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QGIS Suitability Assessment

Claire E. Lush & Mike J. Lush

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For further information please contact:

Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough PE1 1JY
www.jncc.defra.gov.uk

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Summary

The Joint Nature Conservation Committee (JNCC) had used ESRI ArcGIS for a number of years, during which time it had developed various tools, processes and infrastructure to support its work. The organisation was considering whether Quantum GIS (QGIS) would be a suitable alternative to ArcGIS that would also meet its data management requirements, and required an expert review comparing the functionality available in ArcGIS with that in QGIS. It was also necessary to consider any changes to JNCC's IT infrastructure required as a result of implementing QGIS, as well as the associated costs.

A list was provided by JNCC detailing the functionality in ArcGIS that was considered essential, desirable or possibly required in the future. This list was used as the basis for an assessment of functionality within QGIS. Difficulties in this assessment arose where no direct comparison was possible, where functions behaved subtly differently, where almost identical results could be obtained through different means and where ArcGIS specific concepts applied that were not replicated in any other GIS. There was also no clear definition of QGIS functionality, which could be seen to include the functionality of a range of other open source GIS or spatial tools with which it integrated. Additionally, the assessment was not exhaustive, due to the wide ranging functionality of QGIS, its plugins and associated spatial tools.

Each item within the list was assessed to determine whether it occurred within QGIS and associated software, or where relevant whether the same results could be attained using a different process. Functionality was recorded as occurring in full, in part, through a plugin, through associated GIS and spatial tools, through configuration, or through development. ArcGIS specific functionality replicated by no other GIS was regarded as not relevant. Additional notes were provided where they were considered informative.

Important differences between ArcGIS and QGIS included:

- the range and types of file formats that could be edited natively. In particular, proprietary ArcGIS data formats such as map documents (MXD), layer (LYR), ESRI TIN, ESRI grid, grid stacks and raster attribute tables could not be used in QGIS. Additionally, key data formats such as file and personal geodatabases could be read and saved by QGIS, but not edited;
- more limited CAD file support in QGIS;
- ArcGIS specific feature types that were not supported by QGIS, such as annotations and graphics, coverages, raster mosaics, representations, subtypes and workspaces;
- ArcGIS functionality fully absent in QGIS, including the ability to create 2D or 3D graphs and group attribute editing;
- ArcGIS functionality partially absent in QGIS, including snapping types, vector transformation types, topology rules, and advanced editing, feature management, spatial statistics and raster conversion tools;
- collections of specialist functionality in ArcGIS that appear to be absent from QGIS, such as the cartography tools and coordinate geometry;
- a more limited number of map layout export formats in QGIS;
- metadata management functionality was extremely limited in QGIS;
- QGIS Browser is much more limited than ArcCatalog;
- no QGIS equivalent of the ArcScan extension to ArcGIS;
- functionality in Spatial Analysis was only partially met by QGIS and associated GIS and spatial tools;
- very limited 3D functionality within QGIS compared with 3D Analyst.

Functionality within ArcGIS with equivalents in QGIS included most basic functionality, many of the analysis and processing tools, the geoprocessing toolbox, ArcGIS for Server, ArcGIS online, raster catalogs and raster colour tables. Note that this assessment did not consider functionality available through QGIS that was not also available through ArcGIS.

Implementation of QGIS within JNCC had a number of implications. Because QGIS is open source there is no limit on the number of active copies that can be in use at any one time, which may alone be sufficient to offset the loss of some functionality available in ArcGIS. Some of the lost functionality was considered to be essential to JNCC's operations, but in the long term this functionality could be developed as either core QGIS functionality or plugins. In the short term, implementation of QGIS could lead to a reduction in the number of ArcGIS licenses required by JNCC, though the licenses to be retained would include the more expensive Advanced licenses and plugins in order to gain benefit from otherwise unavailable functionality. The costs of QGIS implementation have been estimated.

QGIS would best be delivered as a published application through JNCC's Citrix system. This would involve the establishment of a JNCC implementation of QGIS, including all of the required plugins. It should then be possible to create a functional copy by moving all installed files to another location and creating a single registry key. This should allow easy publication via Citrix and allow updates or additions to be trialled prior to publication.

In order to gain the maximum benefit from QGIS, and to duplicate the functionality available from ESRI geodatabases, the implementation of a spatial database server is recommended, ideally PostGIS. This should be installed on a central JNCC server and used to store the majority of vector data. Raster data may be best stored as GeoTIFFs, though the equivalent of raster catalogs can be created in PostGIS or as external virtual rasters. Some data may additionally need to be stored in other formats due to the requirements placed on them. Existing spatial data will need to be migrated to these new formats. All data management should be governed by data management guidelines, which will need to be created and disseminated as part of the implementation process.

A trial of QGIS and PostGIS delivery and performance is recommended to determine how easily they can be implemented through JNCC's IT infrastructure, how well they function and how quickly JNCC staff can acquire the knowledge to use QGIS effectively.

A limited number of ArcGIS licences would need to be retained to benefit from functionality essential to JNCC's work that is missing from QGIS. ArcGIS will also be required for checking data and creating map documents for disseminating to partner organisations. ArcGIS should be delivered to JNCC staff via Citrix or virtual machines, though it will be necessary to restrict its use to reduce the risk of no licences being available when a member of staff requires the functionality that does not exist in QGIS. Should the missing essential functionality be developed for QGIS and the requirement for map documents be reduced these ArcGIS licences may no longer be required.

JNCC staff will need training in QGIS use. Established foundation and intermediate courses are available that would provide staff with the basic knowledge required, but it is clear that some advanced training would be required to meet JNCC's needs. These advanced courses would need to be bespoke, so would involve costly development of training materials, but once created would be cheaper to repeat.

Support available from the QGIS developers is limited, so a third party QGIS support contract is recommended. There is also some functionality that is essential to JNCC that would need to be developed for QGIS: INSPIRE compliant metadata functionality and an equivalent to raster attribute tables. These would need to be funded by JNCC to ensure their development.

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1 Introduction

The Joint Nature Conservation Committee (JNCC) had been using ESRI ArcGIS for spatial data management, analysis and map production for a number of years. During this time it had developed various tools, processes and infrastructure to support its work, which were designed to support the use of ArcGIS. Due to improvements in the availability, functionality and packaging of open source GIS, JNCC were considering whether Quantum GIS (QGIS) would be a suitable alternative to ArcGIS that would also meet its data management requirements.

Comparison of functionality between GIS is not straightforward. Whilst ArcGIS and QGIS often had comparable functionality in many cases a direct comparison was not possible. In other cases similar functionality might behave subtly different or almost identical results could be obtained through different means. There were many concepts specific to ArcGIS that were not shared by QGIS, or by the majority of GIS.

In addition to these complexities, it was not easy to define what was considered to be QGIS functionality. QGIS is essentially a combination of numerous modules, with the option to readily add new modules. In addition, QGIS was highly integrated with other open source GIS, such as GRASS and SAGA, as well as being able to draw on the functionality of packages such as the statistical software R. Given the flexibility available and the ability to access the source code and develop new functionality, it would be possible to replicate most, if not all functionality within ArcGIS, though this may generally be available by sacrificing user friendliness.

JNCC required expert advice to untangle the complexities of this assessment and indicate whether essential functionality would be available through QGIS. They also required an assessment of the compatibility of QGIS with JNCC's existing data and infrastructure, with recommendations should a move to QGIS proceed.

The specific aims of this work were to:

- review a list of functionality that JNCC considered to be essential, desirable or possibly required in the future, to determine whether it can be met by QGIS;
- consider any changes to JNCC's desktop and network infrastructure required as part of a proposed move to QGIS use, along with estimates of cost.

1.1 User types within JNCC

Key to the assessment of the suitability of QGIS was an understanding of the GIS user types within JNCC. These were categorised by the level of expertise required, as it was thought likely that some advanced functionality would be used by very few individuals. A breakdown of user types is provided in Table 1.

Table 1 – Breakdown of GIS user types within JNCC. Some users considered themselves to be a combination of user types and have been allocated proportionally to the relevant categories.

User type	Definition	No. users
Basic user	Opens data, queries data and produces simple maps, does simple digitising e.g. manual digitising or tracing	50.17
Advanced digitising	Uses advanced digitising tools e.g. digitising by distances and bearings, curves etc, COGO toolbar, raster editing	3.33
Advanced mapping	Uses the Cartography and Advanced Labelling tools	3.33
Advanced analysis	Uses Spatial Analyst	11.17
Total		68

2 Methodology

2.1 Assessment approach

A full annotated functionality list was provided by JNCC, based around the functional groups in ArcGIS. Related items of functionality were grouped and JNCC had scored each group according to whether they were essential, desirable, possibly required in the future or not required.

Each essential, desirable and possibly required item within the list was assessed to determine whether it occurred within QGIS and associated software, or where relevant whether the same results could be attained using a different process. This assessment involved the following:

- i. Review of the functionality within ArcGIS, to confirm how it worked and what it produced, to ensure that the comparison was well founded. This was only required for some of the less frequently used functionality.
- ii. Review of identical or similar functionality within QGIS. This included:
 - a. An initial assessment to quickly determine whether the functionality was available, wherever necessary flagging more difficult assessments for more targeted investigation.
 - b. Clarification of the precise functionality required for complex or advanced items, especially where JNCC's use of the functionality is unclear.
 - c. Further consideration of unassessed answers, drawing upon the knowledge of advanced ArcGIS and QGIS experts where required.
- iii. Update of the table provided by JNCC, classifying each item by whether it meets the requirement:
 - a. In full.
 - b. In part (where functionality is not completely identical to ArcGIS).
 - c. Through a plugin.
 - d. Through GRASS, SAGA or other functionality available through the QGIS interface.
 - e. Through configuration of QGIS.
 - f. Through the development of new functionality.

