Major urban water and wastewater systems in Minoan Crete, Greece
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ABSTRACT

During the Minoan era a number of remarkable developments occurred on the Greek island of Crete which have been widely recognized. However, one of the salient characteristics was the architectural and hydraulic function of its water supply, sewerage, and drainage systems in the Minoan palaces, cities, and other settlements. It might be inferred, therefore, that Minoan master craftsmen in Bronze Age Crete were aware of some of the basic principles of what we call today water and environmental technologies. The scope of this study is the presentation of the most characteristic examples of extant hydraulic works and related hydro-technologies in Minoan Crete. During Minoan times the focus of water management was on sustainable, small-scale safe, cost-efficient and environmentally-friendly practices which might be relevant today, as the water supply and wastewater management problems of modern societies are not very different from those faced by Minoans.

INTRODUCTION

Farming villages of the Near and Middle East became cities about 6,000–7,000 years ago. During the Neolithic age (ca. 5700–3200 BC), the first successful efforts to control the flow of water were driven by agricultural needs (irrigation) and were implemented in Mesopotamia and Egypt. Remains of these prehistoric irrigation canals still exist (Mays et al. 2007). However, urban hydraulic systems go back to the Bronze Age (ca. 3200–1100 BC). There are several astonishing examples of urban water supply, wastewater, and stormwater systems dating from about the mid-third millennium BC. Mohenjo-Daro, located in the province of Sindh, Pakistan, was one of the largest settlements of the ancient Indus Valley civilization, which developed sophisticated systems for water supply, sewerage, and drainage. Founded ca. 2600 BC, it was one of the world’s earliest major urban settlements, roughly concurrent with civilizations of ancient Egypt, Mesopotamia, and Minoan Crete. Water came from more than 700 wells and supplied not only domestic needs but also a system of private baths and a Great Bath for public use (Jansen 1989).

By ca. 3000 BC, a brilliant civilization named ‘Minoan’, had evolved in Crete, noted for its impressive palatial and urban architecture. Palaces built in ashlar masonry and decorated with frescoes were the most refined features of this distinctive culture. Apart from their aesthetic accomplishments in palatial frescoes and architecture, fine artifacts of pottery, metals, precious and semi-precious stones, the Minoans had to grapple with practical problems related to water and wastewater matters. Thus, extensive and elaborate structures for water supply, sewerage, and drainage systems were planned and constructed to serve the needs of the growing population of the island (Mays et al. 2007; De Feo et al. 2011). Major Minoan water supply, wastewater, and stormwater systems are shown in Figure 1.

In the Minoan palaces and settlements, water supply varied according to local conditions, determined by climate mainly, rainfall, aquifers and terrain (Mays et al. 2007). In Minoan Crete, various water supply, wastewater, and stormwater systems and techniques, such as collection and storage facilities, wells and groundwater exploitation,
aqueducts, water distribution and use, construction and use of fountains, sewers, bathrooms, and other sanitary facilities, were developed and applied. In this synoptic paper a description of the main concepts of water supply and wastewater management during the Minoan era is attempted.

CISTERNs

In ancient Crete the technology of surface and stormwater storage was highly developed. Rainwater was stored in cisterns in places where there was no other source of water. This technique is still practiced today in areas of the eastern island. Cretan cities of the Hellenistic and Roman periods, such as Lato and Aptera (in eastern and western Crete, respectively), depended on rainwater storage, the former using a large number of small domestic cisterns, while the latter utilized two major cisterns with some hundreds of cubic meters in each. Several ancient cities depended exclusively on rainwater storage and thus, became self-sufficient and ensured their survival in case of a siege. Such was not the fate of Carthage in Northern Africa, which was provided with an aqueduct a century after its destruction by the Romans in 146 BC. In the case of Crete, later evidence from the Venetian period suggests the existence of more than 500 cisterns in the city of Iraklion after ca. 1500 AD (Koutsoyiannis et al. 2008; Angelakis & Spyridakis 2010).

