SUCCESSFUL DEMONSTRATION OF THE FEASIBILITY OF APPLYING THE USGS RESOURCE ASSESSMENT METHODOLOGY TO NEAR-EARTH OBJECTS. L. Keszthelyi[1], D. Trilling[2], J. Hagerty[1], N. Moskovitz[3], [1]USGS Astrogeology Science Center, Flagstaff, AZ 86001, [2]Northern Arizona University, Flagstaff, AZ 86001, [3]Lowell Observatory, Flagstaff, AZ 86001.

Introduction: In 2017 the United States Geological Survey published report on the feasibility of assessing natural resources in asteroids [1]. Here we provide a synopsis of this study, emphasizing our rationale for the need for this type of assessment. We also provide a brief summary of the USGS resource assessment methodology, with a discussion of how these methods were modified for application to asteroids. We also suggest some areas of research that would enable an actual resource assessment in the future.

Rationale for Solar System Resource Assessment: The long-term goal of the United States space program is establishing a human presence on Mars. This goal has been remarkably stable for decades through changes in administration, geopolitical situations, economic conditions, and generations of the American public. One can debate the merit of this goal, but it can be expected to persist at the core of our Nation's space policy for decades to come.

Several major challenges must be overcome before there are human footprints on Mars. The most problematic obstacle may be the price tag, a large fraction of which comes from hauling material out of Earth's gravity well and landing it gently onto the surface of Mars. Obtaining key resources (e.g., water and metals) in the space between Earth and Mars could dramatically reduce the costs of a trip to Mars. A sustained human presence on Mars is only practical if local resources can be utilized. The most obvious way to obtain such resources is to mine near-Earth objects (NEOs) and the shallow subsurface of Mars (and perhaps the Moon). Enabling such mining will almost certainly be a key component of the future US space program.

Before such mining can be prudently undertaken, unbiased, quantitative, and reliable assessments of key resources will be needed. Creating such assessments is the Congressionally mandated responsibility of the United States Geological Survey. The "Organic Act" of 1879 established the USGS with a few specific obligations, one of which was "the classification of public lands and examination of the geologic structure, mineral resources, and products…" In 1962, Congress extended those examinations to "beyond the borders of the United States."

In 2015 the USGS recognized that this phrase extends the USGS legal obligation to space. At this time Congress has not provided funding specifically to assess extra-terrestrial resources. Nevertheless, the USGS Mineral Resources Program leadership decided that it was prudent to fund a small feasibility study to examine if current USGS methods can be applied to asteroids.

The USGS Resource Assessment Methodology: The USGS minerals, energy, and water resource assessments are all designed to produce unbiased and reliable results in a format readily understood by decision makers who are not technical experts in the field [2]. Here we adopt the terminology used in mineral assessments, but the concepts are similar for all resources. This methodology is often called the "three-part" model because it combines three separate quantitative models via numerical methods to produce the statistics for the final assessment.

For each resource, a prerequisite for quantitative assessments is the development of qualitative *descriptive models* of each geologic setting in which the resource can be found. This is a description of the association between the resource and geologic units and processes.

The first of the three quantitative models is the *spatial model*, which delineates tracts that contain the geologic setting described in the *descriptive model*. In other words, the *spatial model* is a map of the areas where the geology permits the existence of deposits of the resource, not a map of the resource deposits themselves [2]. The second model is the *grade-tonnage model* for each geologic setting. "Grade" is the concentration (or quality) of the resource and "tonnage" is mass (or quantity) of the deposit. These models are usually expressed mathematically as multivariate probability density functions (pdfs) for the resource concentrations and ore tonnages of the deposits in the assessment area. The third model is the *deposit-density model*, a mathematical description of the expected number of deposits per unit area.

The *deposit density* and *grade-tonnage models* are statistically combined to calculate the expected size and quality distribution of deposits per unit area at various confidence levels (typically 10, 50, and 90%). Monte Carlo methods are the most commonly used statistical method because of their flexibility and mathematical simplicity. An economic model that describes the cost to set up an extraction operation and then operate it can be applied. Even a simple parametric model is usually sufficient to indicate whether the expected deposits are worth extracting. After combining with the areas identified in the *spatial model*, the final outputs are (1) the minimum number, size, and quality of economically viable deposits at various confidence levels and (2) a map of where these deposits may exist.

It is worth re-iterating that this methodology can apply to any type of resource and decades of experience has shown that this is the most useful format to provide the assessment to decision makers.