Alternatively, some items of functionality were regarded as not relevant, as they related to ArcGIS specific functionality that were not required in QGIS to meet analytical and data management needs.
- iv. Making notes where the comparison was not straightforward, as this more nuanced information was sometimes more useful than the standardised assessment.

Following the initial review a consultation meeting was held with JNCC that helped to highlight particular issues and concerns. These were resolved within the meeting and clarified within this report.

2.2 Limitations

QGIS functionality is not always well packaged or documented. The assessment of QGIS functionality therefore relied upon expert knowledge and web searches to locate similar functionality. Inevitably neither were exhaustive. It is therefore not possible to conclude with complete confidence that QGIS lacks a particular item of ArcGIS functionality, only that we were unable to find anything that replicated it. We cannot guarantee that functionality is not available in QGIS and linked open source tools that we haven't tested.

It has also not been possible to test every item of functionality in QGIS. It is clear that in many instances the precise algorithms used and outputs produced by QGIS and ArcGIS for similar functions are not identical. Even if they had been tested it is likely that there would still be uncertainty for some functions: whilst it would be possible to access the code and deconstruct the algorithm for QGIS, ArcGIS is proprietary and it is therefore necessary to rely upon the details that they release. We therefore cannot guarantee that QGIS functionality performs and outputs exactly as similar functionality in ArcGIS.

Because it has not been possible to test every item of functionality we cannot be certain that all documented QGIS functionality actually works. The nature of open source software means that it is variable in quality and stability, which is true of some QGIS plugins although core functionality has been well tested. Additionally, some of the documented functionality were plugins that were considered experimental and are more likely to be unstable.

2.3 Review of infrastructure

JNCC's IT manager provided a brief summarising the organisation's IT infrastructure. JNCC's infrastructure and the possible mechanisms for delivering QGIS within the organisation were further discussed at the consultation meeting, which helped to clarify uncertainties. Other information was gained during the consultation covering the users concerns about the implementation of QGIS and the potential impact upon working practices. This information was used as the basis for the review of infrastructure and subsequent recommendations.

3 Overview of QGIS suitability

The assessment of QGIS functionality was structured upon two spreadsheets provided by JNCC, which were in turn based upon functionality as documented in ESRI's functionality matrix for ArcGIS, spatial analyst and 3D analyst. The results of the assessment are provided in the same structure, with separate Excel spreadsheets provided in Appendices 1 and 2.

3.1 Data types

QGIS supports import and export of a wide range of file formats through the integration of the GDAL OGR libraries, including vector, raster and CAD data, but the range of file formats that can be edited are more limited.

The predominant formats used for editing vector data are Shapefile or spatial databases such as Oracle, PostGreSQL, SpatialLite or SQL Server. Memory layers can be also used for temporary editing.

The majority of raster processing tools in QGIS write to GeoTiff, as it is a full-featured public domain format that stores geographic information with the image. QGIS can handle very large GeoTiffs and rendering is generally quick. QGIS can convert GeoTiff to a range of alternative formats using GDAL. Rasters can also be stored in spatial databases such as Oracle or PostGreSQL, depending on database configuration, and there are plugins that allow these rasters to be viewed in QGIS.

QGIS can also read other data such as Excel spreadsheet, DBF and text files. These data formats can be opened as vector data and are shown as tables in QGIS. Databases such as Microsoft Access can be opened via ODBC support, but it is essential to ensure that both QGIS and the ODBC driver use the same processor architecture i.e. 32 bit QGIS must be installed to connect to 32 bit Access.

3.2 Data infrastructure

Data processing and storage in ArcGIS relies upon:

- shapefiles;
- standalone rasters e.g. ESRI grid;
- feature classes in personal or file geodatabases;
- feature classes in enterprise geodatabases.

For QGIS feature classes cannot be stored in personal or file geodatabases for processing and transferring data. The key formats used for data processing and storage in QGIS are:

- shapefiles;
- standalone rasters e.g. GeoTiff;
- feature classes in SpatialLite database;
- feature classes in enterprise spatial database e.g. PostGIS.

Shapefile

Shapefile is a standalone data format that can be readily opened by the majority of commercial and open source GIS packages.

A shapefile is a single layer comprised of a set of linked files. The advantage of shapefiles is that they can be transferred easily to another location or supplied to a third party, but it is essential to ensure that all associated files are included. One disadvantage is that the data structure is non-relational, so related non-spatial data cannot be stored.

Spatial processing of data in shapefile format requires GIS software and is less efficient than for feature classes in spatial databases. QGIS does not read or write the ArcGIS xml metadata file, but a metadata plugin can be used to generate metadata files.

Standalone rasters

Raster data is commonly supplied as graphic files. Spatial reference information can either be stored in the file, such as GeoTiff, or stored in an associated world file. The majority of raster formats can be readily opened by commercial and open source GIS packages and graphics packages.

The advantage of standalone rasters is that they can be transferred easily to another location or supplied to a third party. In QGIS the virtual raster tile (VRT) format allows collections of rasters to be displayed and processed as a single raster.

SpatiaLite database

A SpatiaLite database in QGIS is a lightweight spatial database format that allows vector and non-spatial data to be stored in a relational database structure in a single file (.sqlite, .db). The entire database can therefore be easily transferred to another location.

Existing data would need to be imported into SpatiaLite or exported to be supplied as a single layer, but these functions are possible using DB Manager in QGIS. Views can be created to combine or filter layers for display.

The range of software that supports SpatiaLite databases is limited to recent versions of commercial software, such as ArcGIS 10.2 or later, AutoCADMap 2013, FME and MapInfo Professional 11.5.2 or later, so it has limited use for supplying data to third parties who are not using QGIS, but it could be used internally for storing and transferring multiple vector layers.

A graphical user interface (GUI) for database management and additional command line tools are available to manage SpatiaLite databases outside QGIS if required (GAIA GIS n.d.).

Spatial databases

Spatial databases allow spatial and non-spatial data to be stored in a relational database structure and are recommended for the storage of multiple datasets to be used by many users. The database may be commercial, such as Oracle Spatial or SQL Server 2008 or later, or open source, such as PostgreSQL with PostGIS.

A spatial database can store multiple vector, raster and non-spatial datasets in a single central location. Spatial databases support both attribute and spatial indexes and multi-user editing. Views can be created to combine or filter layers for display.

Some key advantages of spatial databases are:

- functions and stored procedures can be defined and set to run as scheduled tasks. This functionality can be useful to maintain data within the database;
- spatial processing can be undertaken through the database management GUI which is often faster than processing through a GIS package;
- backups of the database can be scheduled using either the database management GUI or a script set as a scheduled task.

Existing data would need to be imported into the database or exported to be supplied as a single layer, but these functions are possible using DB Manager or the Browser window in QGIS. It is also possible to export the full database so that it can be easily transferred to another location.

A PostgreSQL database with PostGIS offers the highest level of integration for QGIS when compared with Oracle Spatial or SQL Server, as it can be managed using DB Manager. It is the preferred database for many QGIS users, so sample scripts for performing spatial tasks are often provided in PostGIS syntax. In addition, there are supplementary schemas, functions and plugins available to support raster, routing and topology data, as well as versioning.

3.3 Projections

Both ArcGIS and QGIS use the PROJ4 projection definitions, but this does not guarantee that projections will be identical between QGIS and ArcGIS. This may be due to:

- rounding errors due to the precision of the parameters. For example the scale factor for British National Grid is rounded to 6 decimal places in ArcGIS, whilst it is 10 decimal places in QGIS;
- erroneous parameters for a specific projections;
- differences in the algorithm and parameters used to transform data.

QGIS can reproject layers in different projections so that they can be displayed in the same map. By default the preferred EPSG transformation is used when 'on-the-fly' reprojection is used, but the options in QGIS can be configured to ask which datum transformation to use whenever data in a different projection are loaded. When a transformation is selected QGIS shows the EPSG transformation code. This code can be compared with the well-known ID (WKID) of the required transformation in ArcGIS using the geographic transformations document (ESRI 2012). There is an option to save the selected transformation as the default.

For GPS data that needs converting to British National Grid, Ordnance Survey recommend using the OSTN02 corrections. The NTV2 binary file (.gsb) can be downloaded from the Ordnance Survey website (Ordnance Survey 2014) and placed in the QGIS proj folder for use with the corresponding transformation in QGIS.

3.4 Links to other open source GIS

QGIS has strong links to other open source GIS, such as GRASS and SAGA, plus other tools with spatial functionality. These software components are either installed as part of the QGIS install or can be configured to work with QGIS, which allows QGIS to draw upon existing processing libraries, rather than necessitating the development of QGIS functions that undertake the same process.

These functions are available through the QGIS Processing Toolbox, with links to full GRASS functionality provided via the QGIS GRASS plugin. Whilst the functions in the processing toolbox can be directly implemented on any data open within QGIS the GRASS toolbox requires that data are first translated to GRASS format.

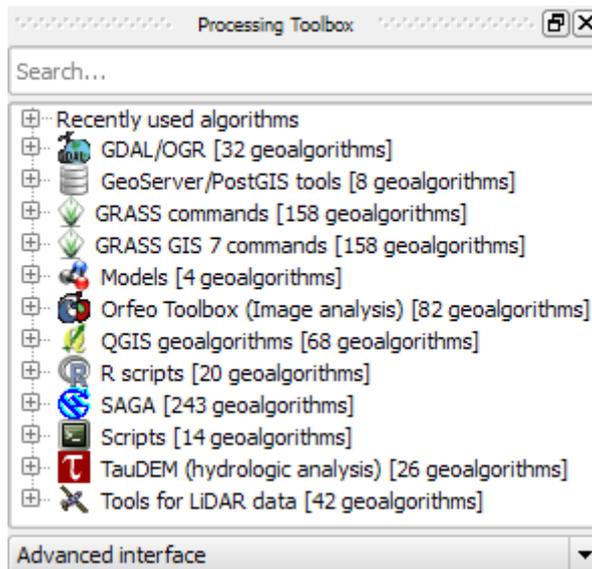


Figure 1 – the QGIS Processing Toolbox, showing functionality available from other open source spatial tools.