One of the earliest prehistoric cisterns on the island was found in the center of a pre-palatial house complex on a hill at Chamaizi, traceable to the early-middle Minoan period in the closing years of the third and the dawning of the second millennium BC. Its rooms were clustered around a small open court with a deep circular rock-cut cistern 3.5 m deep and 1.5 m in diameter, lined with masonry in its upper part (Davaras 1972). In addition, four cisterns of the middle-late period have been identified, of which two are in Myrtos-Pyrgos (Ierapetra) and one each in Archanes and Zakros. In Myrtos-Pyrgos, one is located on the top of the hill-settlement and the other on its slope (Cadogan 2007). The latter is the larger, with a volume of 66 m³ (Figure 2, top). In the Zakros palace on the side of the Central Court, across the so-called ‘King’s Apartment’, a colonnade with a central pillar on a high base was located, while on the eastern side a large wooden pier-and-door partition system led into the spacious rectangular Hall of the Cistern. In its center, a circular cistern below ground level was found (Platon, N. 1974; Angelakis & Spyridakis 1996). It is about 50 m³ in volume and has steps constructed for cleaning and drawing purposes and belongs to the late period (ca. 1500 BC). Various theories regarding its use have been proposed, such as a swimming pool or aquarium. Since the room must have had a ceremonial/administrative character as suggested by its layout, the cistern most likely performed a central role in this context as it constitutes the core feature of this particular space (Angelakis et al. 2012b). Also the possibility that it was used as a means of estimating the precipitation required to satisfy the demand of agricultural crops provided to the storage areas of the palace should not be excluded. Most likely, however, the cistern served
multiple purposes, including recreational ones (Angelakis et al. 2012b).

A similar cistern of the middle late period (ca. 1500 BC) has been found at Archanes-Tourkoyeitonia (Sakellarakis & Sapouna-Sakellaraki 1997). It is of a similar cylindrical shape to that of the Zakros palace and was built in limestone ashlar masonry, and was probably roofed (Angelakis et al. 2012b). Finally, a cistern belonging to the post palatial period (ca. 1350–1200 BC) was found in Tylissos (Hazzidakis 1994). Its size and shape remind us of the cisterns from Zakro and Archanes with similar steps and plastered walls. It was used to store spring water transported through the Tylissos aqueduct (see below). A small lithic tank, probably used for the removal of sediments from the water before its storage in the main cistern is located a few meters upstream of it. Similar basins for the treatment of rainwater before storage were found at the eastern entrance of Knossos palace stairway with parabolic runnels. These runnels, with their parabolic curves following the turns of outer stairways, ensure the precipitation of sediments in intermediate little tanks, constructed at proper intervals, to allow the suspended solids to settle to the bottom. This elaborate technology of collection and storage of rainwater, freed from impurities, in a downstream main tank for washing or other purposes, is only one aspect of the highly skilled hydraulic and hygienic knowledge attained by the Minoans (Angelakis & Spyridakis 1996; Gorokhovich et al. 2011).

In general the Minoan water cisterns were of cylindrical shape, constructed with stones under the soil surface, with a diameter ranging from 1.5 to 7.0 m and depth from 2.5 to 5.0 m. At least one layer of hydraulic plaster prevented water losses through the bottom and the walls. Minoan cisterns are of two basic types: (a) collection and storage of rainwater; and (b) storage of spring water through aqueducts. The characteristics of the major Minoan cisterns are shown in Table 1.

GROUNDWATER AND WELLS

A variety of techniques for the water supply to palaces, cities, and other settlements, which were adapted to local conditions, were applied in Minoan Crete. In eastern Crete with its low water availability, water supply was mainly based on groundwater. Groundwater wells were used in Crete in Neolithic times, and in Minoan Crete since the first stage of the Middle Minoan period. In the Knossos palace several wells were used for drawing drinking water. Water wells in the palace have been reported (Angelakis et al. 2012b). The most interesting one with a depth of about 12.5 m and a diameter of about 1.5 m is found in the north-west part of the Little palace area, in the basement of House A, which belongs to the middle period. Its upper circuit was mostly of rubble masonry dated probably to the Roman period. The well was dressed with a series of terracotta collars (Figure 2, bottom). Each collar had three parts, imitating ashlar masonry, and an upper rim. Triangular holes to enter the well for cleaning purposes were occasionally made (Angelakis et al. 2012b).
Additionally several wells were found in the eastern region of the island, including one located near the south-east part of the Central Court in the Zakro palace; here again steps facilitated the water supply. The wood of the windlass was found in the water, along with an offering cup containing, among other offerings, perfectly preserved olives and raisins (Angelakis et al. 2013a). The water supply in the Minoan town of Palaikastro also depended on groundwater (Angelakis & Spyridakis 2013). Here several wells have been discovered to date with depths ranging from 10 to 15 m. Other wells were found north of the Minoan ‘Villa of fountain’s garden’ at Amnissos, east of Iraklion city, constructed probably during the early late period (Driessen & MacDonald 2011).