Adjusting and Applying the USGS Resource Assessment Methodology to NEOs: The closest analog to the concept of a geologic setting in the NEO population is taxonomy based on mineral assemblages. For the sake of this feasibility study, we only consider 3 classes (stony, metal, and carbonaceous). Since NEOs move in 3-dimensional orbits, the spatial distribution of the "deposits" cannot be described in a 2-dimensional static map. However, the concept of "distance" to an object is well-characterized by the energy (i.e., Δv) required to reach it. For demonstration purposes we include all objects with a Δv less than 7 km/s from low-Earth orbit, but the methodology can readily be applied to smaller bins of Δv to provide the equivalent of a spatial map of the resource distribution.

The equivalent of the deposit density model is provided by the detailed sky surveys being conducted to identify the potentially hazardous NEOs. The data are better than 90% complete for the kilometer-scale objects but are poor at the scale of tens of meters or less. We demonstrate how undiscovered objects can be included in the assessment statistics by adding up to 43 undiscovered km-scale objects to the 428 known ones.

The tonnage model, or mass distribution of NEOs is constrained by surveys of potentially hazardous NEOs. A key source of uncertainty is the density of the objects, driven by the poorly understood porosity of asteroids.

The grade model is perhaps the most challenging part of NEO resource assessments. Since few NEOs have any direct chemical or mineralogical analyses, we must rely heavily on meteorite samples. Then spectroscopic observations must be used to link NEOs to meteorites. As described below, new research could significantly reduce the large uncertainties in this model. For this study we consider only water (often in the form of OH in meteorites) and metallic iron.

The combination of the different models via Monte-Carlo methods can be done using numerical techniques identical to those used for terrestrial resource assessments without new innovations.

Figure 1 and Table 1 show the output of the feasibility study. We strenuously emphasize that the values presented here should not be considered an actual USGS assessment. They are intended to be illustrative of the manner in which the results of an assessment are delivered. The values could easily be incorrect by orders of magnitude.

Table 1. Minimum amount of water and metallic iron resources in the near-Earth asteroids

	90% probability	50% probability	10% probability
Water	11,000 Gt	18,000 Gt	38,000 Gt
Iron metal	61,000 Gt	99,000 Gt	200,000 Gt

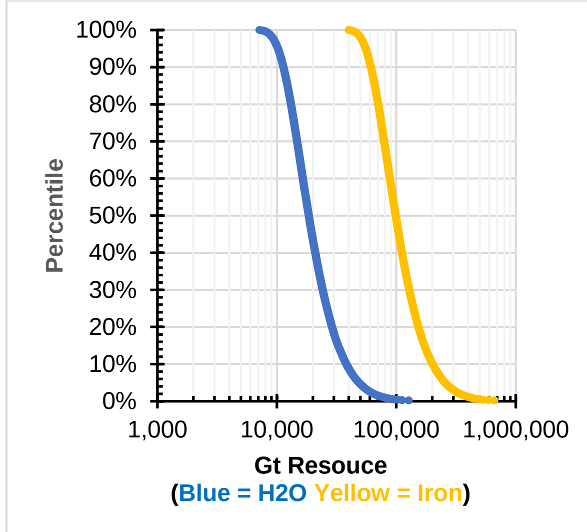

Figure 1. Output of modeling showing how the minimum amount of water and metallic iron resources in near-Earth asteroids would be represented in a USGS resource assessment.

Future Research to Enable Solar System Resource Assessments:

In-situ observations. A proper resource assessment will require many more detailed and systematic observations of the grade of planetary resource deposits. The manner in which the resource is distributed, the mechanical properties of the host material and the types of trace contaminants can greatly affect how much of the desired resource can actually be extracted. To ascertain these types of properties, it is necessary to conduct in-situ studies supported with detailed laboratory investigation of returned samples.

Linking in-situ to remote observations. No resource assessment can rely solely on in-situ data. The key is to link the geologic processes of interest to measurements that can be obtained on a regional scale via remote sensing. For example, the thermal and space-weathering processes that alter the outermost layers of an asteroid may hide key spectral features indicative of the real water content of an asteroid.

Remote sensing observations. The ability to map out the locations with the right geologic setting to contain high abundances of high-grade resource deposits will almost certainly require combining data sets with very different spatial, temporal, and spectral characteristics. Even as future instruments collect robust data from these challenging targets, it will be essential to develop the tools to properly fuse disparate data sets.

References: [1] Keszthelyi L. et al (2017) USGS Open-File Report 2017-1041. [2] Singer D. A. (2007) *USGS Open-File Report 2007-1434*.