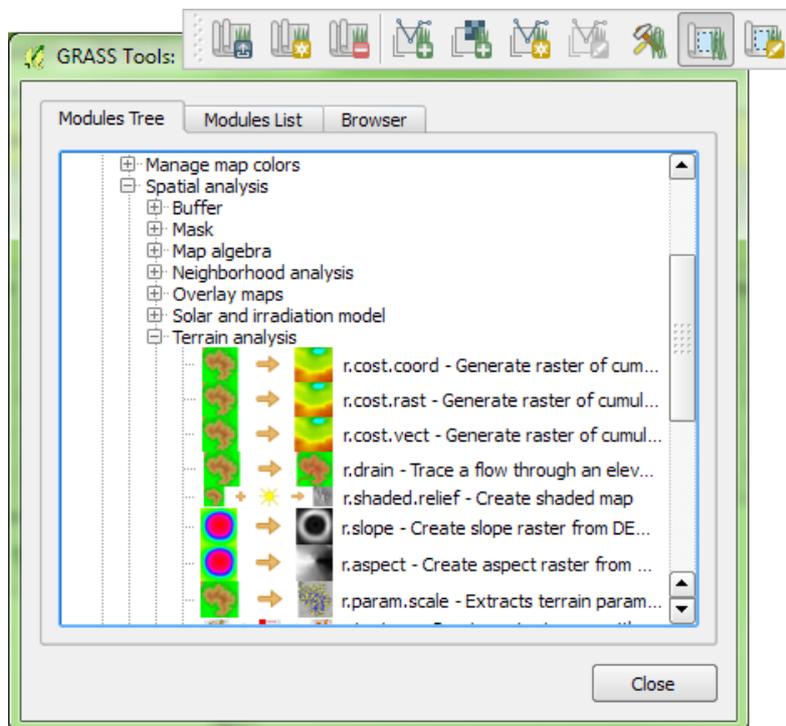


Figure 2 – the QGIS GRASS plugin toolbar and dialog.

3.5 ArcGIS functionality not available in QGIS

This section summarises the software, proprietary file formats, feature types and functions that are specific to ArcGIS where similar functionality does not exist within QGIS.

3.5.1 Software

ArcScan

ArcScan is an extension to ArcGIS that allows manual or automated vectorisation of raster data. There are tools in QGIS that will automatically convert an entire raster to vector, but

there are no utilities for editing rasters. An alternative for editing rasters would be to use the raster editing interface through the GRASS GUI.

3.5.2 Proprietary data formats

All software uses proprietary data formats that are optimised for their storage and processing requirements. The following proprietary data formats in ArcGIS cannot be read by QGIS and would therefore require conversion to an alternative format.

Map document (MXD)

QGIS uses an extended markup language (XML) document with a .qgs file extension to store this information. The existing MXD files could be converted using the MXD2QGS toolbox for ArcGIS 10 that is available online¹. This tool has not been tested by exeGesIS but due to differences between ArcGIS and QGIS we expect that the resulting QGIS project files may require manual modification and layouts are unlikely to be converted.

Layer (LYR)

This format cannot be converted directly. A workaround would be to load the layer file into ArcMap and use the ArcMap2SLD tool (Weiser n.d.). This tool will convert most basic styles but some manual modification will be required. The data can then be opened in QGIS and the SLD file loaded. A QGS layer definition file (.qlr) can be saved if required.

ArcView Legend (AVL)

This is a deprecated ESRI style format that cannot be converted directly. A tool written in Java does exist online to convert AVL to SLD (Poth 2011) but this has not been tested by exeGesIS. An alternative workaround would be to style the layers using the AVL file, then use the ArcMap2SLD tool as for a layer.

Published map file (PMF)

This is an ArcGIS proprietary format that can only be created using the Publisher extension in ArcMap and read using ArcReader. ArcReader could still be used to open existing files as it is free but no new files could be created.

Packages

Layer and map packages are zip files containing a map document or layer file and its associated data. These files should be unpacked and the map or layer file converted for use in QGIS.

Geodatabases

Personal and file geodatabases can be read using QGIS and layers can be saved to a file geodatabase, but these formats are not supported for editing. For QGIS spatial databases, such as Oracle, PostGreSQL and SQL Server, provide a suitable feature-rich replacement for geodatabase and support multi-user editing.

Grid stack

This is a set of overlapping grids used by ESRI for multivariate analysis. For use in QGIS these stacks should be exported as multiband raster images in GeoTiff format.

Raster attribute tables

Raster attribute tables are stored in dBase file (DBF) format, and allow multiple attributes to be stored for each cell. They are not currently supported in QGIS but there is a feature request to add this functionality in future.

¹ <https://sites.google.com/site/lumtegis/files/Mxd2Qgs.zip>

Smart Data Compression (SDC)

SDC format is used for the data and maps supplied with ArcGIS. Any data in this format must be exported to shapefile or geodatabase for use in QGIS.

Triangulated irregular network (TIN)/Terrain

These formats are both based on TIN format and are not used by either QGIS or GRASS. This data must be converted to a raster data format for use in QGIS.

ArcIMS service

The data provided by these services is in a proprietary format that QGIS cannot read directly. OpenLayers does support this format so it may be possible to develop the OpenLayers plugin or a separate tool to add an ArcIMS service to the map.

3.5.3 Feature types

The following feature types are present in ArcGIS but are not replicated in QGIS. Suggested workarounds are given where possible, but development may be required.

Annotations and graphics

ArcGIS allows annotations and graphics to be stored either in the map document or a geodatabase. QGIS does have some annotation tools for adding simple callout boxes to the map but the ability to customise these annotations is limited. Some of this functionality could be replicated manually if the Memory Layer plugin is enabled using:

- point memory layer set as invisible with dynamic labels to replace text;
- point, line or polygon memory layers to replace graphics.

Coverages

Coverages are specific to ArcInfo and there is no equivalent format available in QGIS. A key characteristic of coverages is that the data structure ensured that topology was maintained. Existing coverages can be opened in QGIS, although text will be imported as points.

Most of the functionality available in ArcGIS for coverages is available for vector data in QGIS. Spatial topology for a layer can be maintained by enabling 'topological editing' whilst digitising. PostGIS has a topology schema for vector data, however the tools to edit these layers in QGIS are currently limited.

Feature classes for labels

In ArcGIS it is possible to have multiple label styles for a single layer using queries to identify feature classes. QGIS has a rule-based renderer for symbology but currently allows a single label style per layer. There is a feature request for this functionality². As a workaround additional fields can be added to the table and data defined labelling used to customise the style for each label.

Raster mosaics

Raster mosaics were introduced in ArcGIS 10 as a replacement for raster catalogs. They are combined datasets that allow data to be searched as a catalog and treated as a raster layer for geoprocessing.

Relationship classes

Relationship classes are created by ArcGIS to define table relationships in geodatabases. Similar functionality can be achieved by storing data in a spatial database and defining

² <https://hub.qgis.org/issues/3843>

relationships and constraints for the database tables, but tools to create relationships interactively from QGIS would need to be developed if required.

Representations

Representations are stored in a geodatabase and are created by the cartography tools so that a feature may be represented differently according to rules without altering the geometry. There is some capability in QGIS to alter the styling of objects according to specific criteria using rule based rendering and styles can be saved to PostGIS so that they can easily be reused by all staff.

SubTypes

ArcGIS allows subtypes to be defined for a layer. Domains may be specified for each subtype to ensure valid data is entered. There is no concept of subtypes in QGIS, but for digitising the layer could be split using a filter and different domains assigned in the layer properties.

Workspaces

A workspace is an ArcGIS concept that refers to a collection. This may be either a folder or geodatabase. ArcGIS has a number of functions for managing workspaces that are not present in QGIS. For files these functions are not necessary. For spatial databases it is expected that these functions are managed through the database interface.

3.5.4 Functions

ArcGIS contains some collections of specialist functionality that do not seem to be replicated within QGIS or known plugins. These functions are probably used by a minority of users doing advanced digitising and advanced mapping.

Cartography

ArcMap Standard and Advanced have a suite of cartography tools that allow the user to add geometric effects to features without altering the underlying geometry. These effects are stored in a geodatabase as representations. Development of similar functionality in QGIS would require significant development.

Coordinate geometry

Coordinate geometry is used for digitising surveyor plans that show the location of features relative to each other. Each item within the network is either a point or a line with two vertices. The basic functionality of plotting using azimuth and distance is available but there seems to be no capability to adjust distances based on the projection. Development of the full functionality available in ArcGIS would probably require a COGO schema with associated functions in a spatial database.

3.6 ArcGIS functionality with equivalent in QGIS

This section summarises the software and feature types that are specific to ArcGIS where similar functionality does exist within QGIS and highlights key differences.

3.6.1 Software

ArcGIS for Server

ArcGIS for Server provides a fully-featured 64-bit GIS server that can be installed on a web server or in the cloud. It provides a range of services including web map services (WMS), web feature services (WFS), editable WFS (WFS-T), geocoding, geoprocessing and printing. ArcGIS for Server allows resources to be secured to limit access to particular users. It also

includes ready to use mobile and web applications including ArcGIS Online, Portal for ArcGIS map viewer and ArcGIS Viewer.

QGIS Server provides a far more limited range of functionality. It is a 32-bit GIS server that runs using Apache web services. It can be installed locally or on a web server and provides WMS, WFS, WFS-T and WCS services. An associated Web Client is available that displays maps online in an interface similar to QGIS Desktop and allows maps to be printed. There are limited details on securing the server to limit access to particular users.

As QGIS Server is a 32 bit server it is likely to be slower than ArcGIS for Server, particularly if there are large numbers of external users. It has limited options for securing the server and does not offer processing capabilities³. An alternative would be to use other open source GIS servers with more features e.g. GeoServer.