**AQUEDUCTS**

Minoans were able to provide cities (e.g. Knossos with an estimated 80,000 inhabitants) with complete water supply systems. On the basis of their accomplishments it can be assumed that they were, in a sense, aware of the basic hydraulic principle that water seeks its own level, known today as the principle of communicating vessels. It is manifested in the water supply of the Knossos palace through terracotta pipes fed originally from the spring Mavrokolybos and later on from the Fundana spring, located at a distance of about 10 km southwest of the palace and from the springs of Karidaki and Paradisi, in the Archanes area (Angelakis et al. 2007). The Knossos aqueduct ran along the western edge of the Vlychia ravine (Evans 1921–1935). The water from the spring of Mavrokolybos was transported to the Knossos palace through conduits outside the palace and by terracotta pipes inside the palace. However, the hydraulic head of less than 10 m suggests either a great accuracy of design or a very low efficiency. Due to the small differences in elevation between the Mavrokolybos spring and the palace, the original spring should be located at a distance of about 0.7 km from the palace, and at a height of about 120 m (Angelakis et al. 2013a).

The terracotta pipes of the Knossos aqueduct were constructed in sections of about 60–75 cm each (Figure 3, top). These pipes with their expertly shaped, tightly interlocked sections date from the earliest days of the buildings. One potential advantage of such design is the perfect seal of the joints with clay or other material, so that they could possibly operate under low pressure. Another advantage is the flexibility for change in direction without use of special elbow fittings; additionally it has been speculated in the literature that the velocity increase associated with the narrow end of each pipe section, helped to flush sediment through the pipe and prevent deposits (Angelakis et al. 2013a).

The water supply in the Knossos palace was provided at varying depths through a network of terracotta piping located beneath the floors (Evans 1921–1935). It may be argued that these systems along with other sophisticated techniques, were indications that their users were people of a higher status (Angelakis et al. 2013b). Terracotta pipes, similar to those discovered in the Knossos palace,
were also found at the Guest House (Caravanserai) south of the palace; they were fed with water from springs located in the low hill at Gypsades on the western side of palace. Both the baths and the tykte fountain, found in this House, were supplied from the Gypsades springs. Terracotta pipes were used for both the distribution to, and collection of water from, public facilities (e.g. fountains, bathrooms, and cisterns). They were probably used in the Zakros palace to feed a fountain in an open area from a spring (Platon, E. 2001). There, two handmade tubes about 30 cm long with a narrow opening into a zoomorphic spout, were found (Angelakis et al. 2012b) (Figure 3, bottom).

Aqueducts found in Minoan Crete reveal a plethora of information on matters pertaining to water and the sophisticated urban life of this period. Minoan aqueducts are of two basic types: (a) the open/natural gravity flow system; and (b) the closed/pressured pipe system.

Other major Minoan aqueducts are shown in Table 2. The Tylissos aqueduct, of a total length of 1.4 km, transported water from the Saint Mamas springs located northwest of the archaeological site (two houses), and southwest of Iraklion city (Angelakis et al. 2007). The water of the spring went through a terracotta multilayer filter before flowing into the aqueduct. The remnants suggest that part of the aqueduct was constructed from closed pipes and part of it was a curved channel. Also, the water supply of the Malia palace was probably transported from a spring located west of the hilly area of Profitis Elias ‘Holly Hillock’ by closed pipes (terracotta pipes) or open channels. The total length is estimated to be 2.4 km, which includes the water supply of House A located north of the palace and the port of Agia Varvara located northwest of the palace (Angelakis et al. 2007).

As evidenced from these findings, Minoan engineers had a practical knowledge of the basic hydraulic principles, which enabled them to convey water over relatively large distances in mountainous terrain. Several ancient aqueducts have been identified in Crete (Angelakis et al. 2012b); seven were built during the Minoan period (Table 2).

