri.pharm@knust.edu.gh.

S. N. ODAI
Senior Lecturer in the Department of Civil Engineering of the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. He holds a BSc Degree from the Hohai University in China; MSc and PhD Degrees from the Tokyo University of Agriculture and Technology in Japan; and a Post-Doctoral experience at Imperial College London. He has memberships in the International Association of Hydraulic Research, International Association of Hydrological Science; American Society of Civil Engineering and the Ghana Institution of Engineers. His research interests are hydraulic and hydrological modeling. E-mail: snodai@yahoo.com.

S. ODURO-KWARTENG
Lecturer in the Department of Civil Engineering of the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. He holds a BSc and MSc Degree from the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. He is a member of the Ghana Institution of Engineers. His research interests are water distribution modeling and solid waste management. E-mail: sokwarteng@yahoo.com.

J. OFORI
He holds a PhD in Agronomy and Soil Science from the Shimane University, Japan. He works as a rice agronomist with CSIR-CRI. E-mail: oforijos@yahoolcom.

D. OKUONGHAE
He received his BSc. In Industrial Mathematics (summa cum laude) from the University of Benin, Nigeria and MSc in Mathematical Modelling and Scientific Computing from the University of Oxford, United Kingdom. He is currently doing his doctorate at the University of Benin, where he is also

a lecturer in Applied Mathematics. In 2003, he was awarded a Commonwealth Scholarship from the Commonwealth Scholarship Commission in the United Kingdom. His research interests focus on mathematical models for infectious diseases and related issues.
E-mail: danny.okuonghae@corpus-christi.oxon.org.

N.A.A. OPOKU-ASARE
Lecturer, Department of Art Education, College of Art and Social Sciences, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. She teaches Principles and practice of Education, Instructional Media in Education, Educational Psychology and Research Methodology. She holds a BA in Art (Ceramics), Postgraduate Diploma and MA in Art Education (University of Science and Technology, Kumasi); M.Phil in Educational Technology (University of Sussex, UK); Diploma in Administration (Chartered Institute of Administration, Ghana); and Graduate Diploma in Management (International Professional Managers Association, UK).
Her areas of specialization are Educational Technology, Basic Education, Initial Teacher Education and Quality Assurance. Her research interests include Quality Control, Pedagogy, Pre-School Education, Adolescence/Adolescent Health. E-mail: afia_asare@yahoo.co.uk.

J.E. OSEMWENKHAE
He is a Senior Lecturer in Mathematics with emphasis in Mathematical Statistics and related areas. He had his first degree in Mathematics Education, M.Sc. and Ph.D in Mathematics from the University of Benin, Benin City, Nigeria. He has many articles in national and international publications. He currently lectures in the Department of Mathematics, University of Benin, Benin City, Nigeria.
E-mail: josemwenkhae@yahoo.com.

E.F. OTENG-ABAYIE
Oteng-Abayie is presently a Lecturer in Economics and the Programs Coordinator at the School of Business, Garden City University College, Ghana. He holds MA Economics and BA Economics/Law. He has research interests in applied Macroeconomics, International Trade and Finance, and Applied Econometrics. His areas of teaching expertise include Micro/Macro economics, Mathematical and Statistical Methods for Economics and Business, and Econometrics with computer applications. He has econometrics modeling skills in EViews, Microfit, and PcGive. Oteng-Abayie is a member of the African Finance Association and has worked as a research, management and training consultant to a number of institutions including the Bank of Ghana, GTZ, GHAMFIN and the ARB Apex Bank Ghana Limited. E-mail: oteng_abayie@yahoo.com.

E.O. TERLABI
Lecturer, Department of Biochemistry and Biotechnology, KNUST. He holds BSc. and MPhil in Biochemistry from the University of Ghana (Legon) and KNUST respectively. His research interest is in natural products biochemistry. E-mail: terlarbi@yahoo.com.

E. WOODE
Lecturer, Department of Pharmacology, College of Health Sciences, KNUST, Kumasi, Ghana. He holds a B.Pharm degree from the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana and a PhD in Drug Metabolism from the University of Glasgow. His research interest is in CNS Pharmacology and Antiinflammatory agents from botanical sources.
E-mail: ewoode.pharm@knust.edu.gh.

BRIEF ON JUST ASSESSORS

J.A. ADJEI

A product of the now University College of Education, Winneba, obtained a four-year Diploma in Physical Education at Winneba and was among the last batch of the four-year diploma graduates at the then Specialist Training College.

In the United States, he took up additional courses to upgrade the Diploma to Bachelor of Science in Physical Education with emphasis in Exercise Physiology and Kinesiology. He then pursued the Masters Degree in Physical Education placing emphasis in Exercise Physiology.

He continued with the a Ph.D with minor concentration in Exercise Physiology. His teaching concentration areas are Biomechanics, Exercise Physiology and Kinesiology.

Impressed with Dr. Adjei's academic background and expertise in Exercise Science, KNUST initial Interview Panel made up of the immediate past Vice Chancellor, Professor Kwasi Andam and the current Vice Chancellor, Professor K.K. Adarkwah sought him from the United States to come and establish the Department of Sports and Exercise Sciences which he currently heads at KNUST. He is also currently the Chairman of the KNUST Sports Union. The first batch of his students in the Sports and Exercise Science Programme are now in their third year.

P.Y. BOATENG

He is a Senior Lecturer in the Department of Horticulture, Faculty of Agriculture, College of Agriculture and Natural Resources, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. He holds a Diploma in Tropical Horticulture (DTH), BSc. (Agriculture), MSc. (Horticulture) all from KNUST and a PhD (Horticulture) degree from the Wye College, University of London, UK.

His area of specialization is agronomy/physiology of vegetable crops and plant propagation of non-traditional export crops. He is a Fellow of the Ghana Institute of Horticulturists and an External Assessor of MSc. Examinations for the Department of Crop Science at the University of Cape Coast, Cape Coast, Ghana.

A. BART-PLANGE

Senior Lecturer at the Department of Agricultural Engineering, Faculty of Mechanical and Agricultural Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana.

He holds a BSc. In Agricultural Engineering from KNUST and an MSc. In Agricultural Engineering, Mechanisation in the Animal Production and Farm Structures option, from the University of Hohen-