ArcGIS Online

ArcGIS Online provides a service and an application programming interface (API) to set up a custom website and publish data online. This service includes base maps and reference layers. In QGIS either QGIS Server with the QGIS Web Client (see above) or QGIS Cloud can be used to publish maps online.

QGIS Cloud is a hosted service. The cost of the package per month is based on the level of data storage required and whether the client wishes to customise the page with their own logo and styling. For QGIS Cloud it is recommended to use the Open Layers plugin, which provides Bing, Google and Open Street Map web services as base maps, but does not include reference data.

3.6.2 Feature types

Raster Catalogs

Raster catalogs can be managed or unmanaged and store a link to the raster and the raster footprint in a geodatabase table. They allow rasters to be searched and displayed. In QGIS there are two features that replicate parts of these functions:

- **Tile Index**
A tile index layer is a shapefile that contains the image name, path and footprint. There is a Tile Index Viewer plugin that allows images to be opened from the tile index layer, similar to opening layers from a raster catalog in ArcGIS.
- **Virtual Raster Tiles (VRTs)**
A VRT is an XML file that lists the file path and extent for each of the input layers. The VRT can be opened as a single raster layer as for a raster catalog, but can also be processed as if it was a single raster similar to a raster mosaic. Any modifications require a new VRT file to be created. To improve rendering speed for large VRT files, overviews or pyramids can be created as external files.

3.6.3 Functions

Raster colour tables

ArcGIS has functionality to create, edit and remove raster colour tables for single band rasters. This allows the colour styles to be stored within the raster metadata. QGIS will display data using a pre-defined colour table by selecting the Paletted symbology by default.

³ 3Liz were working on server-side processing using PyWPS in February 2014.

An alternative approach in QGIS is to thematically display the raster using the Pseudocolor symbology. This provides options to create a colour map using colour ramps or manually assign colours. The configuration can be saved to a QGIS style file so that it can be re-used for other layers. Colour tables can also be created and removed in GRASS, but there is not a tool in the Processing toolbox at present.

4 Core functionality

This section summarises the similarities and differences in the core functionality between ArcGIS and QGIS. The spreadsheet containing the full assessment for each element of core functionality can be found in Appendix 1 – Core Functionality. This section has been structured using the worksheet names and headings to assist with cross-referencing, so there is some repetition where similar items were repeated in different worksheets.

Where a function depended upon ArcGIS specific functionality that was not available in QGIS (section 3.4) it is not summarised in the following sections, unless an alternative or work-around for that specific function was available.

4.1 Mapping

4.1.1 Map interaction

Map Navigation

Map navigation in QGIS generally matches the functionality available in ArcGIS, but a few elements of non-essential functionality are not present. For example it is possible to rotate the map in the print composer but not in the main window.

Queries

The majority of query functionality is available in QGIS, but there are some minor differences as some of the functionality is more limited. For example:

- only the active layer in the table of contents is selectable but the layers returned by the Identify tool in top down mode can be configured;
- select data by location has more limited options: contains, intersects and is disjoint.

Tables

Basic table functionality to select records, copy records and replace values is available, but some useful functionality is missing, including:

- the right-click menu to zoom, pan, flash, select and identify features. Some of this functionality is available for selected records via buttons in the table window, but not for a single record;
- the ability to highlight selected records in the table. It is possible to highlight a record from the Identify dialog, but not through the table window;
- customisation of the table, such as reordering or sorting by multiple columns. The table can be sorted by a single column only.

Graphs

There is no functionality in QGIS to create 2D or 3D graphs, although data diagrams can be shown as symbology (see section 4.1.2). Matplotlib in Python can be used to create graphs, but an interface would need to be developed.

4.1.2 Map display

General mapping

Basic functionality including transparency and display scales can be configured for each layer. The map can be visualised on a specific date using the experimental Time Manager plugin but testing would be required to determine similarity to the ArcGIS time functionality.

ArcGIS has several types of grid that can be created. QGIS will add a grid to the map as a decoration using the map units, so this functionality is similar to either a graticule or a measured grid depending on the projection. Reference grids are not supported but are likely to be used less frequently.

Tabular data

The majority of basic functionality for tabular data is at least partially available, but statistics are only available using the Statist plugin to show basic statistics for a single field and sorting is limited to a single field. There are no options in the edit widget to specify a format for numeric fields and it is not possible to create charts or reports for a table.

Vector data

Most functionality for vector data is available, although it is not possible to assign a selection colour to each layer. Symbology cannot be fixed to a specific scale, but a similar effect can be achieved by specifying the size in map units. Most thematic classifications are available through configuration, except dot density as this requires a derived layer to be generated, but there is no interactive histogram.

Symbology

The style settings in QGIS match most of the functionality available in ArcGIS, but the predefined symbols are more limited. There is no built-in option for a halo, but this can be replicated manually by defining an additional marker below the original marker.

Symbols in QGIS can be based upon fonts or scaled vector graphic (SVG) files. Additional predefined symbols and user-imported fill patterns can be applied, but these are based upon SVG files instead of graphic files.

Elevation surface display

Elevation surface display is limited to digital elevation models (DEMs). DEMs displayed based upon elevation or hillshade can be calculated using GDAL and added as a separate layer.

Raster data display

Raster data can be displayed using either multiple bands or a single band. There are options available to define the algorithm, resampling and classification methods used to display rasters but they are generally more limited than in ArcGIS. For example, the pseudocolour symbology can use discrete values, but there is no tool to list all unique values.

Raster layer statistics will calculate statistics for the whole layer and save it to an output file. Layer statistics for the image are also shown in the layer metadata, but there is no option to save current display statistics.

4.1.3 Page layout and printing

Map elements

The majority of map elements are available, except OLE objects and reference grids, but some elements require configuration. For example neatlines cannot be added automatically around objects but rectangles can be added. A grid can be added in map units as for map display (section 4.1.2). HTML objects can be added to display formatted text.

Export formats

Most graphic export formats are available, except graphic interchange format (GIF). Export to enhanced metafile (EMF) and encapsulated postscript (EPS) are not supported. These formats are often used to export scalable images for printing and so developing them may be useful. For Adobe Illustrator an alternative method would be to export to portable document format (PDF) or SVG, or print to postscript (PS), then import into Illustrator.

4.1.4 Publishing and sharing maps

Creating dynamic maps

Most of the functionality in this section is specific to ArcGIS for Server and not relevant to QGIS. Maps can be published to QGIS Server by copying the project document to the server. The maps are displayed using the QGIS Web Client using layer symbology as shown in QGIS Desktop.

Sharing maps, layers and data

It is possible to consolidate a map using the QConsolidate plugin, but the creation of packages would require development. Maps could be shared using the QGIS Cloud plugin (see section 3.5.1).

4.1.5 Map Text

Labels

The majority of label functions are available and labelling can be defined using attributes, but the options for conflict detection and label placement rules are more limited than in ArcGIS. It is possible to create a conditional label expression but QGIS is not currently able to assign different label styles based on label classes or set advanced text formatting tags, but there are open feature requests for this functionality.

Annotation

Annotation layers are ArcGIS specific, but QGIS does have annotation tools that create simple horizontal callouts. These annotations are stored in the project file. Annotation values can be taken from map layers using the Form annotation or given custom styling using the HTML annotation.

Advanced Labelling

Advanced labelling is generally limited and may require development. Font reduction is not automatic but data defined labels could be used to reduce the size of individual labels. Word and character spreading are available and labels can be placed on polygon boundaries, but curved labelling is currently only available for polylines.

4.1.6 Cartography

Cartographic representations are specific to ArcGIS but some of the cartographic editing tools can be partially replicated by:

- altering symbology, transparency and visibility for specific features using rule-based rendering;
- using the marker outline style to place point symbols along lines or polygons;
- using the Style Manager to modify line width, hatch size and orientation.

4.2 Framework and Data Automation

4.2.1 Application customisation

Application look and feel

The majority of this functionality is available in QGIS, but windows do not auto-hide. QGIS can be translated into many languages but some translations, such as Chinese, are incomplete.

Customisation

As QGIS is open source there are virtually no limits to how the package can be customised. For most users, the interface is less customisable as toolbars can be rearranged but tools cannot be arranged or new toolbars or menus created without programming. QGIS can be extended by creating plugins in C++ or Python.

4.2.2 Data editing

General editing

Most of the general editing functionality is available. QGIS does not have feature templates to predefine editing tasks, but it would be worth investigating whether actions will reproduce some of this functionality. QGIS has a single snapping environment, similar to ArcGIS classic snapping, with a dockable snapping window.

Snapping types and tolerance

QGIS will snap to vertices, edges and intersections, but does not support the more advanced snapping types in ArcGIS e.g. midpoint. Point and End snapping are possible using vertex snapping as for ArcGIS classic snapping. Tolerance can be specified in pixels or map units as in ArcGIS.

Geometry construction options

The majority of construction options are available using the experimental CADInput plugin and the Autotrace plugin, but some advanced functionality such as tangent curves is not available. Functionality to flip features and trim features to length is not available, but should be relatively simple to develop.

Geometry creation tools

Point and click digitising is available in core QGIS and stream digitising is available using the Freehand Editing plugin. A coordinate could be added in decimal degrees (DD) using the experimental CADInput plugin if the projection unit was degrees. The remaining tools are not available, but are relatively specialised and not likely to be required by the majority of users.

Feature manipulation tasks

All feature manipulation tasks are available, except splitting lines at intersections. Mirror copies can be created using copy and paste but the advanced copy and scale tool would require development. The Numerical Vertex Edit tool should be tested to determine whether it modifies coordinate values correctly.

Attribute editing

QGIS does not have an equivalent to the attributes dialog that allows rows to be modified as a group but the rest of the functionality is available.

Multipart features

Parts can be added and removed using the advanced digitizing toolbar, but it is not possible to zoom to a single part. Vertices can be edited as for single part features. fTools has a function to explode multipart polygons, but this function creates a new layer.