Table 2 | Characteristics of major aqueducts in Minoan Crete (adapted from Angelakis et al. (2012b))

<table>
<thead>
<tr>
<th>Aqueduct name</th>
<th>Location</th>
<th>Construction</th>
<th>Reconstruction</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gournia</td>
<td>Paneromeni, Asari</td>
<td>Minoan</td>
<td>Reconstruction</td>
<td>7</td>
</tr>
<tr>
<td>Karphi</td>
<td>Karphi, Lassithi</td>
<td>Minoan</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>Knossos (Mavrokolypos)</td>
<td>Knossos</td>
<td>Minoan</td>
<td>Roman</td>
<td>0.7</td>
</tr>
<tr>
<td>Malia</td>
<td>Profitis Ilias, Malia</td>
<td>Minoan</td>
<td>Hellenistic; Roman</td>
<td>0.85 or 1.15</td>
</tr>
<tr>
<td>Mochlos</td>
<td>Mochlos, Lassithi</td>
<td>Minoan</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Tylissos</td>
<td>Tylissos</td>
<td>Minoan</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

na: not available.
SEWERAGE AND DRAINAGE SYSTEMS

It is evident that during the Minoan civilization extensive sewerage and drainage systems were planned, designed and built to supply the growing population centres and agriculture with water (Angelakis & Koutsoyiannis 2003; Viollet 2007). Thus, in several Minoan palaces discovered by archaeologists in the 20th century, one of the most important characteristics was the provision and distribution of water and the sewerage and drainage systems by sophisticated hydraulic means (Viollet 2007).

In several Minoan cities and palaces there existed well established sewerage and drainage systems, which are in good functional condition even today. Stormwater from the flat roofs of the palace at Knossos was carried off by vertical pipes; one of these, located in the eastern wing, emptied into a stone sewerhead from which a stone channel carried the flow of stormwater (Evans 1921–1935). In general palaces, cities, and other settlements were also equipped with elaborate storm drains and sewers (Figure 4). In fact, all palaces had applied strategies to dispose of water and wastewater (MacDonald & Driessen 1990). Open terracotta and stone conduits were used to convey and remove stormwater and limited quantities of wastewater. Pipes, however, were rarely used for this purpose. Larger sewers, sometimes large enough for a man to enter and clean them, were found in Minoan palaces at Knossos, Phaistos and Zakro. These large sewers may have inspired the genesis of the idea of the labyrinth, the subterranean structure in the form of a maze that hosted the Minotaur, a hybrid monster. Some palaces had toilets with flushing systems operated by pouring water in a conduit (Angelakis et al. 2005). However, the best example of such an installation was found in the Cycladic island of Thera (modern Santorini). This is the most refined and best-preserved pattern belonging to the late (ca. 1550 BC) Bronze Age settlement of Akrotiri, which shares identical cultural characteristics with Crete (Angelakis & Spyridakis 1996).

One of the most advanced Minoan sanitary and storm sewer systems was discovered in Hagia Triadha (close to the south coast of Crete, few kilometres west of Phaistos) (Figure 4). The Italian writer Angelo Mosso, who visited the villa of Hagia Triadha in the beginning of the 20th century and inspected the storm sewer system, noticed that all the sewers of the villa functioned perfectly and was amazed to see stormwater come out of the sewers, 4,000 years after their construction (Gray 1940). Also Gray (1940) relates this story and quotes Mosso (see the quotation in the beginning of the paper) adding the following statement: Perhaps we also may be permitted to doubt whether our modern sewerage and drainage systems will still be functioning after even 1,000 years.

It may be concluded that in the entire history of human-kind there exists no other example of a sewerage and drainage system still functional more than 4,500 years after its original construction. Thus, the existence today of several Minoan archaeological sites is mainly due to their very advanced drainage and sewerage systems.

FOUNTAINS

Minoan fountains manifest another interesting technology. Most of them are subterranean structures supplied with water directly or from other springs via ducts. The construction of steps, or alternatively shallow basins, suggest that water was to be directly taken out with the use of containers. This recalls the type of fountain of the later Classical and Hellenistic period known as arykrene. Most typical of these fountains is that of the Zakro palace. Here, in the southwest corner of the Hall of the Cistern an opening led into a small chamber where water was collected and channelled under the floor into the base of a square
underground fountain built further south. Its dimensions are $3 \times 4$ m and it is dated in the late period (ca. 1500 BC). It was built of regular limestone with a staircase of 14 steps (Figure 5). This structure was thought to correspond with the Tykte fountain mentioned in the Odyssey (Platon, N. 1974). Another fountain similar to the Tykte was found at the Guest House (Caravanserai) in Knossos and consists of a rectangular basin of three steps with dimensions of $2.0 \times 1.6$ m; the water comes directly from a spring in the floor of the square (Evans 1921–1935). A ritual function of these particular fountains is also proposed, as artefacts of ritual content have also been unearthed. Another type of fountain known in later periods as rookrene, which supplied a constant flow of fresh water, was also found in Zakro. This pattern along with the two zoomorphic water-spouts was presented above as part of the closed/pressured pipe system (Figure 3, bottom).

Finally, a remarkable fragment from a fresco composition depicting a fountain of a supposedly Minoan garden, proposed for several palaces, was found in the House of Frescoes in Knossos (Angelakis & Spyridakis 1996). The fragment has been restored to what appears to have been a jet d’eau fountain. Although the actual summit of the fresco was not found, the object depicted in the upper part of the field is clearly some type of fountain or ‘jet d’eau’ with the spout of the water made to rise from a forked base. The lower part of the fragment, with the same forked base and falling drops seems, moreover, to be the base of another column of water drawn in a similar conventional manner but with a small section of the contour of the ground projecting an undulating bank beneath it. The background here is white, the central column of water and the falling drops on either side a deep blue, while the drops falling in front of the main jet are painted white, thus becoming quite distinct and visible (Angelakis et al. 2012b).

As no geysers or sulphurous ebullitions, like those of Palici in Sicily, exist in Crete, it is highly unlikely that these designs were copied from any natural fountains found on the island. Moreover, the first fountains in the form of jets were introduced in the Hellenistic period (Lax & Strasser 1992). This makes the representation quite uncertain, although another restoration of the fragments argues for a natural gush from the Cretan landscape of the Bronze Age.

**BATHROOMS AND/OR LUSTRAL CHAMBERS**

Besides sewers and drains, bathrooms were not considered necessary and most Minoan settlements did not have them. Although the function of Minoan rooms is difficult to define, Evans (1921–1935), the famous archaeologist who discovered the Knossos palace, identified three rooms as bathrooms. The main type which resembles the bathrooms discovered at Phaistos and Malia, is that found near the Queen’s Hall in Knossos. However, there is a notable difference distinguishing it from those found in the palaces at Phaistos and Malia. The point of distinction is that it is on the level of the floor and consequently there is an absence of steps. Evans (1921–1935) described the latter type as a ‘lus- tral chamber’. Also, Graham (1987) assumed that a room which started out as a ‘lus-tral chamber’ later became an ordinary bathroom. In fact, as a result of investigations by Platon, M. (1990) it must be assumed that this also happened twice in the houses at Tylissos; and a careful investigation might show the same to be true for the bathroom of the Queen’s Hall in the palace of Minos (Graham 1987). Thus, it should be supposed that the Minoans of the latter period began putting cleanliness before godliness.

In Phaistos, a luxurious bathroom is located in the southwest corner of the King’s Megaron, decorated with wall paintings and with the usual steps descending into it (Figure 6, top). Also, its walls and floor are faced with alabaster slabs, and an attic on the east side. On the west side an alabaster slab forming a step with a hole has been
interpreted as a toilet. Similar bathrooms have been reported in other Minoan sites, such as that shown in Figure 6 (bottom). Platon, M. (1990) has provided us with some preliminary statistical data on Minoan cisterns, bathrooms and other sanitary and purgatory facilities. She concluded that, in terms of chronology, most of them should be placed in the Middle Minoan period; with regard to location, 16 are found next to domestic rooms, seven near holy altars and two in palace entrances. In only two cases were various facilities for baths found, seven were filled up with earth and two had been rebuilt and converted into bathrooms.