Map navigation whilst editing

Zoom to feature vertex or feature part is not available, only zoom to feature. Continuous pan/zoom option is not available, but for QGIS this functionality is not necessary as the user can either use the arrow keys or switch to the pan or zoom tools then resume digitising by clicking back to the original digitising tool.

Vector data transformation

These functions are the equivalent of raster georeferencing for vector data and are therefore rather specialised. Affine transformations can be performed using the either Affine Transformation plugin or v.transform.points in the GRASS toolbox. The remaining transformation types would need to be developed if required.

Generalisation

fTools will simplify line or polygon features using the Douglas-Peucker algorithm, whilst the v.generalize function in the GRASS toolbox will perform more advanced smoothing using various algorithms.

4.2.3 Raster Editing and Vectorisation – ArcScan

Although QGIS does not have a plugin that is similar to the ArcScan extension, it does have some tools that can be used to vectorise raster data. The GDAL Polygonize tool and similar tools in the GRASS and SAGA toolboxes will convert an entire raster to a polygon layer. QGIS does not have a raster snapping environment for manual digitising. d.rast.edit could be run through the GRASS GUI if raster editing is required, but the functionality available within this package would require investigation.

4.2.4 Multiuser geodatabase editing

Geodatabases are not supported in QGIS, but multi-user editing is supported when editing spatial databases such as Oracle, PostgreSQL or SQL Server. QGIS 2.4 does not appear to have any versioning tools at present.

There was a plugin for older versions of QGIS (pre v2.0) called PG Version that allowed versioning to be enabled for specified tables in a PostgreSQL database. From the available documentation it appears that the versioning functionality did not follow an identical process to that in ArcGIS, but it did offer similar functionality. It may be worthwhile to investigate this plugin further to determine whether it met the requirements, as it may be more cost effective to fund an upgrade to this plugin for QGIS 2.4 than developing a different approach.

Alternatively a simple approach may be to add database triggers to archive records whenever changes are made to specific tables.

4.2.5 Spatial referencing of image data (georeferencing)

Tools

Most of the georeferencing tool functionality is available in QGIS using the GDAL Georeferencer. Unlike ArcGIS the image is opened in a separate window so there is no need to shift, rotate or fit image to display. Control points are added to the image and the corresponding map location can be selected from the map in QGIS.

Transformation methods

All of the transformation methods are available except Adjust, as that transformation is a combination of polynomial and TIN interpolation specific to ArcGIS.

Save Spatial Reference

For the majority of transformation methods a new dataset must be created, similar to rectifying an image in ArcGIS. For linear transformations the GDAL Georeferencer has the option to create a world file to store the spatial reference information.

The Georeferencer rectifies images in a separate window, rather than the main map window, so shift, flip, rotate and fit functions are unnecessary. It doesn't replicate the adjust functionality in ArcGIS, but this is likely to be rarely used.

4.3 Data manipulation and analysis

4.3.1 Coverage geoprocessing

As stated in section 3.4.3, coverages are not supported in QGIS for editing. The majority of the coverage geoprocessing tools are therefore not relevant to QGIS. Some of the functionality is duplicated and will be covered in the next section.

The only tool that is not covered elsewhere and is available in QGIS is cleaning topology. The Topology Checker tool allows simple rules to be defined and validated interactively in QGIS. The GRASS toolbox has a v.clean function that performs a similar function or alternatively PostgreSQL tools could be used.

4.3.2 Geoprocessing

Geoprocessing is undertaken in ArcGIS through the toolbox. A similar processing toolbox is now available in QGIS. The review of geoprocessing capability has focussed on functionality available via the toolbox, unless it is specifically stated that a particular function is only possible interactively. Some of the ArcGIS tools are combinations of existing tools that could be replicated using a model to run the relevant functions sequentially.

Environment

The geoprocessing environment includes almost all of the functionality available in ArcGIS. Looping models cannot be created with the Graphical Modeller, but could be added manually if the model was exported as a Python script.

Supported scripting environments

Python is the only scripting environment supported within QGIS. QGIS 2.4 uses Python 2.7. It is possible to write plugins using either C++ or Python.

General data management

Copy, merge and calculate values are possible through the processing toolbox. It is possible to append and sort data interactively, but there is no corresponding tool. There is a feature

request for the ability to rename and delete files through QGIS Browser, but it is unclear whether corresponding tools will also be added to the toolbox. Merge branch is not possible with the Graphical Modeller, but could be done manually if the model was exported as a Python script. Finding and deleting identical values would require development.

Data comparison

There is no comparable functionality in QGIS. It is possible to perform comparisons in PostgreSQL with the exception of file comparison, but an interface would need to be developed.

Table management

Rows can be copied using the 'save selected features' tool and deleted interactively, but the remaining tools are not available. These tools in ArcGIS are specific to geodatabase tables. Equivalent tools in QGIS could be developed to perform these functions for spatial databases. It is possible that some of these functions could be executed using the PostGIS execute SQL tool, but an appropriate SQL query would be required.

Editing

The densify, generalise and snap tools are available, but some of the options are more limited than in ArcGIS. The remaining tools would require development. A Python script is available online to flip lines, so a tool could easily be created.

Field management

The majority of this functionality is available in the toolbox. Default values in both ArcGIS and QGIS can only be defined for database tables. It is possible to assign a default value for PostGIS or SpatialLite tables interactively through the DB Manager. The Field Calculator tool can be used to convert time fields and calculate end times, so a simple model could be developed, but transposing fields would require development.

Feature class management

Fishnets and random points can be created using the processing toolbox. Integrate could be recreated using `v.in.ogr.qgis` with an appropriate snapping tolerance. This could possibly be created as a Python script.

Feature management

Most feature management functionality is available in QGIS. The following functions are not currently possible:

- XY to line;
- dice;
- minimum bounding geometry;
- feature envelope to polygon;
- split line at point.

Generalisation

Dissolve, eliminate and eliminate polygon part are possible using the processing toolbox. Most of the cartography tools are not available within QGIS, with the exception of the simplify line and polygons tools. Similar functionality to smooth polygon should be possible using a model, but the remainder would require development.

Projections and transformations

Most of this functionality is available interactively in QGIS, but not through the toolbox. There is not a tool for conversion of degrees decimal to DMS, but a model could be created to do this using the Field Calculator.

Raster management

Most of the raster management tools are available in the toolbox, but some functions can only be performed manually, such as export raster catalog paths and delete raster catalog items. The following functionality is not available:

- build pyramids and statistics;
- export raster world file, but this is unnecessary for GeoTiffs as they contain spatial reference information;
- repair raster catalog paths;
- split raster.

Raster mosaics

Raster mosaics are not supported in QGIS. Some of the functionality is possible using VRT files in QGIS and has therefore been evaluated on this basis, but VRT files cannot be created or edited using the toolbox.

Raster conversion

Rasters can be converted to and from the majority of formats supported by ArcGIS using the Polygonize, Rasterize and GDAL Translate tools. The exceptions are:

- conversions to and from float format;
- conversion to point;
- conversion to polyline.

Raster transformation/projection

Most of the functionality is possible using the GDAL translate and warp tools, but the required parameters are not available in the toolbox, so models would be required. The flip, mirror and rotate tools would require development. Functions to flip and mirror rasters are available in R.

Conversion

Conversion between most formats is supported using the OGR Convert Format tool. Several functions import to geodatabase, but this is only possible interactively by saving to a file geodatabase. Development would be required to export to CAD or export a whole map to KML.

Layers and table views

It is possible to make the equivalent of a query table using a query to filter data in PostGIS or SQL Server, but most of the other functionality is not possible through the QGIS toolbox. Select layer by attribute or location is not completely replicated in QGIS, though similar functionality should be possible using a memory layer.

Packing

There are no tools available in the toolbox to perform these tasks, as they rely on plugins or functionality that would need to be developed.

Core analysis

Most of this functionality is available through the processing toolbox, but split and update would require models to link the required tools sequentially. Two tools would require development: multiple ring buffer and identity.

Spatial statistics tools

A significant amount of development would be required to match the functionality in ArcGIS. Some functions are available in QGIS and SAGA but these tools do not fully match the ArcGIS functionality:

- average nearest neighbour;
- mean centre;
- standard distance;
- ordinary least squares regression;
- geographically weighted regression.

Database management

Most of this functionality is not relevant, as it is specific to ESRI personal or file geodatabases. The following functionality is also relevant to spatial databases, but there are no tools within the QGIS toolbox as it is assumed that this will be undertaken using the database management software:

- change privileges;
- compress;
- migrate storage.

Table joins

There are two tools in the toolbox that will create a join between tables. The output is a temporary layer, so a tool to remove the join is not necessary as the source layers are not affected.

Data indexing

Spatial indexes can be created interactively. Spatial indexes for shapefiles can be removed by deleting the .qix file. For spatial databases it is assumed that attribute and spatial indexes will be created and removed using the database management software.

4.4 Data management and validation

4.4.1 Data management

General

QGIS Browser is similar to ArcCatalog, but functionality to manage datasets is limited. It is possible to create shapefiles and connect to spatial databases, but functionality to create and manage feature classes in ESRI geodatabases is not supported.

Search for GIS data

Data in the Browser window can be filtered by name, but it is not possible to search GIS data within QGIS.

Geodatabase administration

Data cannot be loaded into ESRI geodatabases, but data can be loaded into PostGIS and new tables created through DB Manager. Update of RDBMS statistics would generally be done through the database management software.

Geodatabase XML file import/export

All of this functionality would generally be undertaken outside of QGIS. Import and export of XML would generally be done through the underlying database. Zip files can be created through Windows Explorer or Z files can be created using GZip (.gz) or 7Zip (.7z). It is possible to use GZip with PostGIS to export directly to zip or gz format.

4.4.2 Attribute Validation

Domains

The QGIS equivalent of domains can be defined in the value map for a field through the layer properties window, but the domain categories cannot be saved to a table.

Relationships

Relationships can be defined between spatial database tables, but this would generally be done through database management software.

4.4.3 Topology

The topology rules available in QGIS are limited to the rules required for snapping. Greater topological control could be implemented through a fully topological data format, such as GRASS or PostGIS. The experimental PostGIS Topology Editor plugin should allow control of PostGIS topologies from QGIS, but the functionality is currently limited.

Topology can be validated in QGIS using the Topology Checker plugin, but this tool cannot validate all of the rules that are available in ArcGIS.

4.4.4 Utility (Geometric) network analysis

There is generally no networking functionality built into QGIS. Most of the functionality that is available is either in GRASS or PostGIS pgRouting using the pgRoutingLayer plugin. Some additional functionality would need to be developed. Although pgRouting currently appears to have more restricted functionality, development may be easier using the pgRouting schema than using GRASS.

4.4.5 Linear Referencing Routes

The majority of this functionality seems to be possible using the LRS plugin, but this plugin could not be tested within the limited timescale due to the need to set up a full network. It was decided that this was not worth pursuing further as JNCC do not see an immediate need for this functionality. Further investigation and testing should be undertaken by JNCC if a requirement for this functionality arises in future.

4.4.6 Metadata

In addition to the basic layer metadata that is generated by QGIS for all layers, there are two plugins in QGIS that will create and edit metadata. Both plugins are experimental and bugs were encountered whilst checking functionality.

Metatools does not appear to be INSPIRE compliant and appears to work for shapefiles only. Qsphere is INSPIRE compliant but the lookup tables are entirely in French and would need to be translated. Qsphere can export XML data to ISO19139, but will not import from any format. In order to use either of these plugins some additional development would be required to fix bugs and ensure that the metadata created meets the UK GEMINI and INSPIRE requirements.

An alternative approach would be to develop a plugin that would allow users to link to the new UK Location Metadata Editor. This new online tool allows:

- creation of UK GEMINI 2.2/INSPIRE compliant metadata;
- files can be imported/exported, with some options on data format;

- all metadata are stored in a central location and automatically published;
- metadata file can be downloaded to the local file system.

Discussions with JNCC clearly suggest that they want to be able to keep easily viewed metadata with the data, rather than in a separate location, so the UK Location Metadata Editor will not meet their needs.

4.5 Data support and interoperability

4.5.1 Raster data support

Direct read of raster data

All of the raster formats listed for direct read should be opened using the OGR libraries, provided the required additional libraries have been installed. It is not clear whether ESRI band interleaved by pixel (BIP), ESRI band sequential (BSQ) and floating point raster (FLT) can definitely be read, so these formats should be tested prior to switching to QGIS if necessary.

Direct read and write of raster data

QGIS will read all of the raster formats listed except ESRI grid stacks and geodatabase rasters, which should first be exported to alternative formats. The majority of raster processing tools in QGIS write to GeoTiff only, but GeoTiff can be converted to alternative formats.

Geodatabase raster management

The raster data type in PostGIS or Oracle could be used as an alternative to geodatabase rasters. Creation, management and compression of raster data would generally be undertaken in database management software. QGIS does not have an equivalent to raster mosaics, although VRT format allows some similar functionality.

4.5.2 Document and data support

Map and Symbology files

There are equivalent files in QGIS which will allow layer styling and map projects to be shared between users, but the ArcGIS formats are not supported (see section 3.4.2).

Direct read of vector and raster data

QGIS is very strong on reading a wide range of file formats, due to the integration of GDAL OGR. Personal geodatabases can be read, but QGIS must be the same architecture as Access i.e. it is not possible for 64 bit QGIS to work with the 32 bit Access ODBC driver or vice versa.

Other than ArcGIS proprietary formats the only data format that is not compatible is ArcGIS for Server vector services. ArcGIS for Server raster services could be added through the REST service, but a tool would need to be developed to access vector data via the SOAP service.

Direct editing of vector data

Editing of shapefiles is possible and is the default standalone format for vector data in QGIS. Editing of personal and file geodatabases is not supported, but equivalent spatial databases such as Oracle, PostGIS and SQL Server can be edited.

Direct read of other data

All other data formats can be read with the exception of ArcGIS proprietary formats, including terrains, TINs and INFO files. Data can be read from Excel or DBF as vector layers, but points cannot be created unless a tool is developed. A workaround would be to export this data to CSV and import as delimited text specifying x and y columns. Both tables and views can be opened via OLE DB/ODBC, but the ODBC driver architecture must match the installed version of QGIS.

4.5.3 CAD Support

CAD file support

Data can be read from drawing exchange format (DXF) and MicroStation design file (DGN). AutoCAD drawing files (DWG) may be supported if GDAL is built with DWG support, but will not open the most recent file versions. Export to CAD is limited to saving as DXF.

Direct read of CAD data

Most functionality is available in QGIS. CAD layers are imported as separate layers in the map, but the format of the layers in QGIS seems to be different to ArcGIS. Standard AutoCAD attributes can be read, but as for ArcGIS the AutoCAD Map attribute tables are not readable.

Editing with CAD data

CAD layers are treated as any other vector layer once they have been opened in QGIS so all of this functionality is available.

Coordinate systems

The coordinate system for the CAD data can be specified as the data is imported, but this is not saved with the CAD data. QGIS can perform an affine transformation to align CAD data, but the data would need to be saved as a shapefile first, rather than storing the transformation with the original file.

4.6 Data

4.6.1 ArcGIS Online Services

The OpenLayers plugin in QGIS provides services to add Bing and Google maps, as well as data from Open Street Map, subject to the data provider's terms of service. For the remaining data alternative sources of similar WMS/WFS and data should be investigated.

5 Review of Spatial Analyst and 3D Analyst functionality

This section summarises the similarities and differences between the Spatial Analyst and 3D Analyst functionality in ArcGIS and equivalent functionality in QGIS. The spreadsheet containing the assessment for each element of functionality can be found in Appendix 2 – Spatial/3D Analyst Functionality. This section has been structured using the worksheet names and headings to assist with cross-referencing, so there is some repetition where similar items were repeated in different worksheets.

Please note that the SAGA and GRASS raster calculators expect single band rasters and unexpected results may occur if multiband rasters are used.

5.1 Spatial Analyst

Conditional

There are no specific tools for these functions, but they are all possible using the QGIS or SAGA raster calculators so models could be created.

Density

Point and kernel density functionality are available using point inputs in the SAGA and Heatmap plugins, but line and kernel density functionality using line inputs would require development.

Distance

Cost surfaces, Euclidean distance and path distance can be calculated from point inputs using GRASS, or some of the functionality is available in SAGA. The r.walk function in GRASS should be tested to determine whether the outputs are equivalent to path distance in ArcGIS. Corridors can be calculated using the raster calculator so a model could be created. The remaining functionality would require development.

Extraction

Extraction by attributes, mask layer and rectangle are possible. Values can also be extracted to points using SAGA. The remaining functions would require models or development.

Generalisation

All of this functionality is available using GRASS or SAGA, but ArcGIS has additional options.

Hydrology

Most of the hydrology functions are available using GRASS, SAGA or TauDEM. The Fill tool would require testing, as the methodology used is significantly different to ArcGIS.

Interpolation

All of the basic interpolation methods are available in SAGA. Spline with barriers and the topo to raster functions will require development. It may be possible to approximate the output of the topo to raster tool using a combination of GRASS tools in a model.

Local

Cell statistics and combine are available in GRASS. Highest and lowest position can be calculated using the layer of extreme value in SAGA. The frequency tools can be replicated using the raster calculator, but Popularity and Rank will require development.

Map Algebra

Single output map algebra can be undertaken using the QGIS, GRASS or SAGA raster calculators. Multi-output map algebra is no longer supported by ESRI in ArcGIS 10 so layers would need to be generated as single outputs.

Math

The majority of math functions are available using the r.mapcalculator tool in GRASS, but no combinatorial functions are available. Some of the functionality that is not available could be developed using the image processing capabilities in Python and Numerical Python (NumPy).

Multivariate statistics

Image classification in QGIS can be undertaken using the Orfeo or SAGA toolboxes. The process used to classify images varies between tools, so each method should be tested to determine the preferred approach.

Regression can be undertaken using GRASS or SAGA regression tools. The available tools should be tested to determine whether these tools produce equivalent outputs from ArcGIS.

Neighbourhood

The Filter functionality is possible using SAGA. Focal statistics are available for circular and square neighbourhoods, except minority and range. Block, line and point statistics would require some development, as would focal flow.

Overlay

Both weighted overlay and weighted sum can be undertaken using the r.series tool in GRASS, but the rasters would need to be reclassified before this calculation was performed.

Raster creation

GRASS can create all of the raster types listed. The extent and cellsize of the GRASS region must be specified carefully to ensure that the cell size of the resulting raster is correct.

Reclass

Reclassify and reclass by ASCII file are possible using SAGA and GRASS respectively. The remaining functionality would require development.

Surface

The majority of the surface functionality is available, but the configuration options are generally more limited. The Cut/Fill tool would need to be developed but this could be done using a model.

Zonal

Tabulate area and zonal statistics functions are available, but the statistics options are more limited than those in ArcGIS. The remaining functions would require development, but are likely to be used less frequently.

5.2 3D Analyst functionality

The 3D capabilities of QGIS are limited, so a direct comparison with the functionality in ArcGIS 3D Analyst and ArcScene/ArcGlobe was not possible. It was agreed with the client that the available functionality would be reviewed and used to provide an overview of the 3D functionality available in QGIS.

QGIS2ThreeJS plugin

The QGIS2ThreeJS plugin creates an HTML page that displays a 3D model using the 3JS javascript libraries. The browser used to display the resulting web page must support WebGL and ActiveX and javascript must be allowed to run so that the model can be displayed. Internet Explorer 11, Firefox or Chrome configured with appropriate settings would therefore be required.