It must be noted that, in spite of the view of some scholars (Alexiou 1964), the absence of bath facilities in some purgatory cisterns and their existence in other places, should not be considered coincidental. Graham (1987) and Platon, N. (1974) have reported that purgatory cisterns were used for the cleansing of both body and soul. Note also that most Minoan baths were connected to independent septic systems outside, a practice indicative of the advanced water resources management and environmental techniques of that period (Angelakis et al. 2005).

In several bathrooms clay tubs were used. A variety of such tubs have been discovered in Minoan sites. The clay tubs in the Minoan bathrooms must have been filled and emptied by hand rather than directly connected to the sewers. However, in the ‘Caravanserai’, a rest house just south of the palace, a footbath for the weary travellers was supplied by a direct pipe, and the overflow discharged by another conduit; a branch of the water channel also served as a drinking trough (Angelakis & Spyridakis 1996).

**DISCUSSION AND CONCLUSIONS**

Urban hydraulic systems first appeared during the Bronze Age, particularly in the mid-third millennium BC, in an area extending from the Indus river valley (at Mohenjo-Daro and Harappa) to Mesopotamia. In the island of Crete, where the Minoan culture of the Bronze Age flourished, the emergence of the palaces reveals a remarkable development of water management in the urban context. A striking indication of this development is manifested, *inter alia*, in the advanced water management techniques practiced in Crete at that time. These included various scientific fields of water resources such as wells and ground-water hydrology, aqueducts, and domestic water supply according to local conditions in terms of climate and geomorphology.

Different techniques were applied to assure the water supply: (a) management of spring and runoff water locally; and (b) transportation and storage of water. Moreover, these techniques suggest a sophisticated life style. Different techniques were applied suitable to local conditions. While the Knossos palace depended on springs, in the palace of Phaistos the water supply depended on a surface runoff system, while at the Zakro palace a groundwater system was used (Koutsoyannis et al. 2008). Despite this diversity, common construction techniques seem to have been applied. It can be suggested that the people of prehistoric Crete were aware of the principles of technologies relevant to water. This is suggestive of the existence of master
craftsmen responsible for constructing and maintaining the water supply system of a community. They were concerned with the solution of some water related problems and were able to provide palaces and settlements with efficient, even sophisticated water supply, wastewater, and stormwater systems. To accomplish their goals, this group of master craftsmen obviously possessed at least a rudimentary understanding of some basic principles, such as flow and friction, of what we call today water and environmental engineering.

Minoans lived in harmony with nature and their environment; those that did not, failed. Local water supply and wastewater and stormwater management were very advanced in Minoan Crete. When these were exhausted, local and temporal transfers were instituted and the necessary hydraulic structures built. In this context it is noteworthy that the Minoans knew all the necessary basic principles and physical parameters. However, Minoan hydraulic technologies were further developed, mainly by enlargement of the scale of water supply, wastewater, and stormwater systems, at subsequent stages of the Greek civilizations. New, more advanced, water and wastewater technologies were also invented especially in the Hellenistic period that followed Alexander the Great, when they spread over a geographical area from Greece to India to the south. The Romans, whose Empire replaced the Greek rule in most parts of this area, inherited the technologies and developed them further mainly by changing their application scale from small to large and implementing them in most large cities (Angelakis et al. 2012b). However, the development of water science and engineering in Crete appears to be non-linear, often characterized by discontinuities and regressions. Yet Cretan technological achievements were not totally forgotten during the Dark Ages (ca. 1150–900 BC). Probably 'bridges' from the past to the future are always present, albeit often invisible to those who cross them (Angelakis et al. 2012b).

Finally, the following concluding remarks can be made:

- The advanced hydro-technologies in Minoan Crete were subsequently expanded to Mycenaean and then Archaic, Classical and Hellenistic Greece, and beyond, where further developments, mainly on a local scale, were achieved.
- Principles of Minoan hydro-technologies could be applicable today, updated with existing know-how and infrastructures, especially in water-short areas where effective water supply and wastewater management programs are essential.

ACKNOWLEDGEMENTS

Many thanks to Dr V. E. Tzanakakis for his technical assistance. This work was partially supported by the EU-research project FP6–509110 (SHADUF).

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First received 3 December 2012; accepted in revised form 10 January 2013