All layers that you wish to show in the model should be open in QGIS. The DTM and additional vector overlay layers should be set as not visible before launching the tool, particularly if 3D styling is to be applied as the current map view in QGIS is draped over the DTM.

The interface includes options to extrude vector layers relative to the height of the DTM using either a fixed or an attribute value. Once all of the options have been configured, the 3D model can be generated and will automatically display in the default browser. Tools in the web page allow the user to rotate the model, zoom in and out and save the image.

The following example images were created using the QGIS2ThreeJS plugin and were taken from tutorials online:



Figure 3 - 3D model of Tuerkenschanz Park with extruded buildings and trees (Graser 2014)



Figure 4 - 3D model of United States Geological Service DEM and imagery for Mount Rainier (Information on *More 3D Maps and Tips using QGIS2ThreeJS*)

Both the image and the DTM are resampled to suitable resolutions for rapid display online, so this would not be suitable for generating production quality graphics, but it may be suitable for generating quick 3D visualisations of elevation data and associated raster and vector layers.

NVIZ in GRASS

The NVIZ module in GRASS can be run from the toolbox in QGIS and offers the ability to create 3D models, display vector data and volumes, export high resolution images and create video fly-throughs in MPEG format.

A draped model can be created by loading the DTM and composite aerial photograph layer or classified layer into NVIZ. The resolution of the resulting model depends upon the grid resolution so the GRASS region must be set with care.

The interface for NVIZ has more functionality overall, but is not as simple to use as QGIS3ThreeJS, so additional time would be required to determine appropriate workflows.

Globe plugin

The Globe plugin is available in the 32 bit version of QGIS 2.4 and is the QGIS equivalent of ArcGlobe. User data from QGIS can be displayed on a 3D globe and extruded using height attributes. This plugin is experimental and is not suitable for modelling bathymetry or borehole data.

6 Infrastructure review and implementation

6.1 Key background information

JNCC employs approximately 180 staff, of which 77 are considered to be GIS users. These staff are split between offices in Peterborough and Aberdeen, working on a mixture of desktops, laptops and workstations, all expected to be running Windows 7 by 2015. Virtual LAN core networks are implemented in both locations.

Both complete desktop and virtualised applications are delivered to JNCC staff via Citrix Xenapp 6.5. ArcGIS is currently delivered to GIS users in Aberdeen or working from home through a Citrix published application. This would also provide an approach to delivering standard JNCC QGIS builds, with required plugins, to GIS users.

JNCC laptop users have VPN access to network resources.

JNCC operates a Microsoft Hyper-V virtualised platform based upon Windows Server 2012 that delivers virtual Windows 7 desktops. These are accessed by staff using remote desktop connection services, including their own Windows-based home computers.

Desktop security applications used include Checkpoint Secure Client, McAfee Total Defence Suite and McAfee 8.8. Some JNCC staff also use R Studio, which may be linked to QGIS.

6.2 QGIS delivery

Because QGIS is open source there are no limitations on the number of active copies in use at any one time. QGIS is also entirely free. These are the main advantages of QGIS over proprietary GIS, though there are disadvantages.

Based upon this review, it is clear that some functionality in ArcGIS is not available in QGIS, including some functionality JNCC consider to be essential. QGIS is also almost completely unsupported, with no channels that will guarantee issues and bugs are resolved. The potential cost savings will also be partially offset by the cost of training staff to use the software and the potential delays as staff have to relearn how to use frequently updated QGIS versions and plugins. JNCC will need to assess whether the cost savings of reducing

their number of ArcGIS licenses will outweigh the costs and difficulties associated with moving to QGIS.

Should JNCC decide to deliver QGIS, installation is simple. The standard QGIS installer comes as an exe that also contains all required dependencies. Multiple QGIS versions can be installed in parallel, so newly installed versions do not replace old versions. As a result updating to a new version involves installing the new version and then uninstalling the old version.

Alternatively QGIS can be installed using the OSGeo4W network installer (<http://trac.osgeo.org/osgeo4w/>). This also installs a range of other open source geospatial software, including many that are valuable to QGIS users. One advantage is the ability to use the QSGeo4W installer to update any of these components, including QGIS itself, without having to manually uninstall older versions. However, care is needed to ensure that the intended version of QGIS is installed, which can be achieved through advanced install.

Released versions of QGIS are generally stable on release, having been extensively tested during development. However, it there is often a delay between release of a new version and plugins being updated to work with the new version, so it is often advisable to delay updating QGIS or install parallel versions so that plugins are still available on the older version. New versions also often include substantial changes to the layout and appearance of QGIS, which may take users a while to get used to and may justify not installing every version if the available functionality and stability is sufficient to meet user needs.

Once QGIS is installed, the installation of plugins generally requires no special windows permissions, as most are simply downloaded DLL's (though there may be plugins that have additional external components).

It is recommended that JNCC deliver QGIS as a Citrix published application. It should be possible to establish a JNCC implementation of QGIS, containing all required plugins, and then copy all installed files to another location. There is one system registry key (QGIS project class) that would need to be created when copying a QGIS install, but other registry settings are not created by the QGIS installer. This implementation could then be published via Citrix. This would also allow updates to QGIS or additions to the implementation to be trialled before being published via Citrix.

It is recommended that all plugins required by staff are made available via Citrix, but that only the most frequently used are enabled in the QGIS implementation. This will reduce the number of icons and menu entries in QGIS, making it more accessible for users. Users that require the more advanced functionality would be able to enable the relevant plugins each time they use QGIS.

6.3 PostgreSQL and PostGIS

PostGIS (<http://postgis.net/>) is a spatial database extension to the PostgreSQL object-relational database, both of which are open source. It is recommended because the spatial functionality in PostGIS is superior to that available in Microsoft SQL Server, it is better integrated into QGIS and its use will help JNCC to meet the UK Government Digital Service Open Standards principles (Cabinet Office 2013). Storage of spatial data within a centralised spatial database server will also ensure that all data are properly backed up.

PostgreSQL 9.3 or above should ideally be installed on a single centrally available server, though if performance becomes an issue it may be sensible to have two synchronised PostgreSQL servers in Peterborough and Aberdeen, for example through the Data Sync

tool. PostGIS can be installed immediately following install of PostgreSQL using the Application Stack Builder, through which an initial spatial database can be created.

PostgreSQL can be configured to use Active Directory when it is built by using either SSPI or GSSAPI authentication (PostgreSQL Global Development Group 2014), though this is not straightforward. In addition, users need to be setup in PostgreSQL and PostgreSQL user groups, which may be time consuming for IT staff. It may therefore be better to use password authentication.

Microsoft SQL Server 2008 or later could be used instead, but is proprietary, cannot store raster data and lacks some valuable functionality available within PostGIS, such as the ability to translate data between coordinate reference systems. QGIS also lacks the functionality to export data to SQL Server. Nevertheless, even if PostGIS is used, data that needs to be kept in SQL Server, such as the Marine Protected Area database, may still be viewed and edited in QGIS.

It should be noted that the only advantage of storing raster data in PostGIS, other than centralisation and easier backup, is increased speed during analysis. The disadvantage is that they dramatically increase the database size. For base map rasters and potentially more generally it may be more appropriate to store them in a separate location as GeoTiffs. These can still be catalogued in PostGIS, which can reference external raster files, allowing them to be treated as a single layer in a similar way to VRT's. Data saved outside of the spatial database server must be in an appropriately backed up location.

6.4 ArcGIS delivery

Even if QGIS is adopted by JNCC it is clear that a limited number of ArcGIS licenses will be required to ensure that some functionality that is lacking in QGIS can still be used. It is possible that some of this advanced functionality will be developed for QGIS in the future, but some ArcGIS use would be required in the short term. ArcGIS may also be useful for checking data and creating map documents⁴ before disseminating to partner organisations. JNCC would need to decide how many users are likely to need ArcGIS or the relevant extensions at any one time and determine the number of licenses required appropriately.

ArcGIS could be delivered via Citrix or virtual machines. Due to the restricted number of licenses its use would need to be strictly controlled, so that staff do not use it for tasks that could be carried out in QGIS at the same time as others have a real need for the advanced functionality. This could either be done through a booking system or restricting access to a smaller number of ArcGIS specialists. The latter may be preferable as staff change, as it will not be necessary to train as many staff in the use of two GIS.

6.5 Data migration

Existing spatial data would need to be migrated to the spatial database server. In many cases this could be done on an *ad hoc* basis, as long as data are being adequately backed up, as data stored in shapefile format can be readily loaded into PostGIS via the QGIS database menu.

Data in other formats will be harder to load into PostGIS. Smaller datasets can be exported to shapefile format and imported as described above, but larger datasets may exceed the file

⁴ Note that it would not be possible to develop a tool for QGIS that could create an ESRI map document, as this is a proprietary format.

size limits for shapefiles. A tool such as GISquirrel (<http://www.gisquirrel.com/>) may help with this, as it has functionality to import any data open in ArcGIS into PostGIS. Additionally, it can make the migration of any existing data in SQL Server to PostGIS more efficient, though such data can be exported from SQL Server as text and then imported into PostGIS. Alternatively it should be possible to further develop the PostGIS integration in QGIS to allow easy import of a greater number of vector data types.

There are very few options available for loading raster data into PostGIS. The currently recommended approach is to use the raster2pgsql command line executable raster loader (PostGIS Development Group 2014). This gives flexibility to import multiple rasters with a single command, but in the future it may be appropriate to have a more user friendly interface available through QGIS, if import of rasters into PostGIS occurs frequently. Unless absolutely required for analysis, it may be more appropriate to store raster datasets outside of PostGIS.

6.6 Data management

Implementing both QGIS and ArcGIS will inevitable mean that clear data management and version control protocols will need to be enforced. These protocols should aim to reduce the risk of outdated versions of data being used where the most up to date version is in an unexpected file format.

Since QGIS would be available to all JNCC staff all current versions of data should be maintained in a QGIS editable format, most appropriately in a PostGIS database. Data to be processed in ArcGIS will need to be migrated to an ArcGIS editable format, processed, and then returned to QGIS format. The temporary ArcGIS versions could then be deleted.

It may nevertheless be necessary to maintain current versions in ArcGIS, where for example data must be maintained in a specified ArcGIS format. Such data should be documented.

Some issues with versioning could be resolved through the use of a tool such as GISquirrel. This allows ArcGIS to use and edit data in PostGIS, which would mean that ArcGIS could process the data used by QGIS directly. However, this would only eliminate the versioning issues associated with vector data processing in ArcGIS.

Data management processes will also need to be implemented in PostGIS, ensuring the removal or archiving of old versions of data from the relevant spatial databases. The versioning functionality available in PostgreSQL could also be used.

6.7 Initial delivery trial and performance testing

There are three key areas of uncertainty that could not be explored during this work:

- the ease with which QGIS can be implemented though JNCC's IT infrastructure;
- performance of QGIS on JNCC's IT infrastructure;
- how quickly JNCC staff can acquire the knowledge to use QGIS effectively.

The only way to resolve these uncertainties is to undertake a trial of QGIS delivery within JNCC and performance testing, which will also provide the opportunity for users to learn to use much of the functionality within QGIS. This is recommended as the next step towards QGIS implementation within JNCC and should cover the following:

- set up and delivery of QGIS through Citrix;
- use of the standard QGIS install vs. the OSGeo4W network installer;

- set up of PostGIS, its use for data storage and its accessibility;
- data migration;
- initial development of data management protocols;
- any issues with firewalls, antivirus or anti spyware;
- raster (geotiff) handling performance;
- performance of specific key datasets within QGIS, such as the Defra Marine Reference Dataset (DEM);
- print composer, to ensure it has the required functionality.

The trial could also be used to help estimate the number of ArcGIS licenses required by determining the frequency of occasions where QGIS cannot undertake required tasks.

Clearly this has cost implications in terms of JNCC staff time. Most likely third party support and training will also be required.

6.8 Training

Though QGIS and ArcGIS often function in very similar ways, there are differences. JNCC staff will therefore need to be trained to use QGIS. Various foundation courses for QGIS exist, which should provide staff with a good grounding in QGIS used. These will be relatively inexpensive, since the costs of preparing training materials are spread between a large number of trainees.

Beyond this basic training, much of the tasks carried out by JNCC staff in GIS will require bespoke training. These will require the preparation of training materials to cover more specialist aspects, some of which are likely to be very advanced and require time to present clearly. This will increase the cost of training, but will allow the use of JNCC data and real world situations to target the training to user needs. Repeat delivery of these training courses will be more cost effective, as the training materials will have already been prepared.

It is appropriate to have a number of separate training courses, targeted towards users that require it, including:

- general foundation and intermediate QGIS use (two courses);
- advanced vector analysis;
- advanced raster analysis;
- network analysis and least cost;
- data management, processing and analysis in PostGIS;
- advanced data processing in GRASS, beyond the QGIS toolbox;
- introduction to Python scripting and use.

Other courses are also possible, such as semi-automatic land cover classification from remote sensed data, but we do not anticipate that JNCC use of such functionality will be extremely limited.

The use of multiple courses will ensure the each course is relatively short and there is sufficient time to cover all of the material. This will help to avoid trainee exhaustion and disillusionment.

6.9 Development

From the review and discussions during the consultation meeting it is clear that there is some functionality that is required by JNCC that is currently absent from QGIS. Such functionality will need to be developed, either by developing core QGIS functionality or through the development of existing or new plugins. This will need to be funded, but we recommend that the resulting code is made open source and any new plugins are added to the QGIS repository.

It is probably initially acceptable to utilise the functionality available in ArcGIS where it is lacking from QGIS, until such time as it is developed and implemented in QGIS. Nevertheless, there are two elements of functionality that should be developed for QGIS as a higher priority:

- **Metadata functionality**
The core metadata functionality and the plugins for QGIS are currently very weak. JNCC requires functionality that attaches INSPIRE compliant metadata to the data and is ideally automatically visible in the QGIS metadata tab. This will require substantial changes to core QGIS functionality, but would potentially benefit a large number of other QGIS users.
- **Raster attribute tables**
JNCC handle categorised raster data on a regular and frequent basis, so need the ability to associate the raster values with their associated categories. The process of assigning a category to an area can often be complicated, being based upon a number of rasters and vector masks. A separate table therefore wouldn't suffice, as the categories to be very clear for ease of use. It should be possible to develop this functionality as a QGIS plugin.

All new functionality will need to be clearly specified prior to development, which will require discussion between JNCC and the development team. New functionality should be thoroughly tested by both the development team and within JNCC, prior to full implementation. Functionality can also be tested by a wider range of users by making functionality available via the nightly build (for core functionality) or as an experimental plugin.

All additional functionality, whether core or plugin, will need to be tested and updated to work with future releases of QGIS. New release versions of QGIS are currently planned for every four months. This potentially means that further development may frequently be required, but may be mitigated by:

- core functionality being 'adopted' and maintained by members the QGIS development team;
- frequency with which JNCC updates the version of QGIS used, as it will not be necessary to update plugins to work with newer versions of QGIS if JNCC have no intention of upgrading;
- inclusion of plugin updates in third party support contracts (Section 6.10).

6.10 QGIS support

As with any open source software, support for users of QGIS and its plugins is limited and there is expressly no warranty in the standard GNY General Public License under which it is distributed. Whilst there is an active QGIS support mailing list the members of the list are not required to answer any queries posted. If a bug is reported in the software the

developers are under no obligation to fix it, and similarly do not need to develop extra functionality requested. All core QGIS development is added to a centralised list, prioritised and allocated to individual developers based upon the need perceived by the developers.

As a result, the QGIS team recommend commercial support contracts with third parties, which is likely to be required by JNCC. The support contract should cover:

- user support and advice;
- IT support and advice;
- development call-off, which would allow for rapid fixing of bugs encountered or the development of new functionality, though note that maintenance of functionality developed for JNCC may suffer due to frequent changes in the support supplier.

It may additionally be appropriate to include the provision of training, as this will ensure that the training provided is consistent and ensure that a long-term relationship can be established between tutor and trainees.

It is also possible to fund the development of functionality through donating or funding the developer directly. In some cases this may be appropriate for functionality already on the list that is expected to meet JNCCs requirements.

6.11 Costs

The full costs of implementing QGIS within JNCC are difficult to assess, as much depends upon the amount of time required for staff to set up and use the software, and the amount of third party support and training required. It is also not clear what price JNCC would have to pay for a reduced number of ArcGIS and licences, as any deal they currently have may change. The cost estimates can be improved following the initial trial and performance testing. Estimated costs for implementing QGIS within JNCC are shown in Table 2.

Table 2 – Estimated costs for implementing QGIS within JNCC.

Item	Estimated cost	
	One time	Annual
QGIS licensing	-	£0
ESRI ArcGIS Desktop Advanced licensing costs ⁵	-	Unknown
ESRI Spatial Analyst costs	-	Unknown
QGIS and PostGIS installation and delivery costs	3-5 days of JNCC staff time	Variable, depending upon frequency of update
Initial delivery trial and performance testing	3-7 days for each JNCC staff member involved, depending upon how thorough the testing is, plus third party training and support costs	-
Development and implementation of ArcGIS booking system	1-2 days of JNCC staff time	-
Data migration	5-15 minutes per dataset on average	-
Development of data management protocols	2-3 days of JNCC staff time	Negligible internal costs in keeping the guidance up to

⁵ ArcGIS installation and delivery costs are excluded, as these are already being met by JNCC.

		date
Third party support	-	£500-£700 per day
Development of metadata functionality	£11,500-£18,000	Variable, depending upon frequency of QGIS update and support arrangements
Development of raster attribute table functionality	£11,500-£18,000	

It is not possible to give a single estimate for JNCC staff training in QGIS, as much depends upon whether a bespoke course is required and the level of expertise required. More advanced courses will take more time to prepare and require a high level of expertise in the area, which will increase the costs. Estimated costs for preparing and delivering the training courses suggested in Section 6.8 at JNCC's offices are provided in Table 3, along with the likely duration of the course.

Table 3 – Estimated costs for training JNCC staff in QGIS use.

Course	Estimated cost	
	Initial creation of materials and delivery	Repeat delivery ⁶
QGIS foundation (2 days)	- ⁷	£1,500-£2,000
QGIS intermediate (2 days)	- ⁷	£1,500-£2,000
Advanced vector analysis (1 day)	£2,350-£3,300	£850-£1,200
Advanced raster analysis (2 days)	£4,000-£5,500	£1,500-£2,000
Network analysis and least cost (2 days)	£4,000-£5,500	£1,500-£2,000
Data management, processing and analysis in PostGIS (2 days)	£3,500-£4,800	£1,500-£2,000
Advanced data processing in GRASS (2 days)	£4,000-£5,500	£1,500-£2,000
An introduction to Python scripting in QGIS (1 day)	£2,350-£3,300	£850-£1,200

Optionally JNCC may also purchase GISquirrel to help with data migration and increase compatibility of ArcGIS and PostGIS data. The cost of GISquirrel is currently £150 plus VAT per license, though JNCC may be eligible for free licences.

We note that JNCC currently uses Fledermaus for 3D analysis and visualisation. Since QGIS offers no replacement functionality JNCC would need to continue to use Fledermaus. The costs of are not shown in the table, as JNCC already have to meet them.

⁶ Some re-familiarisation costs are associated with each new version of QGIS, but will not require additional formal training.

⁷ It is assumed that existing QGIS foundation and intermediate courses will meet JNCC's needs, so course materials will already exist.

7 References

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Appendix 1

Please see the spreadsheet: [Appendix1_CoreFunctionality.xlsx](#)

Appendix 2

Please see the spreadsheet: [Appendix2_Spatial3DAnalystFunctionality.xlsx](#)